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Evaluation of Grouting as a Strengthening Technique for Earthen Structures in Seismic Areas: Case Study Chiripa

Charu Chaudhry
University of Pennsylvania

A Thesis in Historic Preservation Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Master of Science in Historic Preservation 2007.
Advisor: Koenraad van Balen

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In

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MASTER OF SCIENCE

IN HISTORIC PRESERVATION

2007

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FOR SANDEEP

“ . . . It is more likely to be a solution already open to all hybridizations: not the solution that, in its clarity, is able to include and confront authentic differences, but rather a solution that tends to drown such differences in the process of homogenization set in motion by diversity turned into pure ideology . . .”

Gregotti Vittorio
Inside Architecture

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF GRAPHS

LIST OF FIGURES

1.0. RESEARCH OBJECTIVES

1.1. Introduction

Chiripa has been long associated with the pre-contact Andean societies. It was discovered in 1934 by archaeologist Wendell C. Bennett under the auspices of the American Museum of Natural History in New York City. The site has been identified as an early locus of public architecture and ritual paraphernalia in pre Columbian Bolivia. As such, its cultural and archaeological importance suggests both stabilization and display are crucial for public visitation and community pride. The ongoing archaeological excavations and research since the 1930s have made Chiripa a unique and rich repository for scholars, visitors, and students interested not only in the history of ancient Chiripa but also the conservation issues regarding the protection and maintenance of cultural fabric of earthen sites especially in seismic areas. Because Chiripa lies in a vulnerable seismic zone between the cordilleras of the Taraco mountain range, any efforts to preserve and display the site will need to consider remedial and preventive conservation interventions.

This thesis proposes to evaluate grouting as a strengthening technique for earthen-rubble masonry by assessing the earthen walls of a pre Columbian house at Chiripa for the performance characteristics of grout formulations. The assessment will examine the selected physico-chemical properties of the earthen masonry system as well as its compatibility with the chosen grout formulation and the ability of grouting to reintegrate observed failures. Understanding performance and rheological characteristics of grouts is crucial for the design of compatible, low-invasive stabilization. Good working properties are of prime importance because they enhance a homogeneous filling of cracks and voids in the masonry to provide a monolithic mass after setting and of the grout. Hence grouts should re-establish integrity to friable earthen and cobble walls of Chiripa.

1.2. Identification of the Problem

The following sub-problems were identified as critical to the thesis research:

- Defining the notion of "compatibility" of treatments such as grouting for historic masonry systems through qualitative and quantitative limits.
- Determining the structural characteristics of traditional earthen masonry systems at Chiripa
- Determining the properties of the existing earthen construction materials.
- Developing a responsive design solution for the local climate and environment
- Developing a critical review of the literature for grout and grouting techniques specifically applied to earthen masonry in seismic areas.
- Reviewing and identifying test methods for evaluating the critical properties of earthen materials and grouts

1.3. Objectives

The following treatment goals were identified:

- Improving the mechanical behavior of a damaged structure requires the design of a grout with good injectability, low shrinkage and good bonding properties.

- Grouting aims to address the structural discontinuity in masonry through the introduction of an adhesive material with gap filling properties
- The factors that control the seismic strength of the earthen masonry are the type of clays present, the adequate content of coarse sand, low moisture content
- It is important to increase the overall strength of earth masonry to control the cracking in the post elastic stage and maintain its stability.

1.4. Delimitations

This study will attempt to evaluate the process of grouting and grout formulations as applied to crack and void repair of the traditional puddled earthen masonry at Chiripa. Existing data on hydraulic lime grouts will be evaluated as to their compatibility and therefore application for the Chiripa example. Primarily tensile bonding test (4-Point Bending test) will be conducted to evaluate the performance of some grouts to regenerate bond in the earthen material through over-bridging cracks.

1.5. Assumptions

The following assumptions were made in the research:

- The repair and strengthening of historical monuments constructed in seismic zones should be carried out without introducing any changes or strengthening of the main structural systems which could cause preferential damage to the original structure. The improvement in the load carrying and deformability characteristics should be tested experimentally.

- Improving the mechanical behavior of a damaged structure requires the design of a grout with good injectability, low shrinkage and good bonding properties.
- Grouting aims to address the structural discontinuity in masonry through the introduction of an adhesive material with gap filling properties. The reintegration of discontinuities is the principle of strength gain without the associated disruption of the assembly.
- It is important to increase the overall strength of earth masonry to control the cracking in the post elastic stage and maintain its stability.

2.0. SITE OVERVIEW

2.1. Taraco Peninsula

The Taraco Peninsula is an east-west land formation projecting into the southern arm of Late Titicaca. Since antiquity, the Lake Titicaca region of the present day Bolivia-Peru border has been a significant habitat where Pre-Columbian cultures have developed, persisted, and collapsed. The high-altitude basin is located between the eastern and western Andean cordilleras and covers an area of 57,000 km^2. The area adjacent to Lake Titicaca has long been a major center of agricultural production and dense human populations where the earliest agricultural communities date to the Chiripa culture.

Figure 2.1: View of the Lake Titicaca Basin from the Temple Mound (TAP 2006)

The archaeological site of Chiripa is associated with the Tiwanaku culture and was occupied between 1000 BC and 1100 AD. Chiripa culture developed in the southern

Titicaca watershed in approximately 1500 BC, historically coincident with greater moisture availability and rising lake levels. Cultural development and population expansion occurred under conditions extremely favorable for agriculture and domesticating animals. The cultural settlements flourished modifying their immediate environments significantly leading to an alteration of the local biogeochemical cycles. A recent analysis of Titicaca sediment cores document a prolonged dry period that began in approximately 1100 AD. This drought was essentially associated with the raised field abandonment and cultural decline leading to collapse of the entire region including that of Chiripa[1].

2.1.1. Local Geology and Sub Soil

The conglomerates of the Taraco Formation are composed predominantly of quartzite cobbles. The ground surface over most of the peninsula is covered with quartzite cobbles of all sizes. Gravels predominate in clasts with diameters of upto 20 centimeters embedded in a sandy-clayish matrix.[2] However, the formation also contains large quantities of chert pebbles and cobbles. These are smaller than the quartzite cobbles, rarely exceeding 8 cm. These chert nodules were frequently worked using a hammer and anvil bipolar technique to extract short small flakes. As a result the entire

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[1] Abbott, M.B., M.W. Binford, M. Brenner, and K.R. Kelts. 1997. A 3500 ^{14}C yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. Quaternary Research 47:169-180

[2] Argollo, Jaime, Leocadio Ticcla, Alan Kolata, and Oswaldo Rivera, 1996, Geology, geomorphology and soils of the Twiaqnaku and Catari River Basins, In Tiwanaku and its hinterland, edited by Alan Kolata, Smithsonian Inst., Washington DC, pp. 57-88

surface of the peninsula is a low-density lithic scatter. The quartzites of the Taraco Formation contain fossils, frequently trilobites[3].

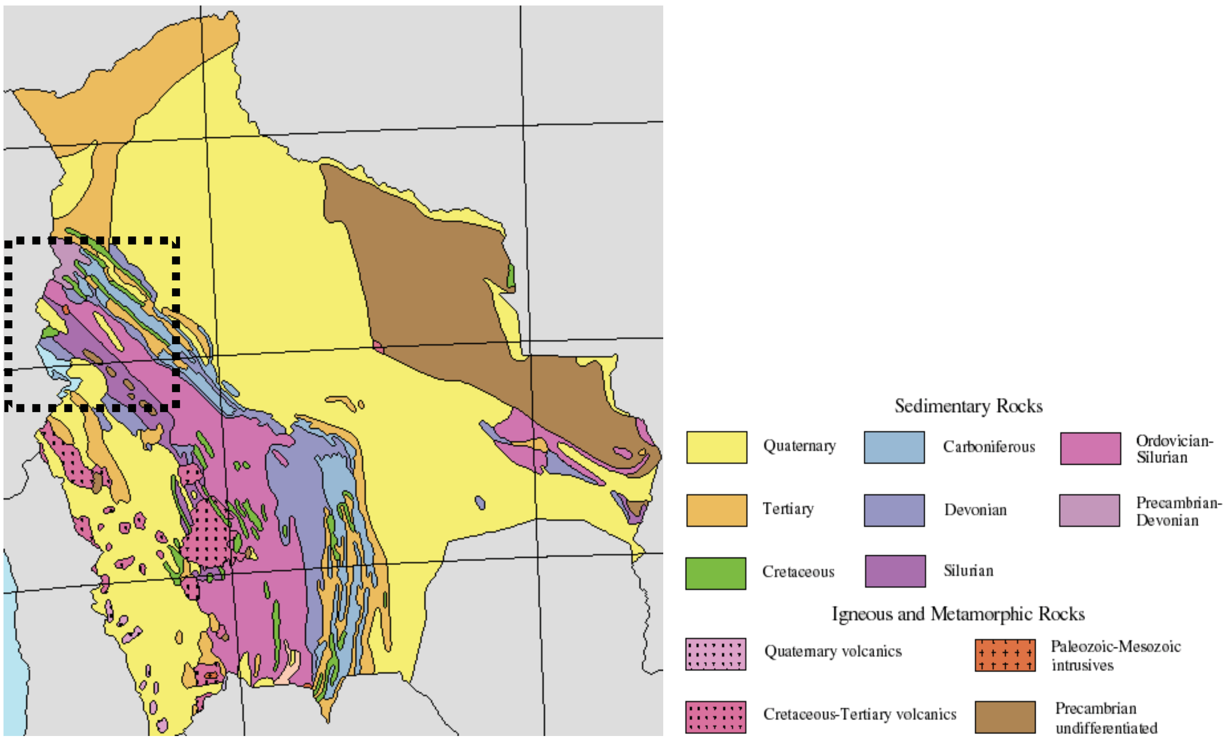

Figure 2.2: Geological Map of Bolivia

The Taraco region is also composed of silty fine sands and clays that are glacial deposits. These are interbedded with coarser clasts from sedimentary deposition through the glacial cycles. The soils are poorly consolidated and the permeability ranges from low to medium.[4] The soils around Montículo are also characterized by a predominance of fine

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[3] Bandy, Mathew "Population and History in Ancient Titicaca Region" PhD Dissertation, Graduate Division of the University of California, Berkeley, 2001
[4] Argollo, Jaime et.al, 1996, Geology, geomorphology and soils of the Twiaqnaku and Catari River Basins, In Tiwanaku and its hinterland, edited by Alan Kolata, Smithsonian Inst., Washington DC, pp. 57-88

sands and silts derived from carbonate and igneous rocks, most likely from the Taraco Mountain range. The particle size sorting and fine clay coatings on coarse sand grains suggest deposition by water and may represent fine matrix flowing down into this area. There were also observed biological processes used to substantially mix the soil to encourage soil movement and aerate the soil[5].

A number of features associated with the post depositional disturbances were noted including more visible biological processes and microscopic mineralization of the soils. Secondary mineral formation of amorphous calcium carbonate is distributed in the soil and the neoformation of calcitic crystals have been observed within pores. The second process of clay alluviation, forms coatings on pores in the upper layers of Montículo. Third sesquioxide (iron and manganese) impregnation is well distributed in soils suggesting that these metals are leaching into soil waters[6].

2.1.2. Climate and Seismic Characteristics

The climate of the Titicaca Basin is dominated by typical tropical wet-dry seasons. The majority of the precipitation is derived from warm air masses arriving from Amazonia, to the east. Located as it is between two major weather systems, the Atlantic-Amazonian and the Pacific, climate in the Titicaca Basin is highly variable.

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[5] Goodman, Melissa, "Soil Micromorphology of Depositional Sequences from the Montículo and Santiago Excavations". In Early Settlement at Chiripa, Bolivia. Ed. Christine Hastorf, 1998, p 51-60
[6] Ibid

Physiographically, the Taraco Mountain Range exhibits a highly folded structure formed by sandstones and red mudstones of the Lower Tertiary Tiwanaku Formation. It is believed that the crustal thickening by structural shortening is responsible for the topographic uplift of this second highest continental plateau. Although shortening is deemed important, virtually nothing is known of the geometry of the major faults or the distribution of shortening at depth. [7]

The spine of the peninsula is formed by the *Lomas de Taraco* - the Taraco hills. These are low, rolling hills whose peaks rarely exceed 4000 meters at sea level. Geologically, the Taraco Hills are formed by the Taraco Formation. The Andes run in two great parallel ranges (*cordilleras*). The western range (Cordillera Occidental) runs along the Peruvian and

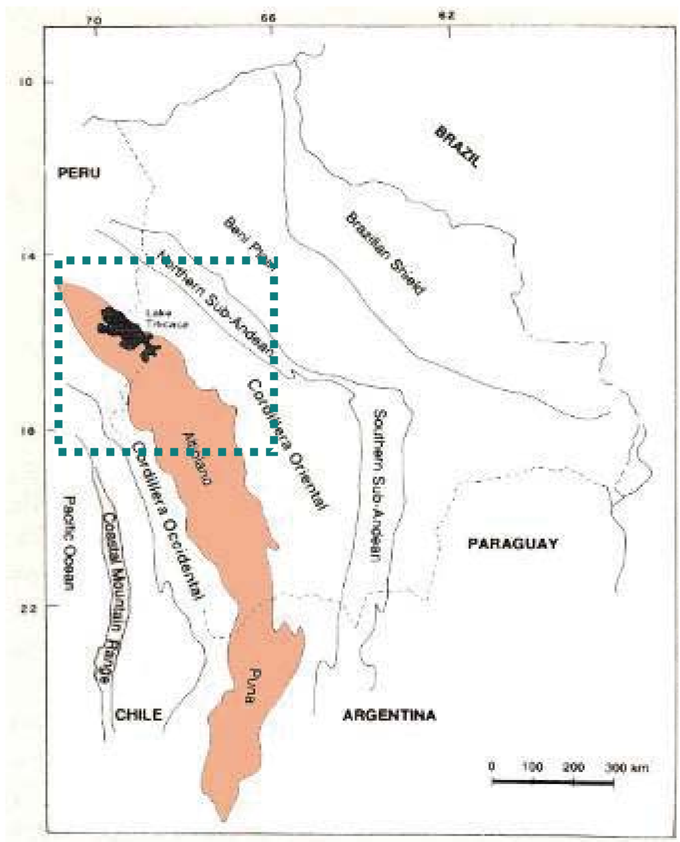

Figure 2.3: View of the Cordilleras around Altipano

[7] Allmendinger, R et al., "Imaging the Andean Structure of the Eastern Cordillera on Reprocessed YPF Seismic Reflection Data". In XIII Congresso Geologico Argentino,Actas, v. II, p. 125-134

Chilean borders. The eastern range (Cordillera Oriental) is a broad and towering system of mountains stretching from Peru to Argentina.

These two tectonic provinces are separated from each other by the Interandean (or Transition) zone which is bounded by two major fault zones, the *Cabalgamiento Frontal* Principal (CFP) and *Cabalgamiento Andino* Principal (CANP). Shortening within the Subandean belt increases progressively northward from less than 60 km in northern Argentina to 100 kms in Southern Bolivia. Many topographic lineations assumed to be related to strike-slip faulting have been identified in the area around Aiquile, however none has been demonstrated to be active.

In June 9, 1994, the largest deep focus earthquake (Mw = 8.2) was recorded in Bolivia. The main rupture was preceded by about 10 sec by a cluster of smaller events with a total moment of 1.2×10^{20} Nm (Mw=7.3)[8]. In 1998, an earthquake (Mw = 6.6) struck the Aiquile region, a town in close proximity to Chiripa. This was the largest shallow earthquake with a strike slip mechanism to occur in Bolivia in over 50 years. La Paz, located about 50 kilometers from Chiripa has witnessed earthquakes with magnitudes ranging between 4.5-5.5 on Richter scale in 2001 and 2007 respectively as well as various post earthquake tremors in the spanning years.

[8] Kikuchi, M., and H. Kanamori (1994), The mechanism of the deep Bolivia earthquake of June 9, 1994, Geophysics. Res. Lett, 21(22), 2341–2344.

2.2. Site Description

2.2.1. Excavation History

The *hacienda* of Chiripa lies on the northern side of Taraco, near the base of the peninsula. It is a large artificial mound with traces of a stone cut temple on top and various houses around it. Almost seventy years of sporadic archaeological research since the early 20th century have demonstrated that the Taraco Peninsula was an early locus of settled village life. The region also saw very early development of public architecture and ritual paraphernalia[9].

1934: Wendell C. Bennett

Excavation of the mound by Wendell C. Bennett[10] in 1934 revealed two Chiripa levels: a lower level "pre-mound" strata, below and an upper level mound or "house" strata. Bennett excavated two houses of the upper level and based on the geometry and plan, speculated the existence of 14 structures forming a rough square or octagon around a central open area.

1940: Maks Portugal Zamora and María Luisa Sánchez

The next researchers to conduct archaeological work on the Taraco Peninsula were Maks Portugal Zamora and María Luisa Sánchez Bustamente de Urioste in 1940.

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[9] Bandy, Mathew S. "Population and History in Ancient Titicaca Region" PhD Dissertation, Graduate Division of the University of California, Berkeley, 2001

[10] W.C Bennett was employed by American Museum of Natural History in New York City

The team further cleared some of the trenches dug by Bennett and discovered another stone structure on the mound.[11]

Figure 2.4: View of the House One as excavated (Kidder 1956, University Museum Bulletin)

1955: Kidder, Cordero, Sawyer, Coe Y "Le Seńora de Kidder"

The next project was that of Alfred Kidder II and William R. Coe in 1955, who were employed at the time by the University of Pennsylvania, and had just completed a series of excavations at Tiwanaku. Alfred Kidder excavated three building episodes and

[11] Bandy, Mathew S. "Population and History in Ancient Titicaca Region" PhD Dissertation, Graduate Division of the University of California, Berkeley, 2001

several occupations and burials in the near vicinity. The project excavated portions of at least three structures first discovered by Bennett and cleaned the remains previously excavated by others. Through careful observation of profiles and earlier excavations, Kidder and his team were able to reconstruct with remarkable precision the form of the entire complex, still buried beneath a meter of later fill. Their excavations beneath the floors also revealed a large mortuary assemblage, including some burials with relatively elaborate treatment. Finally, excavating below the upper structures, they encountered an earlier layer of structures, encapsulated by the remains of the later structures discovered by Bennett[12].

1974: David Browman and Gregorio Cordero Miranda

David Browman of Washington University carried out two seasons of excavations, in 1974 and 1975. According to Browman, the work consisted of two seasons of clearing the sunken court temple located at the center of the mound of Chiripa, including three stratified cuts testing earlier deposits. He also discovered a rectangular sub-terranean court under the central sunken court at the center of the mound.

1996: Taraco Archaeological Project

The Taraco Archaeological Project began excavations in the area in 1996 under the auspices of the University of California Berkeley and the direction of Dr. Christine A. Hastorf. During the 1996 excavations, three trenches were dug on the Mound.

[12] Ibid

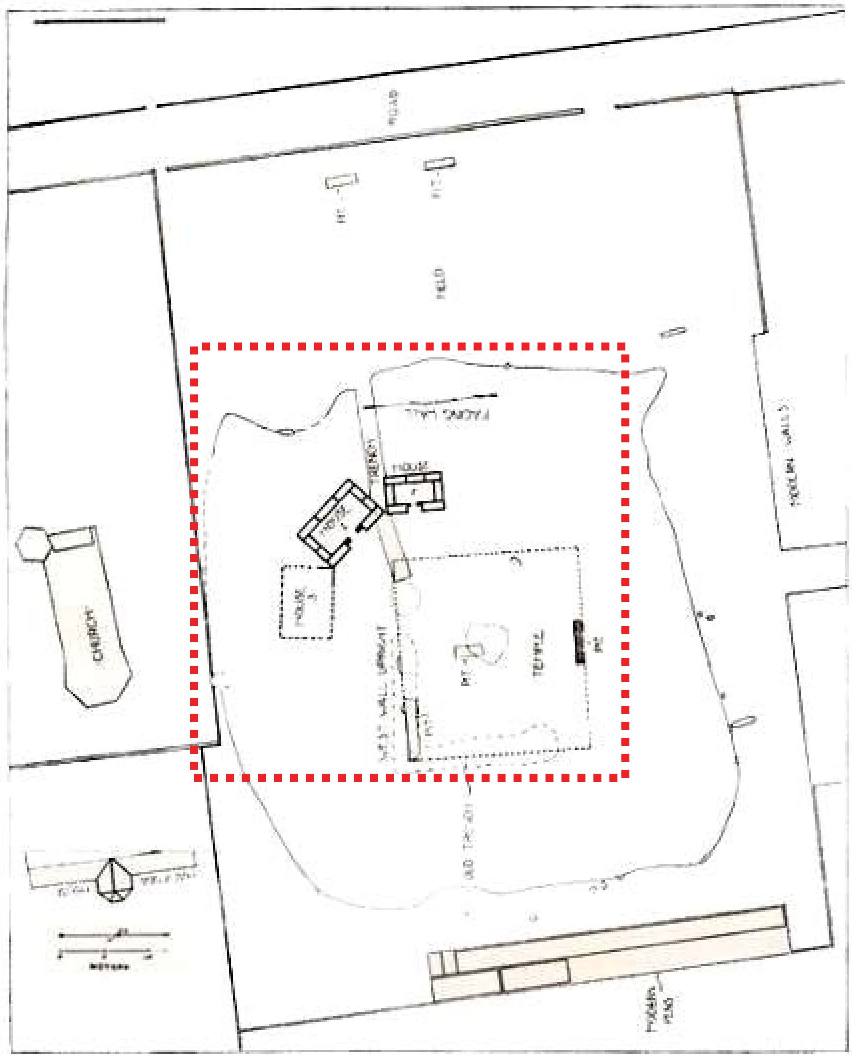

Figure 2.5: Site Plan as Excavated by Kidder (Kidder 1956, University Museum Bulletin)

The upper level structures of the trench Montículo 1A were removed inorder to make way for the walls of the structures below. The evidence suggests that these structures were not inhabited but were more likely to be ceremonial. The storage bins, earlier mentioned by Kidder, do not seem to have held quantities of crops like Inca *collca*. Each structure perhaps was used by an *ayllu*, or an extended family associated with a territory. These structures were made of puddled earth and stone, with plastered surfaces on the walls and floors. Four superimposed structures were seen in the eastern profile and further, it was observed that each structure had a series of yellow plaster floors. Between each re-flooring of these structures, there was evidence of ritual sealing, with sterile soil or sand laid down, often accompanied by a fire. Further evidence of such floor treatment was also seen during the cleaning of historical fill along the south face of the mound. The floors of the "Lower House" were found to have remains of fish and pottery, which suggested the daily domestic activity.

The team excavated another house on the mound in 2003.

2.3. Architecture of the Temple Mound

The Mound and Sunken Court

The mound is approximately 60 m north to 55 m east and about 6 m high at the center and the top about 25 m above the level of Lake Titicaca. The temple at the center of the mound is a sub-terranean or sunken plaza about 23 m x 21.50 m with hard clay floor about 3 m below the top of the west wall upright pillar. The facing wall was aligned and finished on the interior with clay plaster and a white color clay wash. The platform consists of a three-sided retaining wall, 30 cms thick and conformed to the mound on the north and the south sides by sloping up from 50 cms on the west to 12 cms, below an unknown surface. There appears to be no evidence for the fourth west retaining wall[13].

The walls of the Sunken Court were composed of stone uprights or orthostats set at irregular intervals with connecting walls of smaller stones forming an enclosure. Kidder delineated this three-sided structure resembling a Decadent Tiahuanaco Platform with inside dimensions of 6m by 3.5 m.

<u>The Mound Houses</u>

A series of houses encircled the temple court with doorways facing towards the temple as a fortified unit. There are no visible openings towards the outside[14]. From the typology, size and orientation of the two houses excavated, it was estimated that fourteen houses existed around the temple at a level higher than that of the central temple[15]. It was believed that the houses were a part of planned temple storage complex[16]. The first step in the construction of the house was to make a nearly vertical cut in the sterile soil of the mound, forming a U-shaped linear trough in the contours of the mound. This would provide a flat surface for the building to be constructed.

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[13] Kidder, Alfred, "Digging in the Titicaca Basin" University Museum Bulletin (University of Pennsylvania), Vol 20, no.3 pp 16-29. 1956
[14] Ibid.
[15] Ibid.
[16] Mohr-Chavez, K, "The Significance of Chiripa in Lake Titicaca Basin Developments" In *Expedition* 30, 3, p 17

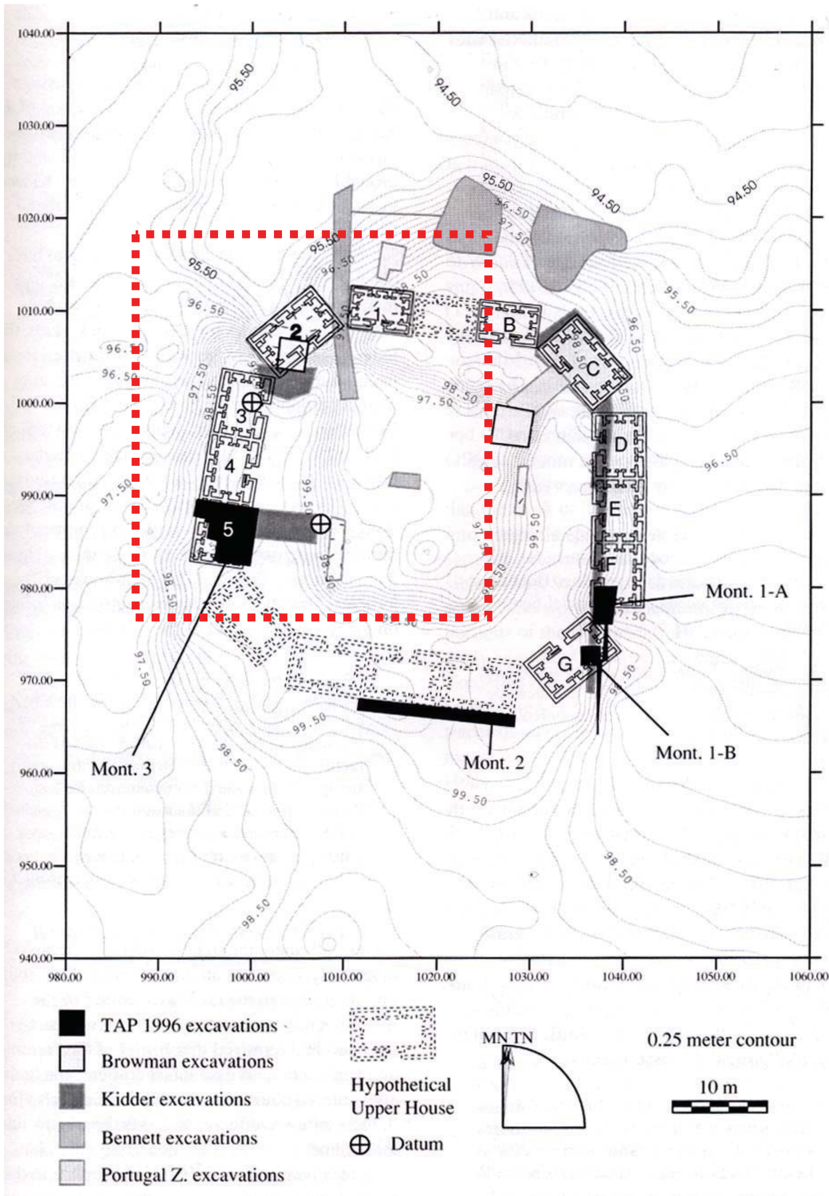

Figure 2.6: Site Plan of Montículo (TAP 2006)

Then, the base of the wall was constructed of local rounded cobbles upto 70 cms in size set in clay atop roughly dressed stone foundations almost 70 cms deep. This gave the structure a sub-terranean character[17]. The entryway to the houses was completely paved with flat stones upto the doorway which had a stone sill placed under the doors with probable stone or wooden shutters.

Figure 2.7: View of three-sided Tiahuanaco Platform under restoration (TAP 2006)

The houses are constructed of well-consolidated puddled or hand formed balls of earth and masonry. These were single storey units with stone foundations and cobble and earth constructions on top covered with thatch roofs. The main living area in the houses was surrounded by nine peripheral rooms. The excavation of the houses revealed the foundations and approximately 1.10 m of the walls. Consequently, the construction of the

[17]Hastorf, Christine (Ed.), "Early Settlement of Chiripa, Bolivia: Research of the Taraco Archaeological Project", Berkeley, University of California Press, 1999.

upper part of the houses cannot be accurately determined. However the written accounts from the excavations suggest the probability of earthen construction judging from the remains. In 1955 Kidder excavated two houses alongside the sunken court and his accounts describe rectangular openings in the walls with windows and niches towards the inner side. The windows had puddled earth lintels. The west wall of House One preserved six window niches. The niches were well finished and were not only decorative but also served as entrances to the storage bins behind them. Internally, the rooms were finished with a thick yellow clay wash. Kidder explains that in some parts of House One, the clay wash appears to have been fired and forms a plaster 1.5 cms thick. A considerable amount of ash deposits, burnt puddled earth and stone were discovered during the excavations suggesting that the houses were burnt during their use. The remains were then repaired and then reoccupied. There is no evidence that the houses were replastered after the first fire. A second and final fire is believed to have occurred which led to the destruction of the Chiripa occupation[18].

The elements of the house construction can be further described as:

<u>Foundations:</u>

After the desired area of the ground was well consolidated and compacted for the construction of the house, the grade was set of small cobbles and pebbles and compacted

[18] William Coe Notes, University Museum Archives, University of Pennsylvania, “Kidder, Alfred II Papers, Box 5, Folder: Lake Titicaca: Chiripa, Introduction and Notes” (Archives Notes from Excavation)

mud. The foundations were constructed of roughly squared stones set in earthen mortar upto a height of approximately 70 cms above grade. Two or three courses of large cobbles were set over the stones, over which the walls were built. No data regarding the depth of foundations is presented.

Figure 2.8: View of the Foundations (TAP 2006) Note original grade has been removed in the right hand corner to reveal foundations

Walls:

Accounts of the structure and the material of the wall construction by archaeologists, suggest construction of composite walls consisting of river cobbles and puddled earth units. However, the descriptions of the walls vary in each account. This variability may be comfortably accounted for the existence of variable wall constructions at the mound. The composition of the soil used for the construction of the puddled earth appears to be either from mixed middens or soil mixed with midden debris in the near vicinity areas as well as inclusion of vegetable fiber, presumably for tensile reinforcement of the earthen units. The construction can be further described as:

Double walls with infill clay: The puddled earth was built as a core between two outer veneer walls made of river worn cobbles. Plaster or wash coats of 2 to 5 cm thickness overlay a clay layer. The clay layer was burnt hard for 2.5 cm due to accidental burning of the houses during use. It was plastered dark brown or black, flecked with yellow and had no discernible thickness. The outer and inner walls are about 25 cms thick. The base of the wall is of stone, which extends about 25 to 30 cms below the floor level of the house. The lower wall, which still stands, is of stone mixed with clay. The corners of the outer walls are carefully constructed of rectangular slabs of cut stone, split, but not dressed. Yellow clay plaster was applied to the interior and exterior walls. In some parts this had been fired and forms a plaster 1.5 cms thick and slightly polished. The yellow wash coating covers the entire inside wall, including the frets of the niche decoration [19].

Cobble walls in a clay-rich matrix: The walls of the structure were apparently constructed of waterworn stones held in an adobe clay matrix. The puddled earth units

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[19] Kidder, Alfred, “Digging in the Titicaca Basin” University Museum Bulletin (University of Pennsylvania), Vol 20, no.3 pp 16-29. 1956

varied in size. The height of these hand consolidated or puddled blocks varied from 0.10 meter to 0.17 m, depth from 0.065 m to 0.105 m. No data is given on width of the units.[20]

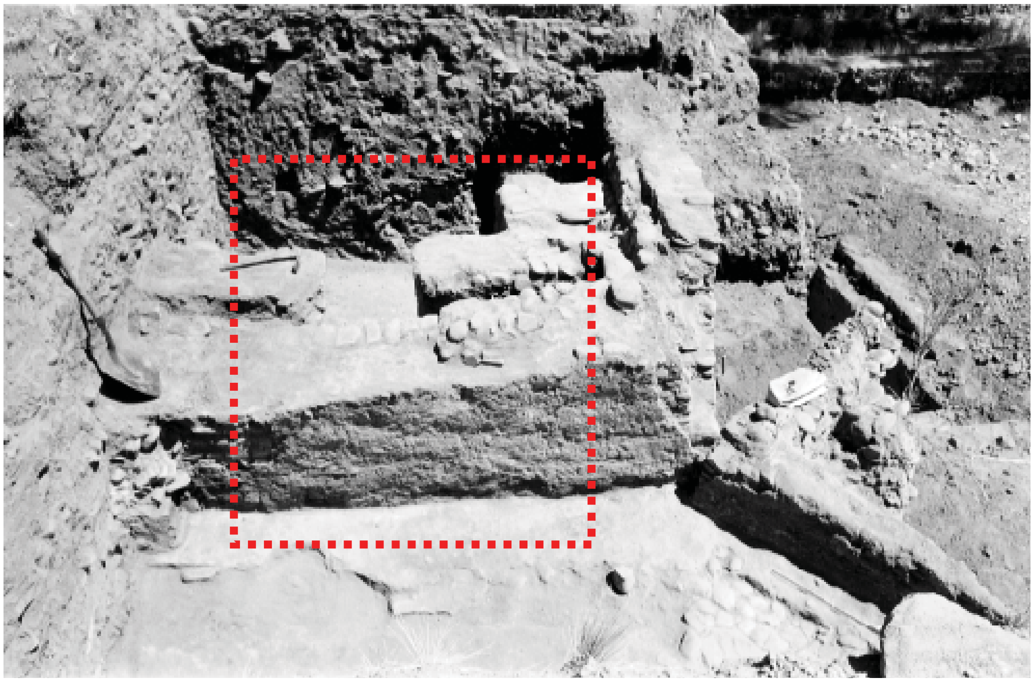

Figure 2.9: View of the double walls with infill puddled earth (University Museum Archives, Kidder Collection 1956)

<u>Cobbles on the outer edge:</u> The accounts by William Coe suggest the presence of cobbles on the outer edge of the walls, which are plastered on the inside with two or three coats of clay plaster. The larger cobbles are placed on the lower edge and the smaller cobbles are placed towards the upper edge of the exterior of the walls. The cobbles are held together in a clay mortar matrix. The walls were finished with layers of clay wash[21].

[20] Sawyer Notes, University Museum Archives, University of Pennsylvania, "Kidder, Alfred II Papers, Box 5, Folder: Lake Titicaca: Chiripa, Introduction and Notes" (Archives Notes from Excavation)
[21] Ibid

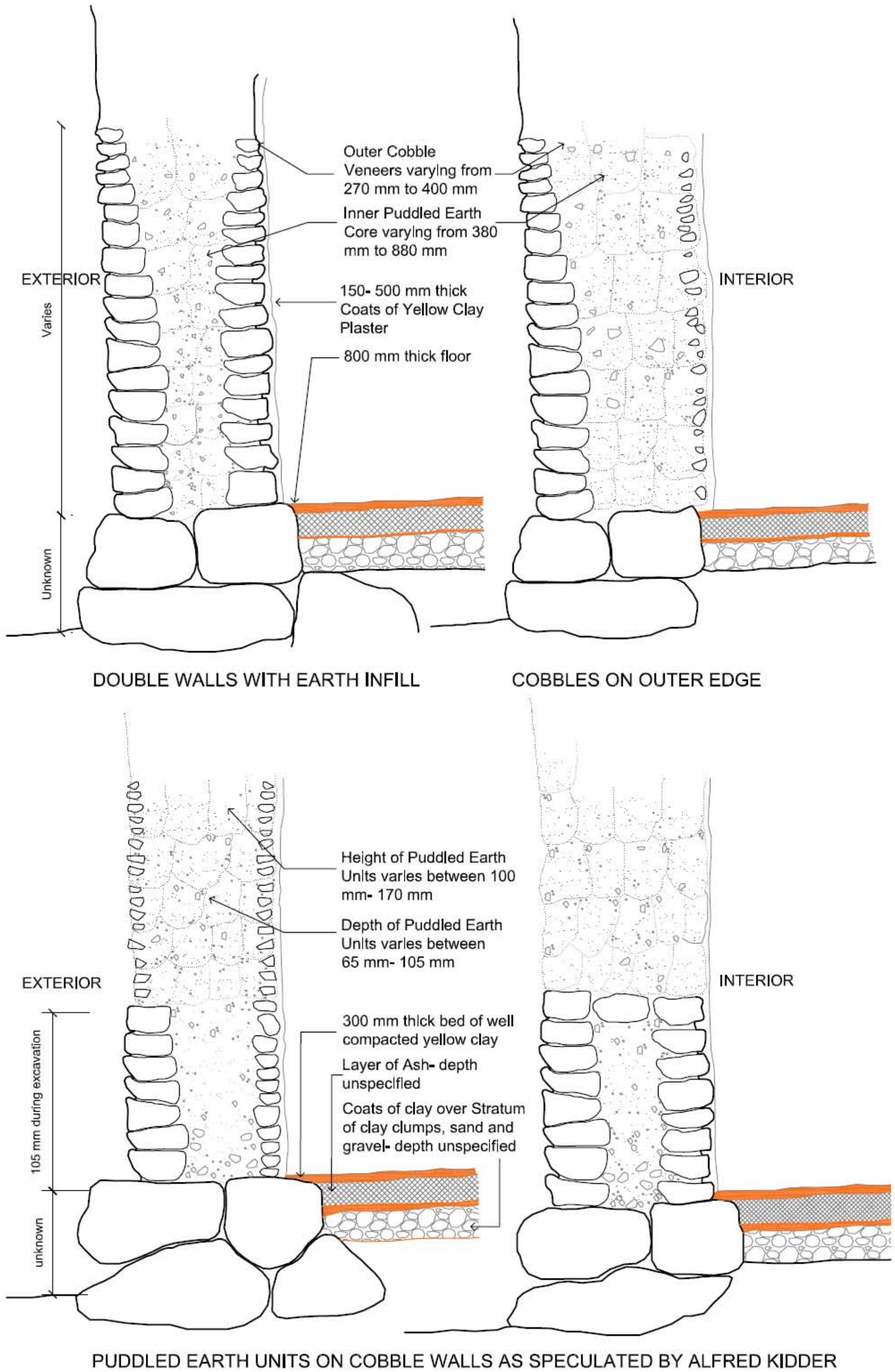

Figure 2.10: View of the Four Typologies of Composite Walls (Chaudhry' 07)

Roofs:

The coverstones, which formed the roof of the peripheral rooms, were made of single slabs of sandstones. These coverstones extended into the walls on either side and were thus held in place by the weight of the upper walls on their ends. Sawyer found one of these slabs still "in situ" while several others were collapsed and found in debris.[22] However, no data is presented on the character of main roofs.

Floors:

The floors of the rooms were a 30 cm thick bed of yellow clay, well smoothed and packed. This floor rests on a stratum of clay clumps, gravel, pebbles and sand that in turn rests on the modified grade level for the house. The floors were found to be finished with clay wash. Most of the floors also revealed ash layers sandwiched between the floors. The floor of the doorway was paved with limestone slabs[23].

2.4. Condition Assessment

The excavated Temple mound and its houses present a conservation challenge. Since the early excavations, conservation has not been attempted on the site. The structures continue to deteriorate, as a consequence both of mechanisms inherent to the nature and composition of the building materials and techniques and of conditions created by the wet climate of the Taraco Peninsula.

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[22] Ibid.
[23] Ibid.

There is general decay of the mound and especially where the erosion has exposed house walls. Current restoration of the Sunken Court will stabilize the inner court walls and orthostats. A stable if not historically accurate exterior slope of the Mound must also be established and vegetation should be encouraged to control the erosion. This will be especially important if any houses are excavated and displayed as their rear walls rest close to perimeter of the mound. The most damaging factor may be the mechanical and chemical effects of water on the site, which produces erosion. The houses behave as troughs trapping moisture and the lack of proper drainage aggravates the moisture related decay. But the threats are not limited to environmental factors; there is intrinsic material decay of the wall fabric. The original tensile reinforcements of the walls have decayed leading to open pores and cracks in the walls. The displacements of the cobbles and chert, which originally formed a veneer to the walls, have caused major detachment of the outer veneer of the walls. This has caused disintegration of the wall fabric and ultimate loss of the materials. The exposure of the earthen walls due to archaeological digs have led to a change in the microclimate of the earthen fabric leading to micro cracking of the puddled earth.

Based on observations made during excavations and subsequently from the excavation photographs, the house structures reveal a variety of conditions, some of which will require remedial stabilization. Prior to complete burial, the original wooden framing, which served to laterally support the walls, was lost leading to wall deformation and collapse probably before and after burial. This in turn would have led to detachment and loss of the cobbles and chert, which originally formed a veneer to the walls and would have caused major collapse of the outer veneer and top of the walls. This was revealed during the excavations. The exposure of the earthen walls from the excavations has disturbed the equilibrium achieved during the burial leading to the micro cracking of the puddled earth and possibly larger through-wall cracks from hygric responses to the new exposed environment, even if only temporarily during excavation.

Nevertheless, the excavation photographs by Kidder suggest the buried walls survived in a reasonably good condition.

Figure 2.11: View of House One showing a general decay; no roofs; no drainage (Kidder Collection 1956)

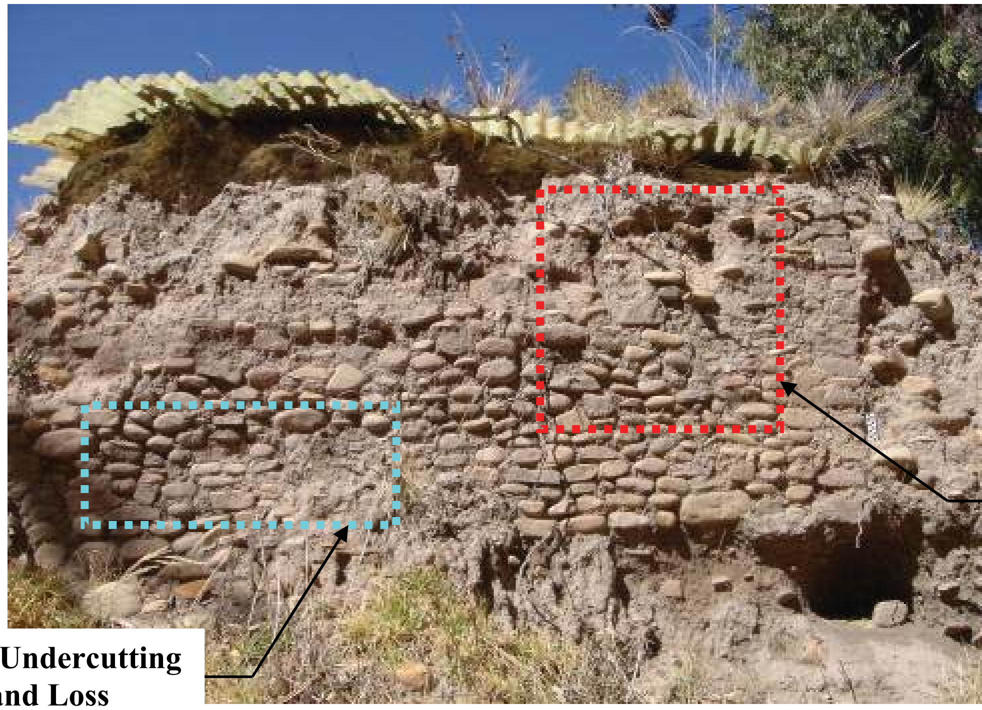

Figure 2.12: View of House Two showing the bulged/ bulging areas of detachments and loss on the walls (TAP 2006)

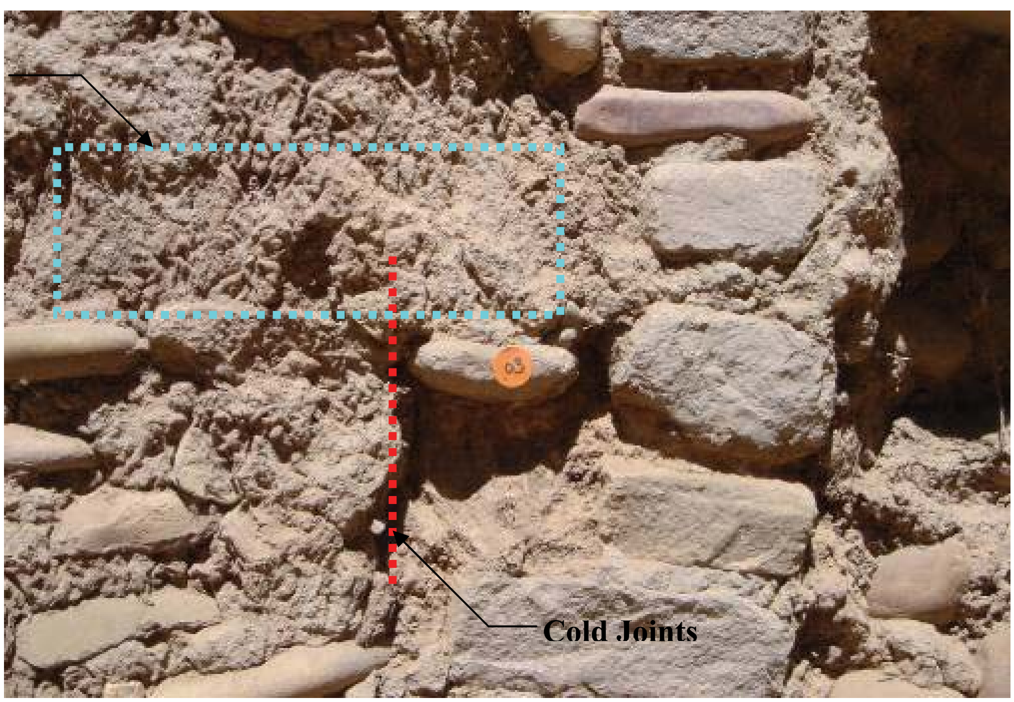

Figure 2.13: Cracks; cold joints on wall surface: House Two (TAP 2006)

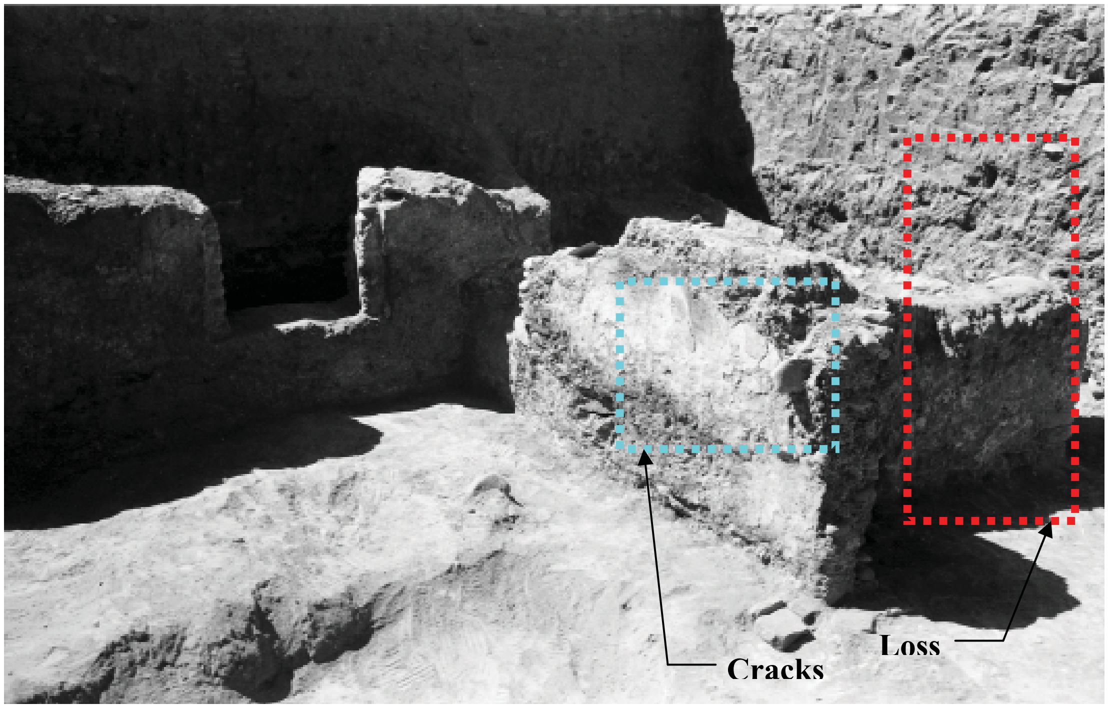

Figure 2.14: Micro cracking and general loss of plaster on wall surfaces: House One (Kidder 1956)

2.5. Conservation Considerations

The changing climatic environment and increasing seismicity of the Taraco mountain range will present a problem to the ultimate stability of the masonry and earthen walls and when the site is excavated for display. The river worn cobbles support and protect the inner puddled earth matrix. The matrix is weak and held by a weak bond with the stones of the outer veneer wythes. In general, the sacrificial plaster layer protecting the cobble joints has been lost leaving the walls vulnerable and prone to rapid decay. The conservation measures for the earthen structures at Chiripa will need to take into account the following considerations:

- The conservation action should consider the fragility of the material due to disturbed moisture equilibrium of the earthen houses due to a long history of excavations.
- The seismic movement leads to cracking and shifting of the filling material of the walls, which in turn can exert a lateral pressure leading to deformation and collapse of the walls and cobble veneer. Conservation intervention should look into the mitigation of the lateral force and compensation of the lost material, especially where basal erosion has occurred.
- The treatment must address the poor structural integrity of the walls.
- The conservation treatment should also look into the detachment of the internal core from the outer wythes due to a weak bond between the outer river worn cobbles and the inner clayey matrix of the walls. It must aim at providing homogeneity to the walls.
- The conservation action must respect the age value and the historic importance of the pre-Columbian houses at Chiripa and any treatment must induce minimal intervention to the fabric of the earthen walls.

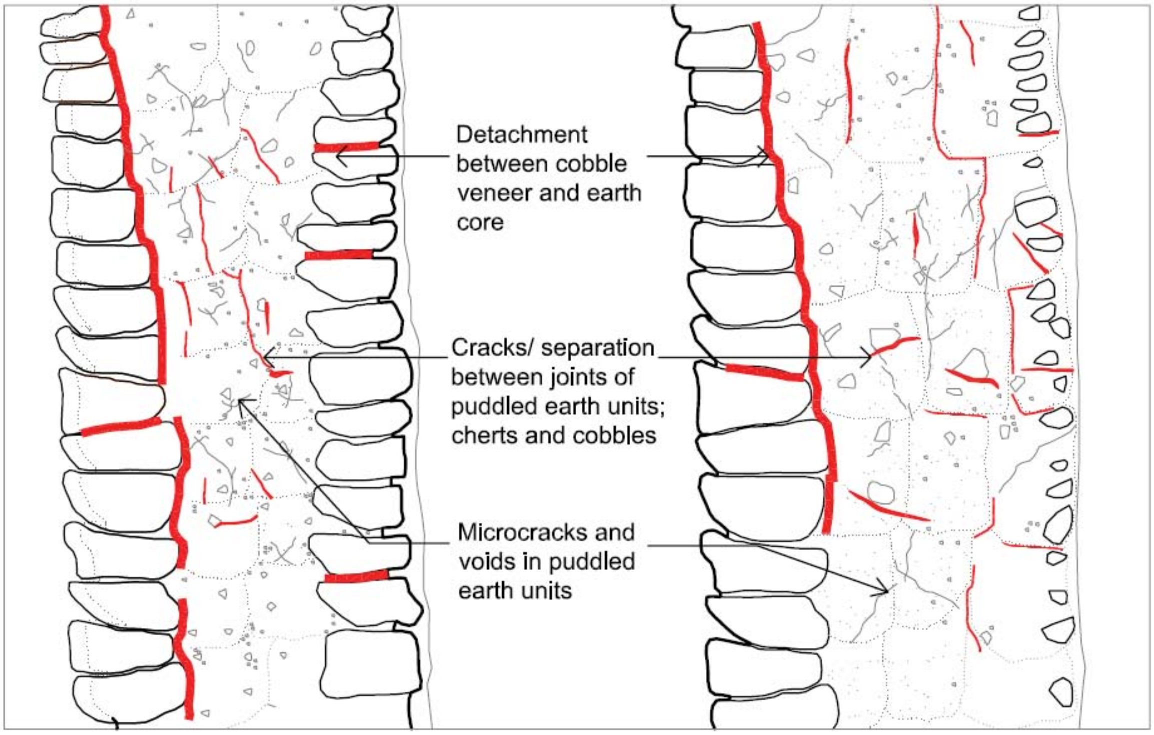

Figure 2.15: Wall Constructions depicting the defects (Chaudhry' 07)

Based on the above discussion and analysis, it can be concluded that any priority intervention for the treatment should address the cracks that could range from very minute (0.05mm- 0.1mm), to medium (5 mm). The larger cracks or discontinuities would comprise the delamination or detachment of the outer cobble layers and the inner puddled earth core. These could range from 10 mm-20 mm.

The irregularities in the matrix would take the form of amorphous voids within the structural matrix of the earthen core. In a general analysis through thin sections, the pores, i.e, the voids comprise unit area of the masonry and vary for the burnt and the unburnt puddled earth. It is also determined that the voids are smaller in case of unburnt but much larger in case of burnt masonry. The distribution and the connectivity of the voids cannot be ascertained without an assessment but might be crucial to determine as these could present structural problems and might require consolidation.

Any treatment would therefore address;

- Instability from basal erosion
- Lack of adhesion between the external cobble veneer and the inner earthen core
- Poor bond strength of the earthen mortar in the cobble walls
- High porosity and low strength of the puddled earth due to voids
- High water absorption potential of the puddled earth and mortars

3.0. DISCUSSION AND ANALYSIS

3. 1. Earthquakes and Earthen Construction

Tectonic activity deep within the earth's crust causes continual movement of the near surface geomaterials. Such activity dictates the formation of various types of discontinuities and other internal voids especially in unreinforced masonry[24]. Earthen structures have inadequate flexibility, which result in brittle behavior even with low seismic activity. After a seismic event, the observed damage to earthen masonries is often associated with displaced debris, which exerts a lateral pressure against the walls forcing large inelastic deformations throughout the structure. Historically, the seismic performance of adobe structures, as well as those of stone and other forms of unreinforced masonry, has in many cases been very poor. The seismic behavior of such buildings is characterized by sudden, dramatic and catastrophic failure[25]. Based on the data gathered during the assessment of the historic adobe structures after the destruction caused due to Northridge Earthquake, it appears that ground shaking levels of between 0.1g and 0.2g PGA[26] (between MMI[27] of 6 and 6.5) are necessary to initiate damage in

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[24] Unreinforced masonry is the type of masonry where the reinforcement systems occupy less that 25% of the wall surface area.
25 E. Leroy Tolles, Edna E. Kimbro, William S. Ginell, Seismic stabilization of historic adobe structures, Final report of the Getty Seismic Adobe Project Los Angeles: Getty Conservation Institute, 2000.
26 PGA refers to Peak Ground Acceleration. The peak acceleration is the maximum acceleration experienced by the particle during the course of the earthquake motion. This value is important to understand the horizontal force a building will be required to withstand.
27 MMI refers to The Modified Mercalli Intensity scale (MMI), which is a more subjective, qualitative measure of an earthquake's effects. The MMI value assigned depends on vibrations experienced by people in an earthquake, and by the amount of building damage done.

well-maintained, but otherwise unreinforced adobes[28]. The reinforced adobe buildings show an even greater resistance to damage than those that have been retrofitted. The Taraco peninsula has experienced seismic vibrations of higher magnitudes in the past and the tectonic faults are active in the surrounding mountain ranges.

The poor seismic performance of earthen structures can attributed to three main factors: First, earthen buildings are heavy constructions and heavy structures mean high level of lateral forces. Second, earthen buildings are weak in compression and tension, but since the weakness in compression can be overcome with the thickness of the walls, the tensile strength is almost null and cannot be overcome unless additional reinforcement is provided. Finally the third important factor of vulnerability is the fragility of the material that is directly responsible for the sudden collapse of the buildings as soon as tensile forces are present in the building[29]. The remaining architectural fabric at Chiripa is comprised of earthen walls, about 60 cm (2 feet) thick resting on stone foundations. Decay of the original vegetable fiber tensile reinforcement over time has considerably increased the porosity of the material and reduced its tensile strength. The excavated walls have also lost their inherent water content since excavation and are now more friable.

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28 Tolles Leroy E, Webster Fredrick A, Crosby Anthony, Kimbro Edna E. Survey of Damage to Historic adobe Buildings after the January 1994 Northridge Earthquake Los Angeles: Getty Conservation Institute, 1990
[29] Torrealva. D, Neumann. J V. “Structural Engineering Issues for the Reconstruction and Restoration of Bam” Interim Report

The seismic behavior of earthen buildings is affected by their original structural inadequacies, material degradation due to time, and alterations carried out during use over the years leading to cracks, detachments and loss. Irregularities of strength, stiffness and mass are major factors contributing to unsatisfactory earthquake performance.

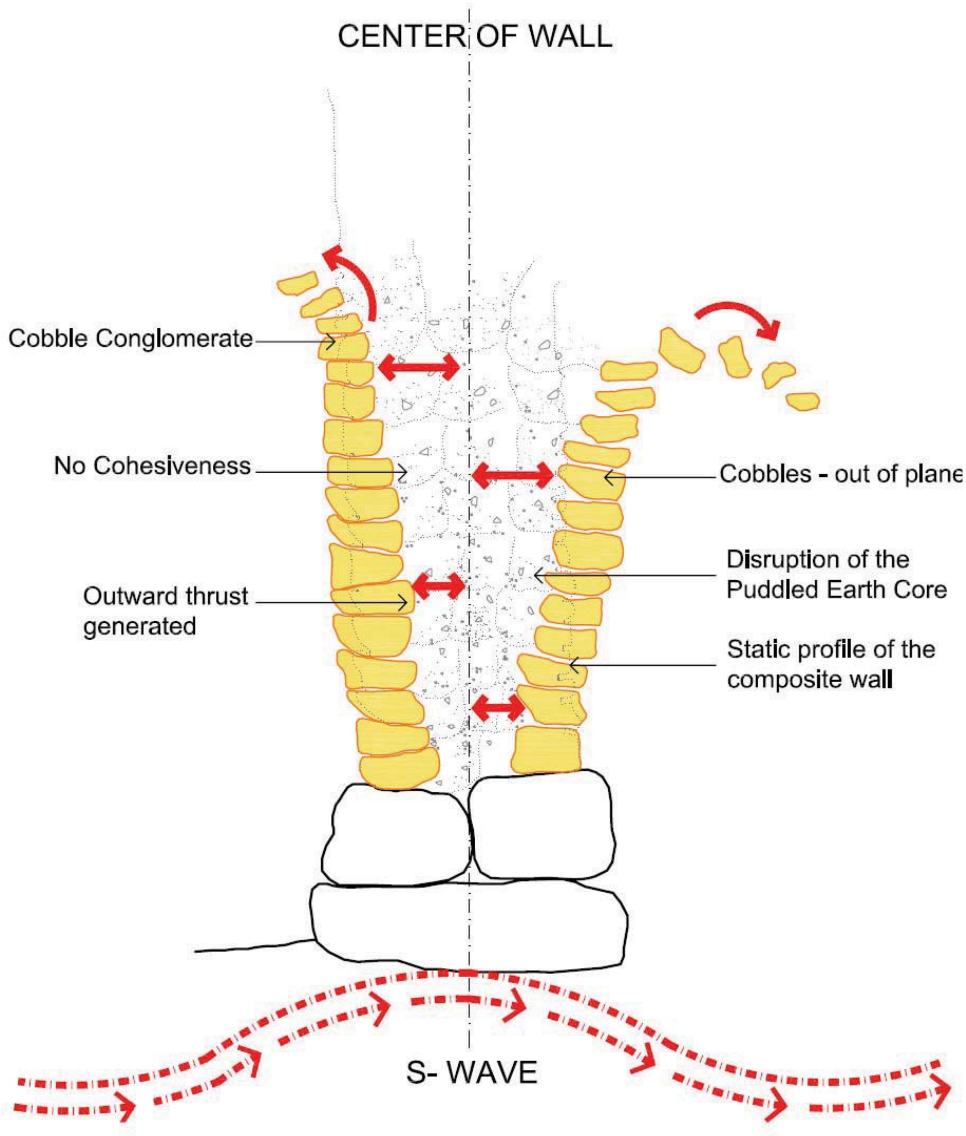

Figure 3.1: Illustration of the behavior of composite wall in seismic event (Chaudhry' 07)

Even fine cracks can lead to the reduction in the resistance of the masonry. The existing earthen walls on the mound have visible signs of decay and deterioration caused by micro cracking in the earth.

The large-scale detachment of cobbles from the masonry has caused voids and negative areas in the walls, especially along the base. These irregularities are sources of weakness and produce concentrated areas of stress in the masonry. The Chiripan walls are standing over stone foundations. The walls are composite constructions generally of hand shaped puddled earth units jacketed by hard dense river cobbles on the two sides. This kind of an arrangement forms a continuous vertical section of the stones with no interconnecting or header courses of the stone, which can form keys in the inner clayey matrix of the walls. Hence the walls, which are relatively thick, can be considered to have independent vertical wythes of stones and earth units. The variability in properties of the materials of the different wythes will lead to independent behavior in a seismic vibration, as the wythes of the walls sway independently of each other.

The extent of damage to these earthen walls subjected to an earthquake is a function of: 1) the severity of the ground motion; 2) the geometry of the structure, i.e., the configuration of the walls and foundations systems; 3) the overall integrity of the adobe masonry; 4) the existence and effectiveness of any tensile retrofit; and 5) the condition of the building at the time of the earthquake. Since replacement is not possible, therefore seismic strengthening of existing damaged or undamaged fabric is a definite requirement for the remaining earthen walls at Chiripa for display. This approach would respect the historic values of the site and would be less invasive in creating a more unified behavior of the lamellar walls in case of an external vibration.

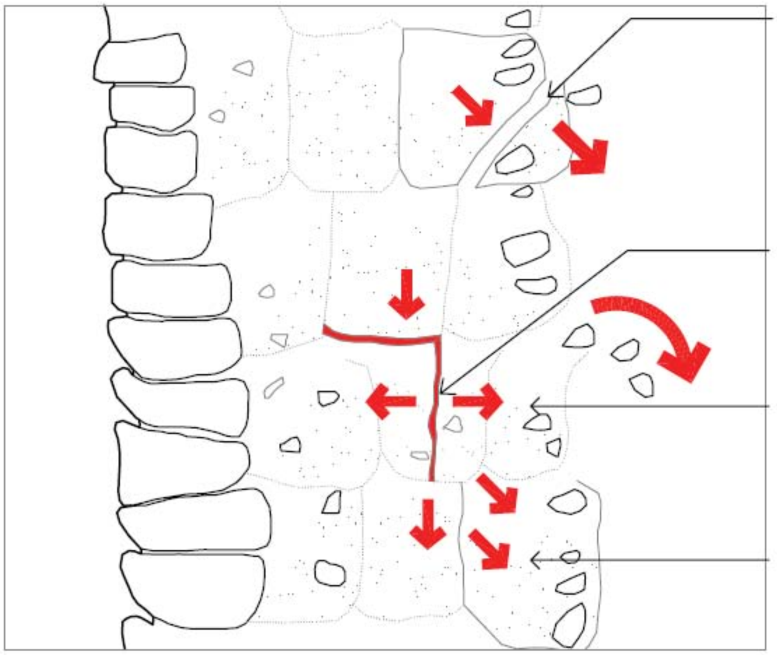

Figure 3.2: Illustration of puddled earth units and stress distribution (Chaudhry' 07)

The use of puddled earth units next to each other creates horizontal and vertical joints or natural joints. These natural joints are the interruptions of the continuity during the construction of courses through the length of the wall. The stresses of puddled earth units are higher at the joints are leading to discontinuities in the load paths. Discontinuity creates weakness and imperfect bond between the units, which creates vulnerability in the wall. It is safe to assume that the degree of compaction of the puddled earth units should be low and highly variable across the length of the wall as they were hand compacted. This would give different densities and hence the related properties like strength to the earth. In such case of variable irregularities and faults, voids or pore spaces, neither the extent nor the volume can be seen or easily understood. These conditions must be investigated sufficiently to gain good understanding of the existing as well as the achievable final properties.

The grain size of the puddled earth is a crucial factor in the measurement of fracture strength of soils since it not only affects the size of cracks, but also influences the fracture parameters (namely fracture energy, fracture toughness, etc). Hence, the grain size cannot be ignored when evaluating fracture parameters of soils[30]. The unburnt soils of Chiripa contain a high fraction of particles below 135 microns, which are silts and clays. For given water content and given clay-sand ratio, the strength increases as the grain size of the sand decreases below 135 microns[31]. The reason for greater strength with the increasing fineness of sand is attributed to the principle of greater surface area upon which forces can act. It is difficult to estimate in advance the amount of unburnt versus the burnt puddled earth, which has a lesser fine fraction and hence lesser strength, across the length of the wall. Low strength adobe when used in thick masonry walls easily develops cracks during seismic vibrations. Diagnosis of the masonry fracture mechanics can give explanation of the failure and mainly crack occurrence. Excessive flexural and diagonal cracks appear which indicate impending failure of the masonry. This would also explain that the brittle failure occurs because of the propagation of

[30] Webster, Frederick A, "Some Thoughts on "Adobe Codes": Research and Code Improvement". On http://www.deatech.com/natural/cobinfo/adobe.html

[31] Trask, PD, "The Effect of Grain Size on strength of mixtures of clay, sand and water". In GSA Bulletin; May 1959; v. 70; no. 5; p. 569-579

cracks. The cracks lead to a decrease in the lateral stiffness of the walls. These cracks get particularly serious when the resulting displacement becomes large leading to collapse of the wall. Like strength, permeability of the entire wall, which is the proportion of voids to solids in the sample adobe, is also quite difficult to determine in absence of some on site investigations, condition assessments and tests. The key is to understand how these composite walls perform and to direct minimal intervention mitigation efforts to the specific needs and structural behaviors.

The Chiripan structures have no roofs. This leaves the walls very vulnerable to rains and the related climatic weathering phenomenon. The site also is practically at the same level as the Lake Titicaca, which is registering rising ground water at the rate of one inch (2.5 cm) per day in recent weeks[32], devouring hundreds of yards of the fertile shoreline, where these pre Columbian earth houses stand. So there are immediate mitigation measures required for rising and falling damp. The strength of the earthen material becomes a major concern when it has been affected by water. Wet earthen walls can reach their plastic limit more easily and begin to deform under their own weight. Also, repeated wet-dry cycles reduce the strength of the adobe so that, even when dry, a wall may be weaker than when originally constructed. When the adobe material at the base of a wall is weakened by moisture intrusion, a through-wall shear plane develops, along which the upper portion of the wall can slip and collapse. These geologic and soil

[32] Reuters, Popper Helen 17 February 2006 “Bolivia: Rising Waters Wreak Havoc for Lake Titicaca Villagers”

conditions can seriously exacerbate the severity as well, and aftershocks can destroy buildings that withstood the initial ground motion. The Chiripa soils have low to medium permeability and can be vulnerable to even minor tremors of tectonic shifts

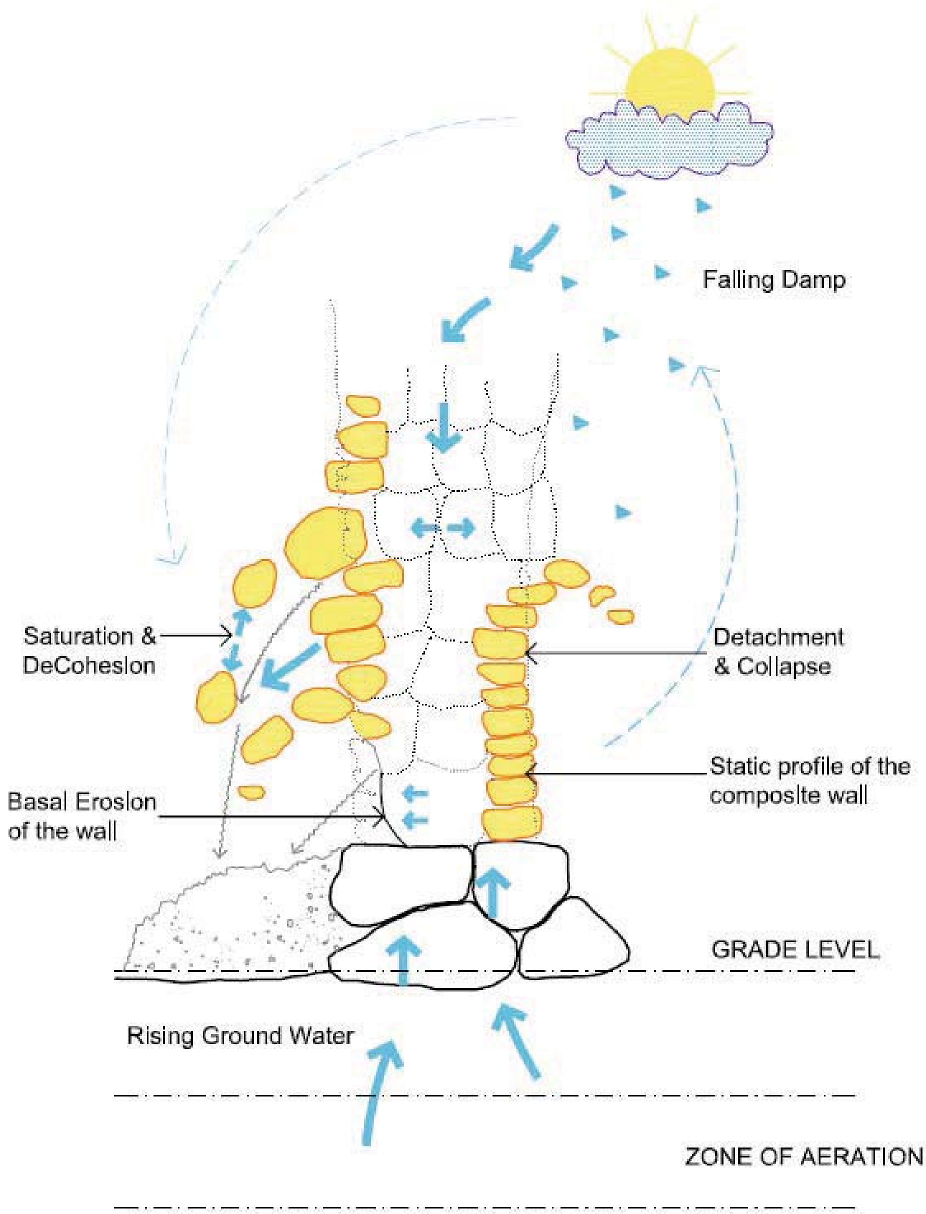

Figure 3.3: Illustration of Composite walls and environmental affects (Chaudhry' 07)

Seismic vibrations induce flexural or tensile stresses in the masonry. Much testing would need to be completed before strength design concepts could be applied to earthen building materials[33]. The minimum requirements are arbitrary, but are meant to produce ductile-type action under earthquake loading. The underlying principle is that the repair material will yield and hold the masonry together. Reinforcement in adobe has always been viewed as impractical, particularly as reinforcement does not bond to the adobe unless it is embedded in a cement-based mortar and grout or unless there is a positive interlacing of reinforcement around the earthen material. On the contrary, it should be understood that placing heavy steel reinforcement in earthen walls actually creates cracking in the walls as the earthen material continues to shrink during the drying process over a long period of time and the unyielding steel tries to hold it from shrinking, thus creating tension stresses that the earthen material cannot sustain[34]. Hence a strengthening technique using elastic materials is a high priority at Chiripa.

Density, moisture content, depth to water, particle shape and size distribution and consolidation potential are all important properties to understand in mitigating the potential damage to earthen structures. The presence of cobbles in the Chiripa masonry should be accounted for in the masonry's properties. The puddled earth was also hand consolidated which provides a great variability in the property distribution and it is difficult to get a range of values constant across a given length of masonry. Uniformity

[33] Webster, Fred, "Research and Code Improvement: Some Thoughts on Adobe Codes". On http://www.deatech.com/natural/cobinfo/adobe.html
[34] Ibid

of mass improvement in the earthen walls of Chiripa can be achieved by grouting. For increasing the soil strength and modulus of elasticity, reinforcing the mass or form structural elements that directly carry the loads is required. This creates zones in the masonry, which are structurally flexible and stronger and/or have reduced permeability. The grout will bond to the existing structure to form a new composite material.

3.2. Stresses and Cracks

A typical unreinforced masonry is subjected to various stresses. Tensile stresses in the masonry cause cracking or microcracking in the masonry elements, the mortar or the bond between them. This cracking is intensified by vibrations, shocks, wind loads etc. Compressive stresses are mostly not harmful to the masonry, except in some cases where buckling might occur. Having that in mind, it is understood that the tensile stresses are causing masonry failure. It is evident that every strengthening method must introduce elements or systems capable or withstanding these tensile stresses.[35]

Due to the presence of cracks, the continuity of the walls is lost and disturbed and this consequently affects the stability of the structure. In order to suggest appropriate means for repairs it is very important to analyze the location and types of cracks and assess probable causes. These cracks may be vertical, horizontal or diagonal and the portions of the wall on each side of the crack may be moving apart (tension crack),

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[35] Van Balen K and Van Gemert D. “Structural Consolidation and Strengthening of Masonry: Historical Overview and Evolution”. In *Stable-unstable? Structural consolidation of ancient buildings*. Leuven University Press

together (compression crack) or sliding against each other (shear cracks)[36]. The width of cracks normally governs the size of aggregate or granulates used in the grout. The idea is that the grout will reach all the cracks and crevices of the material to improve the mass distribution in the wall.

Failure of the earthen material may be viewed on a microscopic level in three steps:

Crack Initiation: The initial crack occurs in this stage. The crack may be caused by surface scratches caused even by tooling of the material; threads; voids, slip bands or dislocations intersecting the surface as a result of previous cyclic loading or hardening of the material.

Crack Propagation: The crack continues to grow during this stage as a result of continuously applied stresses. The tip of the originated crack runs parallel in the direction of tensile stresses.

Failure: Failure occurs when the material that has not been affected by the crack cannot withstand the applied stress. This stage happens very quickly in case of brittle materials like earth.

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[36] Crosby, A. "Common Sources of Deterioration." In *Adobe: Practical and Technical Aspects of Adobe Conservation. Papers From the Conference*, Editors J. W. Garrison, and E. F. Ruffner, Tuscon, Arizona: Heritage Foundation of Arizona, 1983, p- 14

In a seismically active environment, tensile stresses are cyclic and the cracks are dynamic in nature and hence the flexibility of the grout is an important issue to consider. Various permutations of environments can be imagined and discussed here; earth with smaller grain size could stand higher temperatures and stress levels, which tend to mitigate crack initiation. In a situation where the earth materials with larger grain size are coupled with lower temperatures, higher stress levels tend to favor crack propagation. This explains the availability of the greater surface area in the material and hence its density is a crucial factor in mitigating the initiation and the propagation of cracks in earth. Also cyclic stresses call for a self-adjusting earth material to resist cracking.

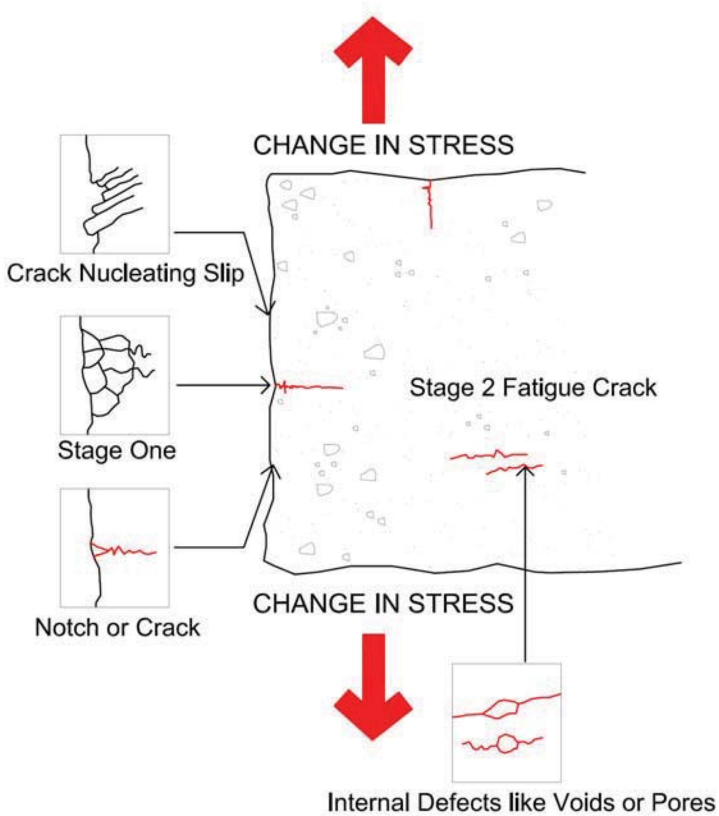

Figure 3.4: Illustration depicting crack stages in puddled earth unit (Chaudhry' 07)

Once a typical unreinforced adobe has cracked, it looses its tensile strength. Prior to this degradation, stress will develop throughout the field of each face, and these stresses will redistribute as the facings crack or fail locally due to the development of principal tension and principal compression stresses due to the applied lateral and gravity loads[37].

3.3. Summary of Discussion

Environment of the structure and its composition are equally important to understand the dynamics of the earthen walls at Chiripa. The material of the walls is weak and the structure is vulnerable to the geological environment, which is hostile and aggressive. Continued existence of the walls relies on the careful understanding of these pathologies and negotiating mitigation.

The characteristics of the soils having the greatest influence on the strength of earthen masonry are those related either to the drying shrinkage process or the dry strength of the material. The characteristic of the material of the structure helps to understand the mechanics of the structure in its context.

To elaborate a few of the large-scale factors, the following characteristics of the earthen material are extremely vital for durable performance:

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[37] Webster, Fred, "Research and Code Improvement: Some Thoughts on Adobe Codes". On http://www.deatech.com/natural/cobinfo/adobe.html

Clay: The most important component of the soil is its clay fraction. It provides dry strength and causes drying shrinkage of the soil. The controlled microcracking of the soil mortar due to drying shrinkage is required to obtain strong adobe masonry[38].

Grain Size: The presence of smaller grains imparts greater strength to the material.

Density: Higher density is a qualitative measure of good integrity of earth.

Additives: The use of plant or fibers and to a lesser extent, coarse sand are additives that control microcracking of the mortar due to drying shrinkage, and therefore improve the strength of adobe masonry.

[38] J. Vargas, J. Bariola, M. Blondet, Mehta, PK, "Seismic Strength of Adobe Masonry", In Materials and Structures, Vol 19 No. 4, pp253-258, 6006.

4.0. PRINCIPLE OF GROUTS

4.1 Grouting as a Strengthening Technique

Traditional Repair methods of mechanically repairing cracks in earthen walls by patching lead to discontinuities in the structure by the introduction of new elements. Examinations of the soil structures that have been repaired by such methods often show that new material is incompatible with the old. In particular the joint surface between old and new is prone to rapid decay[39]. Another common method of repair is resetting the masonry elements adjacent to crack with or without reinforcing bars parallel to crack. This can only address the external Wythes but has the probability of propagating the cracks and loosening the areas above the repair. This method installs tensile capacity oriented at right angles to the tensile force that cause the crack[40]. An alternative method is imperative when a higher degree of damage to the earthen houses of Chiripa is expected during an earthquake, as the integrity of the walls is inadequate due to the presence of internal voids, cracks and other discontinuities seriously affecting the seismic resistance. The decision to strengthen it before an earthquake occurs depends on the material and structural condition of the walls and subsurface mechanics. This seismic

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[39] Hughes, R. "Problems and Techniques of Using Fresh Soils in the Structural Repair of Decayed Wall Fabric." In *5th International Meeting of Experts on the Conservation of Earthen Architecture,* Coordinators A. Alva and H. Houben, Grenoble, France: ICCROM//CRATterre//EAG, 1987, p-59-69

[40] Roselund Nels, "Repair of Cracked Unreinforced Brick Walls by Injection of Grout", In *Proceedings of Fourth U.S. National Conference on Earthquake Engineering*, Palm Springs, California: May 20-24, 1990, Volume 3

evaluation will provide a measure of the seismic resistance of the earthen walls. Although the structural system of the deficient walls could be adequately strengthened in order to attain the desired level of seismic resistance, homogeneity of the masonry is an essential principle towards strength gain. The term "strengthening" comprises technical interventions in the structural system of a building that improves its seismic resistance by increasing the strength, stiffness and or ductility of the parent masonry. As a result, the respective characteristics of the structure are influenced, even though the overall structural scheme is unmodified. Euro code 8[41] and FEMA 273[42] recognize grout injections as a technique for enhancement of the unreinforced masonry walls.

4.1.1 Homogeneity of Masonry

Large lateral deformations are induced in the structure due to ground shaking. This imposes that one of the basic tenets of earthquake resistant design is to provide a ductile mechanism of resistance to lateral forces. Because the forces "flow" through many individual elements, the provision of ductility requires that brittle elements be provided with sufficient strength to ensure that ductile behavior develops in those elements capable of ductile response. Also flexible structures with components having inadequate ductility may behave poorly. By strengthening the structure using grouts, the

[41] CEN (2001), "Eurocode 8 – Design Provisions for Earthquake Resistance of Structures – Part 3", Brussels

[42] FEMA (1997), "FEMA 273 – NEHRP Guidelines for the Seismic Rehabilitation of Buildings", Federal Emergency Management Agency, Washington DC, USA

threshold of lateral force at which the damage initiates, can be increased at the global level, leading to improvement of the overall quality of the cracked masonry walls. It provides for the inertia forces generated by the vibration of the building to be transmitted to the members that have the ability to resist them. This imparts stiffness and creates a uniform behavior of the structure. Seismic vibrations create unstable environments with variations in ambient temperature, changes in loads and loading patterns and continual processes of expansion and contraction. These factors often call for a grouting material that will provide flexibility and yet set rapidly filling up the voids and to certain extent the pores of the parent masonry to create a unified behavior by diminishing the discontinuities. This would reduce the differential stiffness of the walls.

4.1.2. Structural and Material Compatibility

Strength enhancement through homogeneity of the material largely depends on the "compatibility" of the injected and the parent materials. The aim can be fulfilled only by knowing with good precision the materials constituting the wall and their composition (in order to avoid chemical and physical incompatibility with the grout), the crack distribution and connection, and the size, the percentage and the distribution of voids[43]. Hence, Physico chemical, mechanical and aesthetic characteristics of the parent masonry structure often dictate the characteristic and composition of the injected materials.

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[43] Binda, L et al, "Repair and Strengthening of Historic Masonry Buildings in Seismic Areas". Source http://www.unesco.org/archi2000/pdf/binda197.pdf

However, to standardize these parameters for earthen structures is quite difficult due to irregularities—compatibility for Performance and Durability of the repair.

4.2. Cohesion

The idea of grouts is to use a material with more cohesion than the parent masonry achieved by materials with good binding properties and a minimal tensile strength. An ideal grout will increase the Cohesion of the parent masonry and its own adhesion to the parent masonry. In principle, this would lead to an enhanced mechanical behavior of the system as a whole. Grouts lead to the reduction in the tensile stresses in the masonry by enhancing the cohesive strength of the masonry. A conceptual plan of the effect of the mechanical properties of the grouts can be illustrated in fig 4.1,

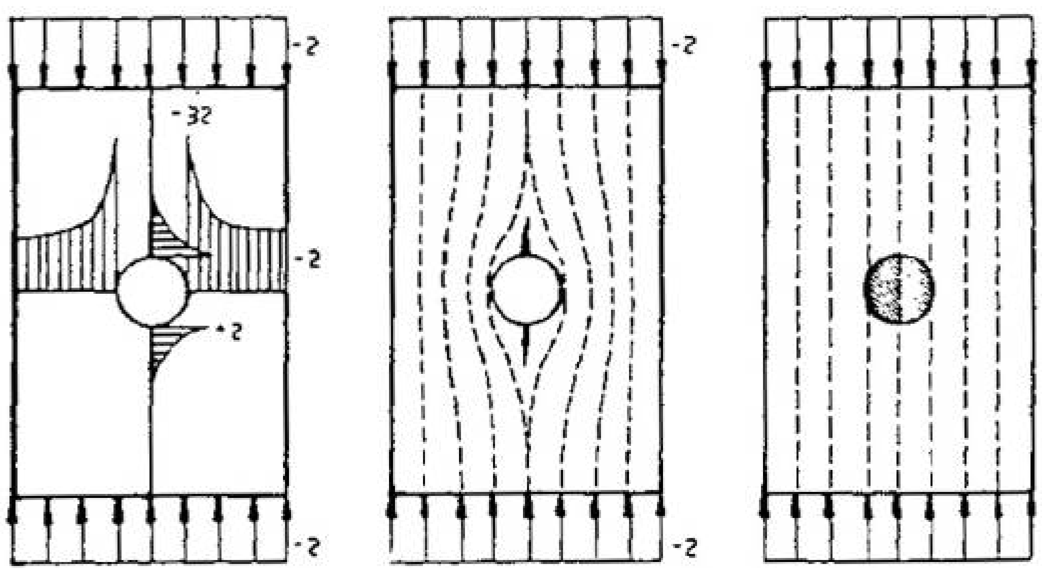

Figure 4.1: Conceptual Sketch of a hole in Masonry inducing higher Stresses (D.Van Gemert, 1984)

To be effective, the repaired crack must withstand tensile forces that are atleast as great as the tensile strength of the earthen masonry. The injection of binding materials is designed to improve mechanical characteristics of the existing masonry wall. The grout creates a friction, which enhances the post elastic behavior of earthen masonry. This type of repair technique is sympathetic to the historic fabric, is low invasive treatment and ensures a high level of structural integrity by over-bridging the cracks. The grout will bond to the existing structure to form a new composite material.

4.2.1. Importance of Bond

The measure of durability of the grout repair depends on its capability to improve the bond with the substrate. Good bonding is vital for the structural upgradation and creating a unified response of the structure to the external aggressive agents. The strength and extent of the bond are affected by many variables of material and workmanship. Complete and intimate contact between the grout and the parent masonry is essential, and workability influences the ease with which the grout spreads and covers the surfaces. Earth units have very porous surface that are highly receptive to the wet grout, which increases adhesion. The moisture content and suction of the units, the water retention of the grout, and curing conditions such as temperature, relative humidity, and wind combine to influence the completeness and integrity of the mechanical and chemical bond. Voids at the grout-to-masonry interface offer little resistance to water infiltration and facilitate subsequent disintegration and failure if freezing occurs.

4.3. Technique of Grouting

Design and analysis of a strengthening scheme using the principles of energy dissipation, is very sensitive to the characteristics of parent masonry, the grouts and the devices used for treatment. Therefore it requires a higher degree of sophistication. Grouting can be carried out by four different methods: manually, by gravity, pumped and also vacuum. Injection of cracks with an external material is designed for flexural or shear strengthening of the material. Grouting in masonry fills voids in the form of the pore system, wherein the principle improvement mechanism is increasing cohesion thereby strengthening the parent masonry. Mixing is accomplished by high pressure jetting of the soil with grout so that the two are combined to form a mixed composition. The external surfaces are cleaned of non-structural materials and plastic injection ports are placed along the surface of the cracks on both sides of the member and are secured in place with a sealant. The masonry is also pre wetted before the grout operation. Pre wetting seems to have a positive effect depending on the nature of binder in the grout and the porometry of the wall[44]. The center-to-center spacing of these ports may be approximately equal to the thickness of the element or the level of deterioration of the wall. After the sealant has cured, a low viscosity grout is injected into one port at a time, beginning at the lowest part of the crack in case it is vertical or at one end of the crack in case it is horizontal.

[44] Binda, L et al, "Repair and Strengthening of Historic Masonry Buildings in Seismic Areas". Source http://www.unesco.org/archi2000/pdf/binda197.pdf

The smaller the crack, higher is the pressure or more closely spaced should be the ports so as to obtain complete penetration of the grout throughout the depth and width of member. Larger cracks will permit larger port spacing, depending upon width of the member.

Strengthening of clay masonry by grouting is a challenging task. This is because (a) the size of voids within a clay material being very small (<0.1 mm), it is very difficult for a grout to penetrate and (b) clay may swell when the fluid grout is injected, thus not permitting the grout to further penetrate and fill voids.[45] In such a case, an approach imparting stability for the seismic upgradation of the earthen masonry should be taken.

[45] Elizabeth Vintzileou, "Grouting of Three-Leaf Stone Masonry: Types of Grouts, Mechanical Properties of Masonry before and after Grouting". (Editors: PB Lourenco, P. Roca, C. Modena, S. Agrawal). In *Structural Analysis of Historical Constructions*, New Delhi Sept 6-8 2006

5.0. LITERATURE REVIEW

5.1. Summary

Literature reviewed for the development of grouts for the strengthening of ancient masonry included published works principally from Western Europe; Italy, Belgium and Greece. Much of the research and experimentation was led by Luigia Binda, Politecnico de Milano on the use of hydraulic lime grouts in the 1980's and the early 1990s. The 1990's also saw the development of cement-based grouts by Androniki- Fezans Miltiadou at the Ecole des Ponts et Chaussées in France and later in Greece in the laboratories of the Services for Monument preservation in collaboration with the Technical University of Athens. However, Belgium leads the field in analytical research and developing binary and ternary modern grouts for the stabilization of historic masonry structures.

Major conferences dealing in the issue of grouting for strengthening of buildings:

- Mortars, Cements and Grouts Used in the Conservation of Historic Buildings, ICCROM, Rome 1981
- International RILEM Workshop on Historic Mortars: Characteristics and Tests, Paisley 1999
- 6th International Conference on the Conservation of Earthen Architecture, Las Cruces, New Mexico, USA. Oct 14-19, 1990. Getty Conservation Institute.
- 5th North American Masonry Conference, Urbana, IL Jun 3-6, 1990.

- Structural Analysis of Historical Constructions, New Delhi, India Nov 6-8, 2006.Major Journals featuring literature:
- International Journal for Restoration of Buildings & Monuments, UK
- Journal of Architectural Conservation, Donhead, UK
- Structural Studies, Repairs and Maintenance of historical buildings, UK
- Construction and Building Materials, UK
- APT Bulletin, US

Major works in the area are identified by

- ICCROM (International Organization for Conservation of Cultural Heritage)
- Politecnico di Milano, Italy
- Katholieke Universitet Leuven

5.2 List of Keywords

Absorption	Grout	Reinforcement
Adhesion	Historic Buildings	Repairs
Bearing stress	Injection	Rheology
Bonding	Injection Grouting	Seismic
Building materials	In Situ testing	Shrinkage
Cohesion	Lime	Strengthening
Compatibility	Masonry	Stabilization
Compressive strength	Masonry repairs	Structural stability
Consolidation	Mechanical Properties	Technology
Dispersion	Mechanical Strength	Unreinforced masonry
Durability	Mechanical Tests	Viscosity

Earthen structures	Moisture content	Void filling
Fill	Non Destructive Testing	
Flexural strength	Permeability	
Flow	Polymers	

5.3. Definitions

Grout may be defined as a binder (either inorganic or organic) injected to masonry with the purpose to fill cracks, voids and (to some extent) pores of the *in situ* materials.[46] It is a thin mortar containing a considerable amount of water so that it has the consistency of a viscous liquid inorder to be pumped into joints, spaces and cracks within the masonry system.[47]

An adequate grout can fill the (visible and invisible) cracks, the voids of the filling material, as well as the void between walls and filling material. By way of consequence, homogenization of masonry takes place and its mechanical properties are enhanced[48].

The standard components of a grout are:

- The binder or adhesive, which binds the components of the grout together

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[46] Elizabeth Vintzileou, "Grouting of Three-Leaf Stone Masonry: Types of Grouts, Mechanical Properties of Masonry before and after Grouting". (Editors: PB Lourenco, P. Roca, C. Modena, S. Agrawal). In *Structural Analysis of Historical Constructions*, New Delhi Sept 6-8 2006
[47] Cyril M Harris, Ed. Dictionary of Architecture and Construction, Third Ed New York: Mc Graw-Hill, 2000.444
[48] Elizabeth Vintzileou, "Grouting of Three-Leaf Stone Masonry: Types of Grouts, Mechanical Properties of Masonry before and after Grouting". (Editors: PB Lourenco, P. Roca, C. Modena, S. Agrawal). In *Structural Analysis of Historical Constructions*, New Delhi Sept 6-8 2006

- The filler or aggregate, which acts as a bulking material, thereby reducing shrinkage and controlling mechanical strength
- The fluid, which controls the rheological properties of the grout (i.e. ensures sufficient flow)
- Any additives, which may modify the working properties and mechanical characteristics of the grout, e.g. improve rheological properties while keeping the water content as low as possible.

5.4. Need for Characterization of Materials

The issue regarding the study of the original (existing) materials of a historic masonry structure and the methodology for the formulation of new or repair ones was for the first time systematically tackled by ICCROM in 1982 through the work that was initiated by Dr. Giorgio Torraca using hydraulic grouts[49,50]. This also became the first works of the use of hydraulic grouts for historic masonry structures[51]. The following fundamental requirements were identified:

In view of the development of repair materials, or materials that may replace the in situ ones, research on new and ancient materials should be carried out in parallel. The procedure of the characterization of the existing materials is necessary for the definition

[49] Daniela Ferragnani et al. "In situ consolidation of wall and floor mosaics by means of injection grouting techniques." In Mosaics No. 3, Conservation In Situ, Aquileia, 1983. Rome: ICCROM, 1985.
[50] E. Toumbakari. "Lime-Pozzolan-Cement grouts and their Structural effects on composite masonry walls." PhD Dissertation, Katholieke Universiteit, Leuven, 2001
[51] Daniela Ferragnani et al." In Adhesives and Consolidants, Eds. Brommelle, N.S.; Pye, E.M.; Smith, P.; and Thompson, G. Paris: IIC, 1984.

of some of the properties that the new materials should have and for the understanding of their pathology.

The new materials should be clearly characterized and very well documented; characterization and testing of repair materials should be standardized.

In the course of the formulation of the restoration materials, the following points should be taken into account, following the ICCROM Recommendations[52]:

- Mechanical resistance,
- Formation of dangerous by-products,
- Behaviour with respect to water (both liquid and vapor),
- Expansion due to heat or water,
- Modifications due to weathering,
- Application (which should be as simple and reliable as possible),
- Limits of reversibility,
- Aesthetic factors (for renderings, fillings and stuccoes) and
- Marking of materials added during conservation work (in the materials themselves or by documentation).

[52] Between 1979 and 1984, an extensive research program financed by the European Economic Community (EEC) and UNESCO grants was undertaken by ICCROM (the International Centre for the Study of the Preservation and the Restoration of Cultural Property) to develop and test grouts used for the reattachment of lime mural plasters and floor mosaics. This was later mentioned by Toumbakari EE (PhD Dissertation, 2002)

5.4. Development of the Use of Grouts for Structures

Guidelines for repair and strengthening of masonry structures in seismic areas were produced in Italy after the Friuli earthquake, which took place in 1976. Since then the technique of grouting by injection has been extensively applied using organic and inorganic grouts[53]. Injection grouting became a priority and research focused on the areas affected by seismic activity in continental Europe. An extended research program was developed through the collaboration between the Politecnico de Milano, University of Padova and ITEA (a Province of Trento Bureau of Public Housing), defined the appropriate guidelines for the optimal choice of injection grout admixtures for the repair and strengthening of masonry structures in seismic areas[54]. The 1985 earthquake in Chile produced extensive damage in reinforced masonry buildings due to in-plane shear actions. In recent earthquakes unreinforced masonry structures, used in historical buildings as well as in current modern construction, have sustained a high degree of damage due to shear action, demonstrating the need for techniques to improve the seismic response of those structures[55].

At the Sixth International Conference on Earthen Architecture in Las Cruces, New Mexico, Kariotis and Associates presented a case where cracked adobe walls were

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[53] Binda L. et al. "Experimental qualification of injection admixtures use for repair and strengthening of stone masonry walls." In 10th International Brick & Block Masonry Conference, July 5-7, 1994, Calgary, Canada 1994

[54] Ibid.

[55] Maria, Santa H. et al., "experimental response of masonry walls externally reinforced with carbon fiber fabrics". In *Proceedings of the 8th U.S. National Conference on Earthquake Engineering* April 18-22, 2006, San Francisco, California, USA

repaired by injection of modified mud. It presented the conclusions from a demonstration project designed to develop a procedure for stabilizing the wall of the Pio Pico Mansion Adobe of Whittier, California, damaged by an earthquake. The 1987 earthquake generated cracks and left portions of the walls loose and likely to become unstable. The procedure called for filling the cracks with mud that had been modified with lime and fly ash for strength and hardness[56].

5.4.1. Bond, Durability, Compatibility

In the 1990s, the scientific researches at the Politecnico de Milano evaluated the performance and durability of grouts for the strengthening of historic masonry structures. The evaluation was given key importance and the need for standardized tests was emphasized.

In 1987, efficacy of injection technique using hydraulic lime mixtures was tested dependant on the physico chemical and mechanical compatibility of the grout and the original material and the penetration and diffusion capacity of the grout. The study tested a lime-pozzolan-sand grout (1:4:9.28 by volume). It displayed a very low cohesive strength and confirmed the incompatibility of the mixture with the original brick

[56] Nels Roselund. “Repair of cracked adobe walls by injection of modified mud.” In *6th International* Conference on the Conservation of Earthen Architecture: Adobe 90 preprints. Las Cruces, New Mexico, U.S.A., October 14-19, 1990. The Getty Conservation Institute (1990): 336-341.

material[57]. This indicated that successful grouting was a result of using and adequate injection technique with a constant (low) injection pressure for filling masonry voids. In another case, test procedures to develop the effectiveness of epoxy resin grouts were measured for stone masonry walls[58].

Other studies conducted through the 1990s focused on the need for selecting the appropriate grout formulation (organic and inorganic) in order to meet chemical, physical, and mechanical requirements for compatibility with existing historic fabric. Grouts considered appropriate possessed characteristics of good penetration under low-pressure, displayed adhesion and chemical compatibility between existing and new materials, met minimal mechanical strength and deformability, and behavior responded to seismic activity. In order to evaluate the efficacy of the selected grout, a control sequence was used for first understanding the wall morphology – the physical, chemical, and mechanical properties of all components of the wall system through *in situ* investigation and testing, the detection of injectability of grout tested in the laboratory and *in situ* when applied to an experimental problem, and finally, the evaluation of the effectiveness of the intervention using non-destructive testing including ultrasonic, sonic vibrational, and flat-jack techniques[59].

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[57] L. Binda et al. “Durability of decayed brick-masonries strengthened by grouting.” In *Fourth International Conference on Durability and Buildings Material and Components*, Singapore, Vol. 1, 1987 Rome: ICCROM (1987): 24.
[58] Binda, L et al. “Repair of Masonries by injection technique: Effectiveness, Bond and durability Problems.” In *Structural Conservation of Stone Masonry International Technical Conference*, Athens, 1989. Rome: ICCROM (1990).
[59] L. Binda et al. “Durability of decayed brick-masonries strengthened by grouting.” In *Fourth*

5.4.2 "Structure" before "Material"

It is thus, important to analyze the existing structural system as a starting point for defining any requirements for stabilization including grout formulations. A study conducted by the collaboration of the Katholieke Universiteit of Leuven in Belgium and National Technical University of Athens in Greece defined design requirements for injection grouts used for consolidating ancient masonry based on rheological and mechanical properties. Structural requirements consequently inform the requirement of the materials and their ratios used for grouts as well as their compositions. Grout requirements concerning the physical behavior of the injected structure include injectability, adhesion with the existing masonry components, and sufficient mechanical properties within a defined span. Those requirements relative to the durability requirements of the injected structure include compatible microstructure, bonding with existing materials, and properties of the raw materials[60]. The study tested several lime-cement formulations with trass and fumed silica and found that compositions containing little Portland cement developed sufficiently high mechanical properties, initially from the cement and fumed silica the continuation of the pozzolanic reaction for a long period. And though the grouts showed high bond tensile strength, their shear strengths were only average; adhesion between the grout and brick were much higher than between limestone

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International Conference on Durability and Buildings Material and Components, Singapore, Vol. 1, 1987. Rome: ICCROM (1987): 24.

[60] E. Toumbakari et al. "Methodology for the Design of Injection Grouts for Consolidation of Ancient Masonry." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests* (Paisely, Scotland), 12-14 May 1999, France: RILEM Publications S.A.R.L. (2000): 396.

and grout due to the smoother surface of limestone and the higher porosity of the brick. Grout porosity was also found to be higher than that of the original hydraulic mortars, even after 180 days; porosity and pore size distribution appeared to be the result of water content used in the mixture, not the fineness of the materials. Fineness combined with the mixing procedure both contributed to the penetrability of grouts. The study also revealed in microstructural observations the pozzolanic reaction and progressive densification of the grout over time[61].

5.5. Properties of Masonry considered for Grouts

The objective of the grout is to revive the structural integrity of the parent masonry. Hence a thorough on site assessment and analysis of the composition and morphology of the walls is essential. Measure of the loss of cohesion between the masonry components is the measure of cracks and voids. Laboratory and In situ tests have been carried on the masonry. Non-Destructive, Destructive and Partially destructive tests have been conducted on the masonry for an assessing and categorizing the properties of the masonry as a unit.

Permeability, pore size distribution and moisture content are the most important properties with regard to the injectability of the grout[62]. The overall condition of the masonry was used to be determined by using coring and analyzing the cores for

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[61] Ibid.
[62] Van Rickstal, F. "Grout injection of masonry, scientific approach and modeling." In *International Journal for Restoration* 7, No. 3-4 (2001): 407-432.

mechanical properties, cracks and condition. Later trends involved the use of non-destructive techniques like ultra sonic measurements or electrical resistivity measurements that are calibrated again by coring. Reliability of non destructive tests as a means to evaluate in situ the degree of mechanical and physical damage of the existing masonries and the efficiency of their strengthening by grouting has been widely investigated using both ultrasonic methods and sonic vibrational techniques. Mineralogical and Petrographical analysis of the masonry has also been carried out by L. Binda for chemical composition.

Much importance has been placed to measure the Water Absorption potential of the masonry. This was considered important to understand how will the masonry react to the water introduced by the grout in its system and what is the potential for absorption. The related properties for the complete understanding of the behavior of the masonry are Bulk Density. Vintzileou discuss the Modulus of Elasticity (stress strain) of the grouted and ungrouted wall samples. Van Gemert, D et al does measurements of Porosity and Pore size distribution and checking of any soluble salts. The main question addressed is the measurement of the strength improvement required in the masonry.

5.6. Working Properties and Performance Characteristics of Grout

The working properties are defined as properties of the material in the state in which it is applied, measuring its practical ease of use, while the performance characteristics of the material relate to its long-term behaviour within a masonry structure. The choice of a suitable grout for repairing old structures is not only dependent on the properties of set grout but also on those of fresh grout, which determine how effective it will be in situ[63]. Some selected working properties found in the literature are listed below.

5.6.1. Working Properties

The improvement of the mechanical behavior of a structure requires a grout with good injectability and bonding properties[64]. Vintzileou states that the Rheological requirements of the grout enable the grout to diffuse into the masonry. The working properties for the grouts most commonly discussed in the literature are:

Penetrability:

Nels Roselund devised a test of the penetrability by injecting the modified earthen grouts into voids between adobe and a plastic panel. S. Ignoul in 2003 injected test grouts over crushed bricks and assessed their penetration through the matrix of cracks.

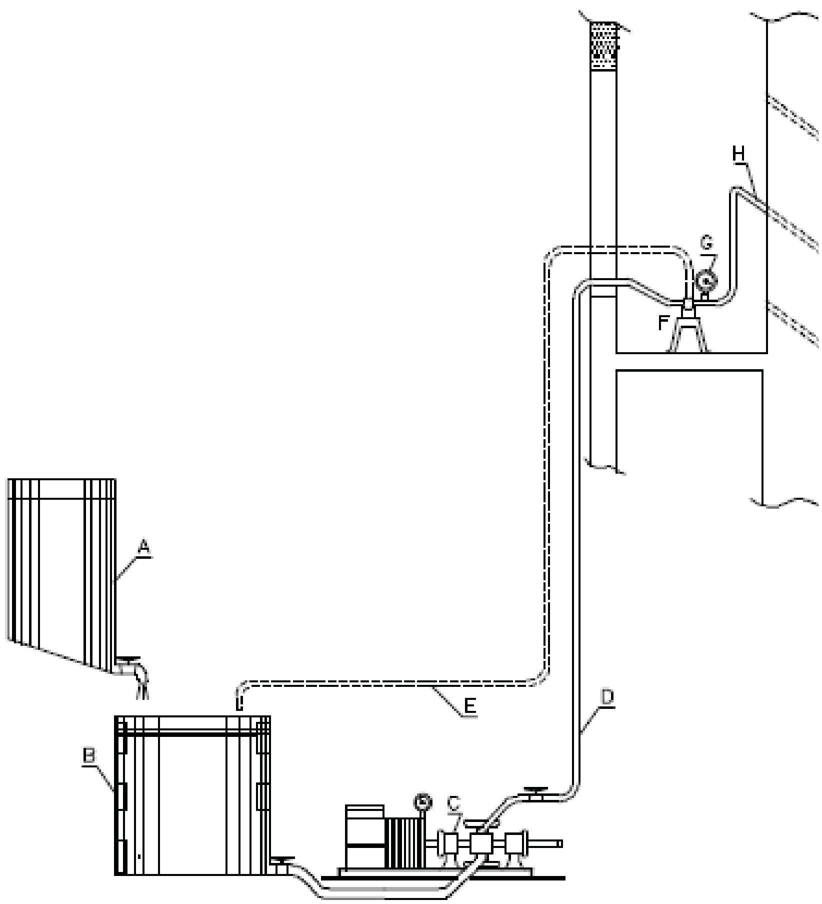
[63] G. Penelis et al. "Grouts for repairing and strengthening old masonry". In Structural Repair and Maintenance of Historical Buildings. Editor: C.A. Brebbia. (Computational Mechanical Publications) pp-178-188. 1989

[64] Van Gemert, D. "The use of grouting for the consolidation of historic masonry constructions. Advantages and limitations of the method." In Stable-unstable? *Structural consolidation of ancient buildings*. Lemaire, R.M. and Van Balen, K., Editors. Leuven: University Press (1988): 265-276.

Viscosity/ Fluidity:

Vintzileou states that Fluidity depends on the grain size, nature and shape of grains and the specific surface of the solid phase. Most studies measure the Viscosity of the grout using a Flow cone method by Barcellona et al. Binda

Injectability:



A= Mixing installation

B= Collector

C= Pumping installation

D, E= Conduits

F=, G, H= Admission System

Figure 5.1: Modern Injection installation. (Van Rickstal, F, PhD, Leuven, 2000)

Studies by S. Ignoul and Van Rickstal specifically deal with the injectability issues of the grout. The test uses a standard sand column method replicating the masonry. Rickstal also uses finite Elemental Analysis to model the movement of the grout.

Workability:

Different mixes with similar workability were prepared by using the most appropriate quantity of water to obtain similar fluidity by Barcellona et al. other studies use the Vicat apparatus to check workability of the grout.

5.6.2. Performance Characteristics

The fundamental performance characteristic mentioned in nearly every study is that the grout or mortar should be compatible with the original materials. Rate of strength development is a controlling factor. Durability of the repair depends on choice of raw materials, compatible microstructure and good bond has been stressed and checked by Toumbakari et al.

Density:

Low-density grouts will perform better in a wall. This has been checked in studies by Binda, Van Gemert et al. This is simply calculated as Mass/ volume.

<u>Minimal volume change upon setting:</u>

The expansion of the binder has been checked using an Ansett test. This has been checked in various studies by Barcellona, Bass Angelyn stressing that the expansion of the binder will produce unstable grouts.

<u>Shrinkage:</u>

One of the most important problems in repair is the shrinkage of the repair materials, which result in a poor bond with the existing ones. Shrinkage is more pronounced in dry environments. A possibility for facing this problem is the use of grouts with expansive properties. The binder particles of the grout are dispersed in water and by the introduction in a substrate the water is absorbed and this could lead to the shrinkage of the grout. Barcellona stresses that problems frequently met in practical restoration activity: water introduced in walling should be minimized to reduce degradation process related to water presence in porous system. Toumbakari et al suggest that although autogeneous shrinkage is unavoidable, relatively low shrinkage is necessary for a good bond. Shrinkage has been calculated both qualitatively and quantitatively.

<u>Water absorption by total immersion</u>

This test gives the water absorption curve by total immersion, at ambient conditions (Normal 7/81). It measures the Imbibition Coefficient. It has been measured by Binda et al and Barcellona et al.

Water vapor permeability

This test measures the quantity of water vapor passing per unit time and per surface unit through a material of prefixed thickness between two parallel surfaces (Normal 21/85). It has been measured by Barcellona et al and Nels Roselund.

Mechanical strength

Strength has been measured for compression, tension, flexure and shear. Studies by Barcellona, Binda, Van Gemert, Cancino suggest Mechanical strength of injected grout should not be excessively greater than the original walling grout. Earlier studies by Binda calculate the compressive strength of the grouts, but later studies by S. Ignoul suggest that tensile strength and adhesion strength are more important than compressive strength. Research by S. Ignoul also indicated that intrinsic mechanical properties of grout hardly influence the final strength of a deteriorated masonry wall in case of comparable rheological properties of the grout. Toumbakari also studied Bond traction tests with Schenck 100 kN capacity machine (speed of 0.1 mm/min and 0.3 mm/min) performed in a deformation controlled mode and Bond shear tests with ELE International shear box (speed of 0.3 mm/min) performed with a soil mechanics with displacements and shear forces automatically recorded.

Young’s modulus of elasticity has been calculated by Toumbakari et al and Binda et al.

5.7. Selection of Materials

Hydrated lime as a binder

When limestone (calcium carbonate, $CaCO_3$) is calcined at around 800 °C it forms quicklime (calcium oxide, CaO). The addition of water to the quicklime is called slaking, and the resulting product is slaked lime, also known as hydrated lime (calcium hydroxide, $Ca(OH)_2$). The slaked lime may be used in powder form or additional water may be worked into it to form a smooth paste, lime putty ($Ca(OH)_2$). When hydrated lime is used as a binder either the hydrated lime powder or putty is mixed with various additives, usually including more water. Hydrated lime sets through carbonation: the $Ca(OH)_2$ reacts with carbon dioxide in the air to form carbonated lime ($CaCO_3$), and water vapor is released during the process. Hydrated lime will therefore only set in the presence of air, although in the absence of air it will dry out and harden to some extent.

The main disadvantage of hydrated lime is that it requires exposure to the carbon dioxide in the air to set. For a grout hidden inside the wall with minimal exposure to the air, carbonation will only proceed very slowly, and so the development of strength and durability will also be slow. Many authors therefore argue that hydrated lime should only be used as a binder if pozzolanic fillers are present to react with the lime and permit a setting reaction in the absence of air[65]. Shrinkage and density of the grouts are also an

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[65] Griffin, I, "Grouts for Conservation of Architectural Surfaces" Literature Review prepared for the Getty Conservation Institute. May 2005 (unpublished report)

issue. Many projects carried out stressed the use of natural and traditional materials and used Binda et al used hydrated lime with powdered bricks as pozzolana in the proportions of 1:2 and 1:3. The grouts were additivated with a superplasticizer inorder to decrease shrinkage, the viscosity and quantity of water.

Hydraulic Lime as a binder

Natural hydraulic lime is made from limestone (calcium carbonate, $CaCO_3$) with naturally occurring clays (SiO_2 and Al_2O_3). When the limestone is calcined at around 1200 °C it forms quicklime (calcium oxide, CaO), as before, but also calcium silicate ($2CaO.SiO_2$) and calcium aluminate ($3CaO.Al_2O_3$). The hydraulic lime is in powder form and is activated by the addition of water, which gives $Ca(OH)_2$ alongside the calcium silicate and calcium aluminate. The lime then sets as the calcium silicate and calcium aluminate undergo hydration to form calcium silicate hydrates and calcium aluminate hydrates. In the presence of air the lime will also undergo carbonation and some $CaCO_3$ will be formed[66].

Disadvantages of these grouts are shrinkage, penetratability and expansion of binder. However the big advantage is that lime is a viscosifying agent and a highly stable binder with most compatible microstructure with porous materials like earth. It sets in the absence of air and in the presence of water. It has been successfully used by the

[66] Ibid

University of Pennsylvania team in their work on earthen and stone masonry), Miltiadou et al (lime with superplasticizer) and Binda et al (lime with pozzolans).

Cement as a binder

Cement is made by combining limestone with clays and heating them at around 1400 °C. Calcium silicates ($2CaO.SiO_2$ and $3CaO.SiO_3$) and calcium aluminate are formed. It sets when the calcium silicates and calcium aluminate undergo hydration to form calcium silicate hydrates and calcium aluminate hydrates. In the presence of air the lime undergoes carbonation and some $CaCO_3$ is also formed.

Disadvantages include the introduction of salts with cement. Research at Katholieke Universiteit proves that cement phase is necessary for strength development and good working properties of the grout. They were initially pure cement grouts. However, it was proven that their injectability properties were inadequate for filling the small size voids and cracks of historic masonries (because of clogging). This drawback of pure cement grouts led Miltiadou (1990) to the addition of ultra fine materials (on the basis of specific granularity criteria).

Use of blended grouts by E. Toumbakari in Belgium, A. Miltiadou in Greece Parthenon and Analytical and practical studies by Van Gemert in cement-blended grouts illustrate the development of good mechanical strength. However there is a caution expressed of thaumasite production due to reaction with gypsum.

Pozzolanas

Pozzolanas may function both as fillers, and through their reaction with lime, they act as binders. They have been defined as ‘materials, which though not cementitious in themselves, contain constituents which will combine with lime at ordinary temperatures in the presence of water to form stable insoluble compounds possessing cementing properties. The compounds formed are calcium silicate hydrates and calcium aluminum hydrates, as formed from the hydration of cement or hydraulic lime[67].

Naturally occurring pozzolans like brick dust, trass (Belgium), silica fume, fly ash etc have been used to make binary and ternary grouts. They have been used for set with lime.

Water

The fluid present in a lime or cement-based grout is nearly always water-based. Aqueous dispersions and emulsions of fluidizers and plasticizers, limewater, casein etc. have also been used[68]. The proportion of water present in the initial grout mix is important: higher water contents give improved flow and injectability, but also lead to a greater volume change upon setting, with more potential for cracking.

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[67] Griffin, I, “Grouts for Conservation of Architectural Surfaces” Literature Review prepared for the Getty Conservation Institute. May 2005 (unpublished report)
[68] Ibid

Fluidizers/ Plasticizers

Fluidizers and plasticizers are used in the grout formulation as they reduce the water content required to achieve the desired working properties. They improve water retention, adhesive properties, and they reduce the uptake of water by capillarity for the grout. Consequences of the reduced water content are reduced volume change upon setting and higher mechanical strength[69]. These characteristics improve the durability of the grout. Miltiadou and Binda used superplasticizer with natural hydraulic lime for the grout.

Organic Systems

Polymer systems can be applied in pure form, pigmented or filled with filling materials. After hardening they form a solid, which is the bonding agent[70]. Silanes, epoxies and acrylics, polyurethanes etc have been used in various projects. Nels Roselund used EMACO RESTO, LEDAN TB1 in Pio Pico Mansion. Silbond 40 grouts were used in Fort Selden. Binda used epoxy resins and found good injectability and diffusion properties. Advantages of resins are noted in strength enhancement. However, the disadvantages can be found in presence of water, which has an effect on the bond strength.

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[69] Griffin, I, "Grouts for Conservation of Architectural Surfaces" Literature Review prepared for the Getty Conservation Institute. May 2005 (unpublished report)
[70] Van Gemert, D. "The use of grouting for the consolidation of historic masonry constructions. Advantages and limitations of the method." In Stable-unstable? *Structural consolidation of ancient buildings*. Lemaire, R.M. and Van Balen, K., Editors. Leuven: University Press (1988): 265-276.

The organic component can be applied in the following forms[71]:

- Physical system: the polymer is applied in solution, and dries through the evaporation of the solvent;
- Reactive system in solution: the solvent not involved in the formation of the polymer is added to reduce the viscosity. The dissolved active ingredient reacts with another component (hardener) and then forms a polymer, whereas the solvent evaporates;
- Active ingredient dissolved in reactive solvent: the solvent used is at the same time a reaction agent, which is incorporated in the final polymer;
- Solvent-free reactive system: in these systems, the components react directly with each other and form the polymer.

5.8. Assessment of Grouts

According to the literature reviewed, the evaluation of the properties for the masonry and the grouts has been done using International standards. These include the NORMAL standards, the RILEM standards, the American standards (ASTM), DIN (DIN Deutsches Institut für Normung e.V. (DIN; in English, the German Institute for Standardization) and the International Society for Rock Mechanics suggested procedures (ISRM).

[71] E. Toumbakari. “Lime-Pozzolan-Cement grouts and their Structural effects on composite masonry walls.” PhD Dissertation, Katholieke Universiteit, Leuven, 2001

6.0. LABORATORY TESTING PROGRAM

6.1. Methodology of Tests

6.1.1. Treatment Selection

Based on the above discussion and analysis, it can be derived that the treatment would address the cracks that could range from very minute (0.05mm- 0.1mm), to medium (5 mm). The larger cracks or discontinuities would comprise the delamination or detachment of the outer cobble layers and the inner puddled earth core. These could range from 10 mm-20 mm. The voids comprise 37.5 % of the per unit area of the masonry for the burnt puddled earth and 27.83% per unit area for the unburnt puddled earth.

The requirements of the physico-chemical compatibility and efficacy of the grout from a structural point of view must be addressed together. Based on the previous research and use reported in the literature and the assumed conditions of the Chiripa structures as suggested by the limited excavation, it is reasonable to assume that low-viscosity non aqueous grout used alone or in concert with other treatments can address the primary damages observed for mechanical enhancement and durability of the walls. The success of the grout ultimately depends on the characteristics of the in situ materials, on the actual state of the masonry, on the target and the overall scheme of the intervention.

The methodology for exploring the use of injection grouting as a viable technique at Chiripa began by analyzing the site, construction techniques and materials. Although no site visit was made, an assessment of the conditions was based on past and current reports and detailed photograph of the Temple Mound at Chiripa. The historic photographic records were also studied to better understand any changes in conditions over time. Given the nature of the materials, building techniques and physico-chemical damage observed, Grouting was deemed appropriate as a viable repair technique should one or more structures be opened and stabilized for interpretation.

The selection of a mix to be applied on a given masonry is based on the results of laboratory tests for the various properties of the grout that are critical to the parent masonry. The effects of the grout on the mechanical properties of the masonry would include looking at the macro and micro properties of the grout and the meso level properties of the interfacial bond with the parent masonry. The role of the bond mechanism on the mechanical properties of the grouts is very important for the selection of the grout that may be composed of materials similar to those in situ or otherwise, see Figure 6.1. Only one grout formulation was prepared and tested, inorder to determine the selected critical properties of flow/ viscosity, shrinkage and set time.

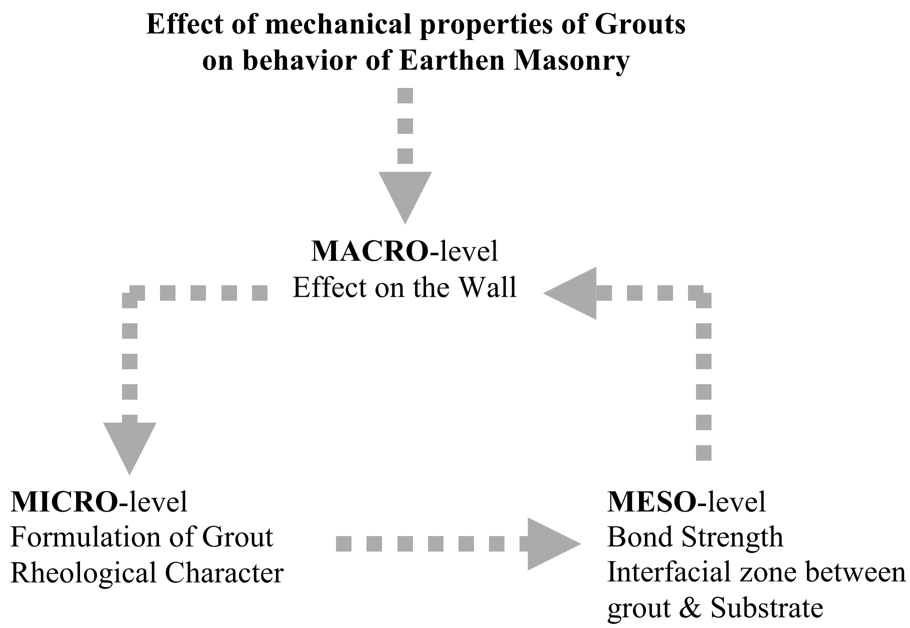

Figure 6.1: Conceptual Sketch of the effect of grout on masonry (Toumbakari E-E, 2001)

The selection of an optimum grout for the earthen walls at Chiripa involved parallel studies on the earthen masonry and the grout. A comprehensive set of tests was designed to define the material and physical characteristics of the historic puddled earth samples of Chiripa preceded the selection of the grout. This laid a set of performance criteria (physical, chemical and mechanical) for the selection of the grout and the interfacial bond was tested for its adhesion and compatibility with the historic earthen masonry, see Figure 6.2.

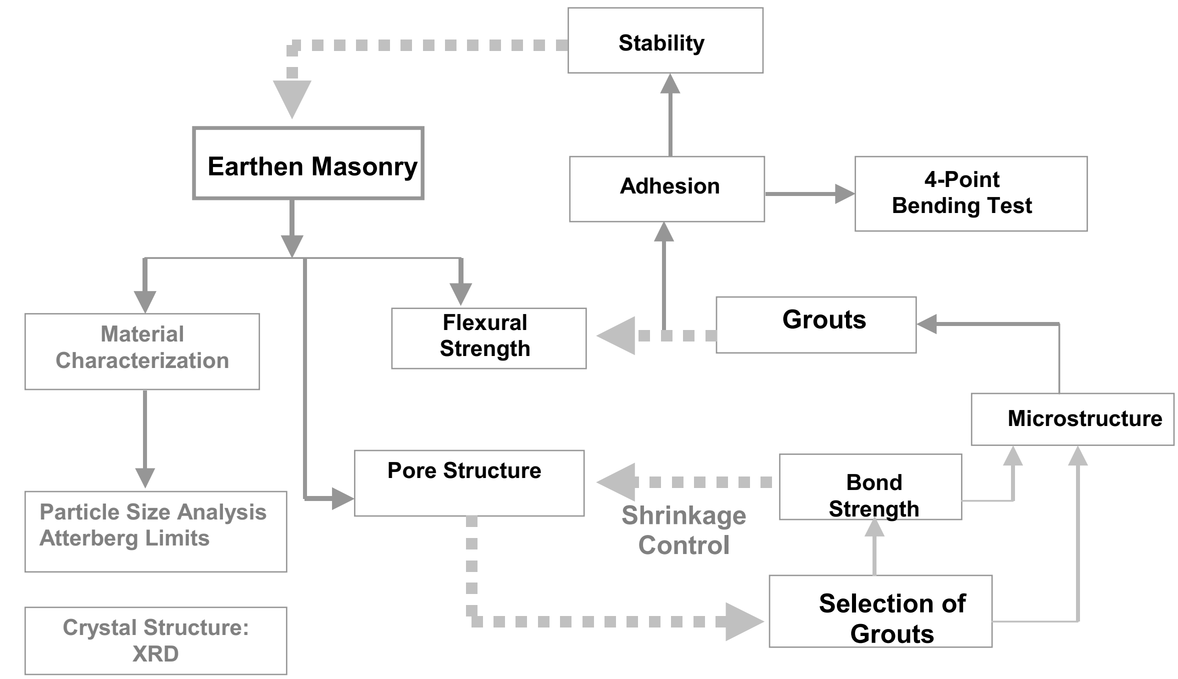

Figure 6.2: Relationship between properties of earthen masonry and grout as considered for tests. (Chaudhry' 07)

Laboratory tests were conducted to understand their properties that would affect the bond with the grout, hence pore structure (porosity), water absorption potential (permeability) and the Flexural Strength for cohesion. Other important aspects were to look at the dimensional change when wetter (Shrinkage) and density of the parent masonry. These properties would lay the parameters for the selection of the grout. The grout should have adequate rheological properties and high injectability must be ensured for the grout to adequately fill the (visible and invisible) cracks, the voids of the filling material, as well as the void between masonry and filling material. By the way of consequence, homogenization of masonry takes place and its mechanical properties are enhanced by achieving a good adhesion leading to better stability of the parent masonry. This adhesion (Durability) was tested by Four-Point Bending Test.

The selected grout was tested for its efflux time and the shrinkage for its use on the historic earthen masonry. Additional important information about the material was also gathered for its particle size distribution, Atterberg Limits (Plastic Limit, Liquid Limit and Plasticity Index) and the identification of the clay species to predict the dimensional response and stability of the material.

The Laboratory tests were supplemented by the use of various analytical tools for an effective understanding of the earthen masonry and its adhesion and the need for its strength modification with the use of the grout.

6.1.2. Performance Criteria for Grout

The primary performance criteria used to evaluate the grout formulations, according to the literature review and project parameters specified for grout injection for the earthen structures at Chiripa include:

Injectability

1. Adequate efflux time and viscosity in the liquid phase to fill voids by low-pressure injection to penetrate voids in earthen masonry core.
2. Penetratability: in voids with diameter even smaller than 0.3 mm (300µm)

3. Stability: no density gradients along the height of the stored grout[72].

Bonding

1. Minimal segregation and shrinkage while producing compositional stability until set to effectively consolidate the earthen masonry.
2. Minimum heat of hydration during the set.
3. Compatible microstructure: porosity and pore size distribution.
4. Setting and hardening in dry as well as wet environment.

Mechanical Properties

1. Low weight and Low Density
2. Development of sufficient mechanical properties.
3. Physico-chemical and mechanical compatibility with historic earthen masonry.
4. Good adhesive bonding to adjacent surfaces and shear strength to resist differential movement caused by seismic activity

[72] Toumbakari, E., D. Van Gemert, and T.P. Tassios. "Methodology for the Design of Injection Grouts for Consolidation of Ancient Masonry." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests* (Paisely, Scotland), 12-14 May 1999, France: RILEM Publications S.A.R.L. (2000): 395-405.

6.2. Summary of Tests

S N	Material	Property	Test	Samples	Size
1	Chiripa Earthen Masonry	Physical Description	Visual Observation	17	N/A
2	Chiripa Earthen Masonry	Physical Description	Cross Sections	4	minute quantites
3	Chiripa Earthen Plasters	Physical Description	Thin Sections	2	minute quantities
4	Chiripa Earthen Masonry	Grain Size Distribution	Particle Size Analysis	2	100-150 gm
5	Chiripa Earthen Masonry	Plastic & Liquid Limits	Atterberg Limits ASTM D4318	2	120 gm (approx for both tests)
6	Chiripa Earthen Masonry	Clay identification	X-Ray Diffraction Analysis	2	minute quantity
7	Chiripa Earthen Masonry	Density	Hydrostatic weighing ASTM C905	4	Prisms of a known mass
8	Chiripa Earthen Masonry	Pore Structure	Thin Sections	2	minute quantities
9	Chiripa Earthen Masonry	Water Resistivity	Water Drop Test CRATerre	3	Prism (55mm x 55mm x 40mm)
10	Chiripa Earthen Masonry	Water Absorption	Water Absorption by Capillary	2	Prism (15 mm x 15 mm x 40 mm)
11	Chiripa Earthen Masonry	Flexural strength	4-Point Bending ASTM D790-91	2	Prism (15mm x 15mm x 70mm)
12	Chiripa Earthen Masonry	Volumetric Shrinkage	ASTM D 4943-89	3	circular disks of known dimensions
13	Grouted Assembly	Bond Strength	4-Point Bending ASTM D790-91	2	(15mm x 15mm x 80mm)

Table 6.1: Table of Laboratory Testing Schedule

6.3. Sample Preparation

Masonry Samples

The preparation of the original earthen masonry samples for the tests was performed using a wet saw, band saw and the hex saw. The prisms obtained were then sanded using several grit papers for uniformity.

Figure 6.3: Prism of the Unburnt Puddled Earth from the gross sample

Grout Preparation

The grout was prepared at the Architectural Conservation Laboratory, University of Pennsylvania. The sand was sieved through a No. 50 sieve (USA). This procedure sorted the finest particles of sand inorder to be perfectly mixed with lime and the microspheres. The sieving procedure followed the ASTM C192-90a general specifications[73]. Once the dry materials were well mixed, a portion measured by volume was selected and placed in a small container in order to be mixed with the Silbond® 40.

[73] Standard Practice for Making and Curing Concrete Specimens in the Laboratory

The best average ratio for this part was 2:1.5 (Dry mix: Silbond® 40)[74]. The grout was first mixed by hand to mix all the dry components thoroughly. Subsequently, the dry components were mixed with Silbond® 40 initially by hand for two minutes. The ingredients were then mixed in 11.8-liter seamless stainless steel pail with tapered sides using hand-held corded Milwaukee 3/8" electric drill of variable speed control between 0-1200 rpm. A 48 cm long vertical stainless steel paint mixer was attached to chuck of the 7.0 AMP corded drill.

Figure 6.4: Hand Mixing of dry ingredients of the mix

[74] The Silbond to dry mix ratio used in the grout formulations was determined by the minimum amount of the mix required to pass the "Marsh Flow Cone" test according to ASTM C939-97 "Standard Test Method for Flow of Grout for Pre placed-Aggregate Concrete (Flow Cone Method)."

Figure 6.5: High turbulence mixing with Milwaukee drill

The grout mix was first mixed using the corded drill at a low setting for five minutes and the speed was increased gradually to achieve a vortex in the pail. This ensured that the various components are in adequate dispersion.

The total mixing time for the grout formulation varied from 20 minutes to 26 minutes. Long time mixing is considered one procedure that contributes to optimal mixing, producing good fluidity and increased stability in grouts[75]. High speed mixing is critical in achieving a high quality grout. Good workability ensures proper injectability through the specified apparatus and provides the grout compositional stability through its set and cure time. Once the grout appeared to be sufficiently mixed to pass the fluidity

75 S. Ignoul et al. "Application of Mineral Grouts for Structural Consolidation of Historical Monuments." International Journal for Restoration of Buildings and Monuments, Vol. 9, No. 4 (2003): 369.

test, the mixing time was recorded. Efflux time was recorded to be 4 and 5 minutes respectively. Before placing the grout in the molds, it was tested to determine its ability to pass through a No. 16 hypodermic needle. After this the grout was then poured into molds to visually assess for Shrinkage. After the grout was produced it was poured into the molds to prepare specimens for further tests.

Masonry-Grout Assembly Preparation

The molds for grouting the masonry samples were prepared at the Fabrication Lab at the University of Pennsylvania. These were made out of ½ inch thick plywood panel. The molds were lined by ethofoam sheet to avoid any damage due to the spillage of the grout. The masonry prisms were broken into two halves and then consolidated with the grout. The consolidation process was achieved by using a plastic container with glass beads lined with filter paper.

The glass container was then filled with Silbond® 40 and the sample prisms were kept in this with their bases were wetted. This allowed suction of the consolidant into the porous earth. After the consolidation process, the faces of the sample halves were grouted for a distance of 5 mm using a No. 16 hypodermic needle. The grouted prisms were covered and then allowed to cure for 14 days under covered conditions and then subjected to Four-Point Bending Test.

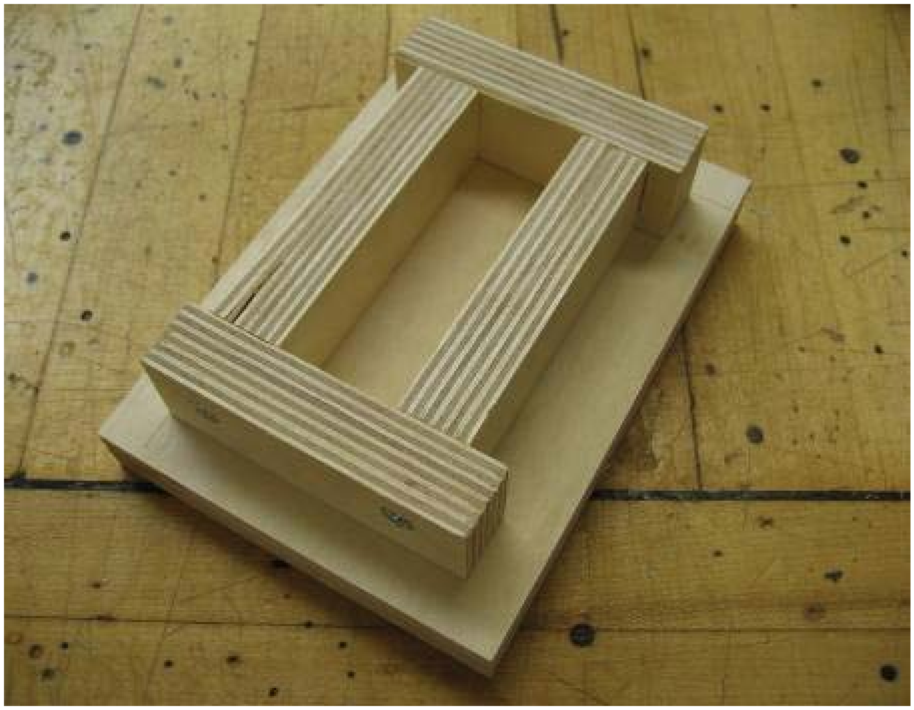

Figure 6.6:Wooden mold used for the injection of the prism

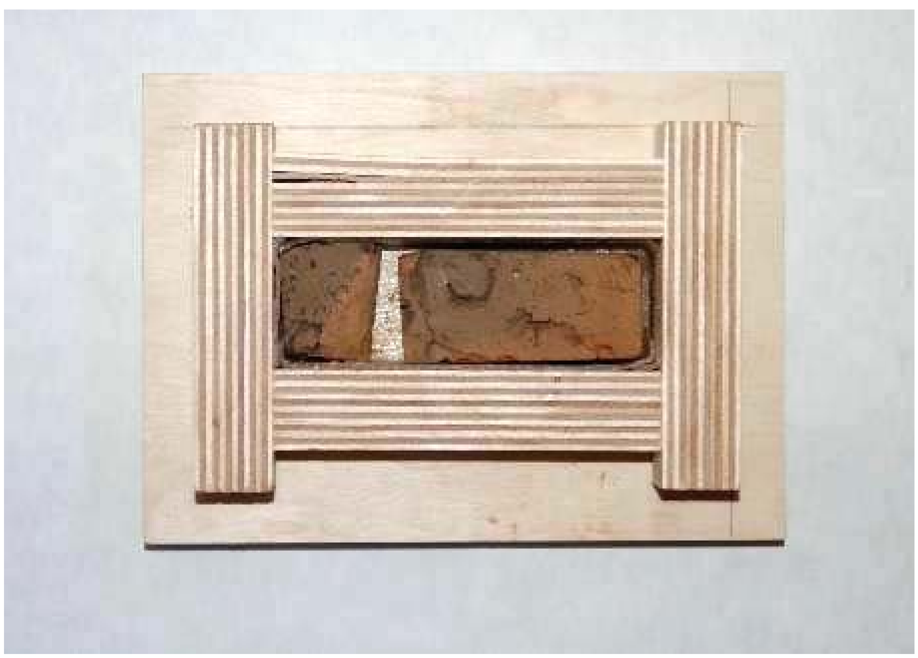

Figure 6.7: View of the prism to be injected at a distance of 5 mm

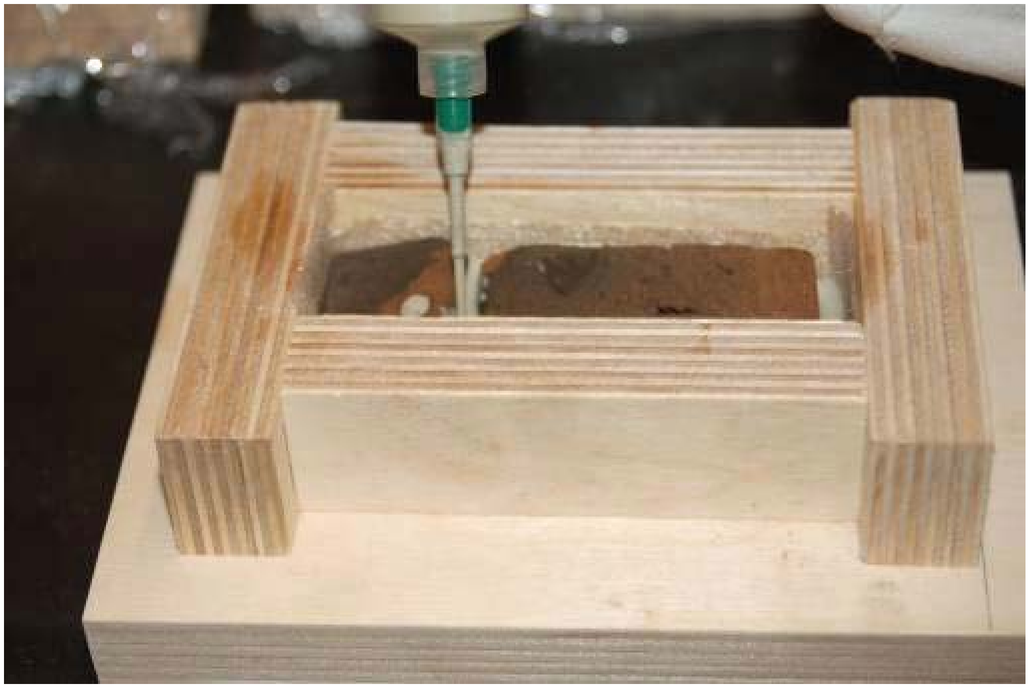

Figure 6.8: View of the prism being injected

6.4. Material Characteristics

6.4.1. Soil Characterization

Soils from the Pre Columbian houses in Chiripa should be characterized and analyzed to understand the basic properties of the puddled earth in question before undertaking any interventions or carrying out any strengthening measures. A number of investigations can be conducted by using standard testing methods, which can help to define the physio-chemical and mechanical behavior. Some of the tests as reported from the literature reviewed were used to assess the puddled wall material from the structure four at the Temple Mound of Chiripa.

6.4.1.1. Visual Observation

Seventeen floor and wall samples were collected by the archaeologists, under the Taraco Archaeological Project in 2006 from the Temple Mound at Chiripa. These were observed under a Nikon SMZ-U stereomicroscope with a Foster 8345 quartz halogen fiber optic light source at varying magnifications under plain reflected light for general geo-physical description.

Color: Soil color is helpful in suggesting soil properties. A dark brown or black colored soil indicates its high organic matter content. A red or yellowish soil often suggests good aeration and a good pore structure. A white color can suggest a marly (lime) soil or the accumulation of alkali salts. Soil colors were determined by comparing the soil samples with a set of 199 standard soil colors found in the Munsell Soil Book according to ASTM 1535[76].

Texture: Soil texture refers to the relative amounts of inorganic particles i.e. Sand, Silt and Clay. Sand grains are large and coarse, clay particles vary between fine and smooth, and silt particles are generally intermediate. Information regarding sand color, shape, particle size, voids, cracks and any other additive was noted.

6.4.2. Cross & Thin Sectional Analysis

Four samples were examined in thin-section under polarized and transmitted light and four samples were examined as opaque cross-sections in reflected light with a Petrographic Microscope (Nikon Microflex ADX- DX) at varying magnifications to observe micromorphology of the soils. The cross-sections were embedded in Melt mount and cut on a variable speed Isomet microsaw at 2-3 mm thick. The sections were then polished by hand or using an Ecomet polisher. Thin sections were commercially prepared by National Petrographic Service, Inc.

Methodology: The cross-sections were examined using a reflected light microscope under a relatively low magnification (30x to 150x). The thin-sections were observed using the reflected and polarized light under varying magnifications of 100x to 200x. The various kinds of information gathered using this technique, relevant to this

[76] ASTM D 1535, Standard Test Method for Specifying Color by the Munsell System, ASTM International

investigation, were the morphology of the particle (such as shape, size, surface character, and its crystal form), color and texture of the soils as well as any additional characteristics or additives. This provided a base for understanding of the material.

6.4.3. Gravimetric Analysis

Gravimetric analysis, by definition, includes all methods of analysis in which the final stage of the analysis involves weighing. Particle size distribution is employed to analyze the size, shape, sphericity, and sorting of grains. The test method utilizes standard sieves to collect particles larger than 75 µm (gravel and sand) and sedimentation with a hydrometer to account for particles smaller than 75 µm (silt and clay). Grain size distribution was determined both by sieving and by the sedimentation method, as described in ASTM standard D422[77]. This test is used to determine the performance of a given soil, its character and behavior by understanding the types and relative proportions of particles.

Grain Size Distribution

Methodology: The sample was soaked in a solution of sodium hexametaphosphate solution to disperse the clay particles, which otherwise tend to flocculate. Following the soaking, the samples and the solution were agitated for 15 minutes with magnetic stirring

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[77] ASTM D422 Standard Test Method for Particle-Size Analysis of Soils. ASTM International

bars and then sieved wet through a 75 µm (0.075 mm) sieve. The liquid suspensions containing the >75 µm soil fraction that passed the sieve were poured into 1000 ml glass sedimentation cylinders. The portion retained on the sieve was oven dried. The oven-dried portion was then sieved through a full set of soil sieves mechanically. The sieve analysis gives the grain size distribution of the sand fraction of the soil. The fine portion passing the 0.075 mm sieve was added to the sedimentation cylinder as fines.

Many classification systems are used for describing the range of the range of particle sizes in soil. The ASTM particle size convention was used for this report.

2mm	Gravel (normally not included in this analysis)
1.0 – 2.0mm	Very Coarse Sand
0.5 - 1.0mm	Coarse Sand
0.25 – 0.5mm	Medium Sand
0.125 - 0.25mm	Fine Sand
0.05 - 0.125mm	Very Fine Sand
0.02 - 0.05mm	Coarse Silt
0.002 – 0.02mm	Medium and Fine Silt
0.002mm	Clay

Table 6.2: Classification of Soil Particles according to US Dept of Agriculture

Generally soils with predominant fractions of fine/ very fine sand and silt display reduced strength. The test method yields quantitative data that can be expressed as ratios of one particle size to another. A well-graded soil or aggregate, one that contains equal proportions of multiple particle sizes, is well suited for building use because naturally occurring voids between larger particles may be occupied by smaller particles, ensuring a more homogenous and consistent material and one that displays less shrinkage. The sedimentation procedure for particles smaller that 75 µm can aid in the determination of the presence and quantity of clays in soils that provide plastic and adhesive properties.

<u>Sedimentation Analysis</u>

Figure 6.9: Sedimentation of Fine Particles in 1000 ml cylinders

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

Methodology: Deionized water was added to the cylinders with the fine fraction of the soil to bring the level of the suspension to 1000 ml. The cylinders were then capped and agitated in order to bring all settled particles into suspension. Hydrometers were inserted into the suspensions and readings were taken at regular intervals over the following 96 hours.

6.4.4. Atterberg Limits

The Atterberg limits are standard geotechnical tests that help to characterize fine grain soils and their response to water. The behavior of soil is related to the amount of water present. The liquid limit of the soil will indicate the point at which a soil, when mixed with water, has physical qualities closer to those of a liquid than a solid. This is attributed to the fact that at high water content, soils are suspensions with the flow properties of liquids. As water content decreases, the soil becomes consecutively paste like, sticky, and then plastic; at a low water content, the soil has the properties of a solid. The plastic limit test uses soil samples that have been mixed with water until they have reached plastic consistency and assesses the point at which, through loss of water into the surrounding environment, the samples lose plasticity. The liquid and plastic limits of the soils were determined according to ASTM D4318-00[78].

The values obtained for the plastic and liquid limits were used to calculate the plasticity index of the sample soils.

Plastic Limit

Plastic Limit is defined as the water content, in percent of the mass of the oven-dried soil, at the boundary between the plastic and semi-solid states. It is the water content at which the soil can be hand rolled from threads of an ellipsoidal mass to app. 3mm threads without crumbling. The first crumbling point is the plastic limit.

Methodology: The unburnt puddled earth sample was subjected to this test. The wet sample was hand-rolled into a round ellipsoidal on a glass plate mass without sticking to the palm into a thread at least 3mm in diameter until the soil thread crumbled.

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[78] ASTM D 4318 'Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils' ASTM International

Figure 6.10: Cutting the 3 mm ellipsoidal hand rolled soil into six halves

The rolling promotes the drying of the sample due to evaporation of water from the mass. At this point the sample was weighed and dried until constant weight. The test was repeated three times for the given sample. The plastic limit is the mass of water lost by the dry weight of the soil. The plastic limits for all trials should be averaged to formulate the plastic limit for the soil.

Liquid Limit

Liquid Limit is defined as the water content, expressed as a percentage of oven-dried soil, at the boundary between the liquid and plastic states. Water content is defined by the number of drops required to close the grove over a distance of about 1cm at the rate of 2 drops/second.

Methodology: The unburnt puddled earth sample was subjected to this test to determine its liquid limits. A portion of wet sample was placed in Casagrande device, and the surface smoothened with help of a spatula. A groove of ½” is then made in the middle so as to divide the sample in two sections. The cup was then listed and dropped by turning the crank handle at a rate of two revolutions per second. Several blows were then applied to this sample till the groove closed over a length of 13 mm. A section of this material was then removed from the bowl, weighed, and dried. This is repeated at least two other times.

Figure 6.11: Casa Grande Device for Liquid Limit calculation

The water contents for all trials were then plotted semi-logarithmically against the number of drops required to close the groove for each trial. This establishes the liquid limit of the sample.

Plasticity Index

The difference between the liquid limit and the plastic limit is calculated to give the plasticity index of the soil: Plasticity Index = Liquid Limit – Plastic Limit
The plasticity index is reported to the nearest whole number.
For a range of soils, the plastic limit varies less than the liquid limit and is somewhat related to the surface area of the clay particles, though not in direct proportion[79].

6.4.5. Clay Mineral Identification by X-Ray Diffraction

Clay mineral particles are too small to be seen with a common optical microscope. The only way to definitively identify clay minerals in a soil sample is to perform an instrumental technique such as x-ray diffraction (XRD). This is an effective method as soil is a crystalline material. The technique takes advantage of the fact that wavelengths of x-rays are approximately the same as the internal spacing of the atomic particles within crystals, which results in diffraction of the x-rays when they pass through

[79] Yong, R.N and Warkentin, B.P, "Soil Properties and Behavior", New York, Elsevier Scientific Publishing Company, 1975 pp66

the crystalline material[80]. By passing x-rays through a prepared soil sample and recording the diffraction patterns, a signature of the clay content can be obtained providing at least 10% is present.

Principle: Crystalline materials diffract light based on the spacing between different atoms in that crystal. According to Bragg's Law, the interaction with X-rays results in secondary diffracted beams, which relate to the interplanar spacing in crystalline sample. It is especially suitable for clays as the inter-molecular spaces within the crystal grains are nearly the same as X-ray wavelengths. Braggs Law is given by

$N\lambda=2d\sin\theta$

Where,

The distance between similar atomic planes in a mineral (the interatomic spacing) called the d-spacing. The angle of diffraction called theta angle. For practical reasons the diffractometer measures an angle twice that of the theta angle. The wavelength of the incident X-radiation

Methodology: A sample was analyzed as powder with grains in random orientations and by directing X rays through to insure that all directions are covered by the beam. The x-ray spectra generated by this technique provided a structural fingerprint of the sample. The diffraction of the rays obtained was compared with the patterns of

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[80]. Moore, Duane M and Reynolds, Robert C., Jr., "X-Ray Diffraction and the Identification and Analysis of Clay Minerals" Oxford, Oxford University Press, 1989 pp13

diffraction with those of other known minerals in a spectra database library. The clay minerals were thus identified and calculated using "whole pattern fitting". The method involves iteratively fitting a simulated pattern (from the database) to the measured pattern and calculating the intensities that provide the best overall fit. The weight percents are calculated from the intensity values however it does not accommodate measurement errors like preferred orientation, so the error could be as large as +/-10%. The samples for this test were glycolated using a 50-50 mix of ethylene glycol and ethylene alcohol.

6.5. Physical Characteristics

6.5.1. Drying Shrinkage Limit

An important characteristic of earthen materials is the ability to dry without unacceptable shrinkage. For the properties as water sensitivity, swelling when wet, shrinking and cracking when drying are important to measure to gauge the shrinkage potential of the soil. Sands experience very little linear shrinkage, and silts are only slightly more active than sands. The clay fraction is by far the most active. Kaolinite-type clays have a shrinkage rate of 3% to 10%; Illites 4% to 11%; and smectites/ montmorillonites 12% to 23%[81]. The effective measure of soil shrinkage is volumetric shrinkage, for soils shrink in all dimensions, not just length.

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[81] Houben and Guillaud, In *Earth Construction*, p 31

Methodology: The process of determining the soil shrinkage by volume is more complex than simple linear shrinkage. The method involves casting the soil in a mold of known dimensions which is adequately greased, and then coating the dried soil with paraffin, and weighing the coated soil in water also called as Hydrostatic weighing.

Figure 6.12: Casting the wet soil into shrinkage dishes

By using all the knowns- soil weight, wax weight, density of wax etc., the unknown volume of dry soil can be calculated, and from that the percent shrinkage. This wax technique for calculation of the Shrinkage Limit is detailed in ASTM Standard 4943[82].

[82] ASTM D 4943 "Standard Test Method for Shrinkage Factors of Soils by the Wax Method" ASTM International

Shrinkage also is related to the amount of water in the wet soil mix, more water often means more shrinkage. The amount of shrinkage apparently is not a linear function of the amount of water in the soil-water mix. High water content used in earth results in considerably increased shrinkage[83].

6.5.2. Pore Structure

Between the soil particles there are empty spaces, which are occupied by air and water and are termed as pore spaces. Pore spaces between the aggregates of soil particles are macro pores and those between the individual particles of the aggregates are micro pores. Sandy soils have a higher percentage of macro pores. Pore structure is an important parameter while considering the strength and hence the earthquake resistance of the material. It has effect on the permeability of the earth. Clay soils contain a higher percentage micro pores when compared to sandy or silty soils.

Methodology: The pore structure calculation was carried out by the use of Petrographic thin sections. This method although based on qualitative calculation was chosen because the porosity calculation using water absorption by total immersion would be an intrusive technique for the puddled earth samples.

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[83] Alva, Alejandro and Teutonico, J M, "Notes on the Manufacture of Adobe Blocks for the Restoration of Earthen Architecture" in Adobe: International Symposium and Training Workshop on the Conservation of Adobe, Lima- Cusco, Peru, Sept 10-22, 1983, 49

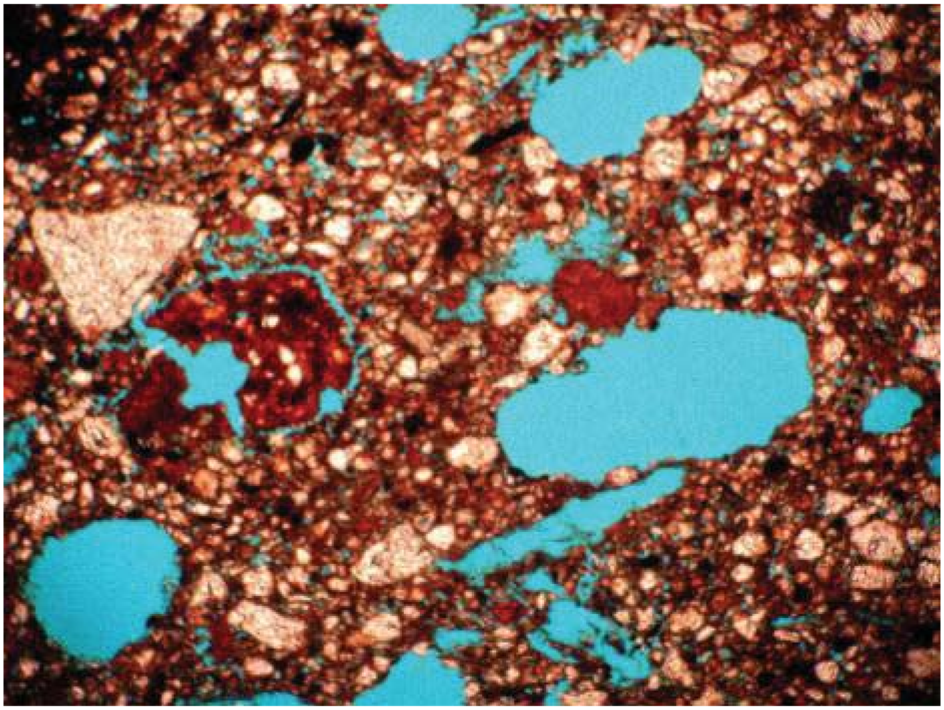

Figure 6.13: Thin Section of the Burnt Puddled Earth in transmitted Light

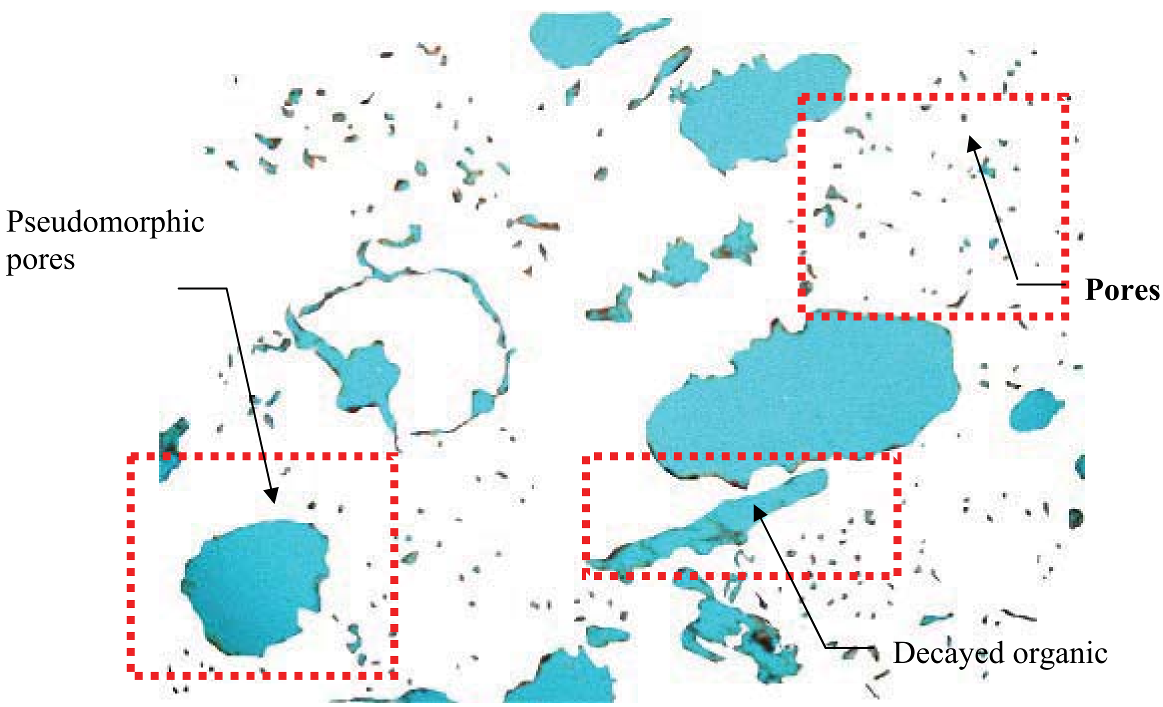

Figure 6.14: Extracted pixels of the pore spaces used for the quantitative calculation of the pseudomorphic voids to the solids

The approximate areas and perimeters of the individual pores are estimated from image analysis of the thin sections. Images of the puddled earth structure were digitized from color photographs of thin sections with increased thresholds. All images were 1536 by 2048 pixels, representing 210mm by 216 mm. The solid particles were made to equal to darker colors with increased threshold, while the pore phase (the light areas) was made to equal to blue color. All images had to be the same resolution for an effective analysis. The solid particles referred to here includes all material that appears solid at the scale of examination. This method includes pores that only become apparent at finer scales of examination. Finally, a percent of the solid to the empty spaces is calculated.

6.5.3. Bulk Density of Earth

The density of soil can be expressed in two ways. (1) The density of solid (particle density), particles of the soil and (2) the density of the whole (Bulk density) soil that is inclusive of pore space. Generally soils with low bulk density have better physical condition than those with higher bulk densities. Texture and structure of a soil, its total pore space and organic matter content are all related to bulk densities.

Principle: Bulk Density of the solid is simply calculated as Mass/ Volume. The volume is calculated by Hydrostatic weighing. By this method, the volume of a solid sample is determined by comparing the weight of the sample in air to the weight of the sample immersed in a liquid of known density. The volume of the sample is equal to the difference in the two weights divided by the density of the liquid. The most common method is the Archimedean Immersion Method, whereby the loss of weight of an object when suspended in a fluid of known density is equal to the mass of fluid displaced, from which its volume and hence density can be calculated. Unless there are good reasons for not selecting it, water is the most common immersion medium, the primary reason being its low sensitivity of density to temperature compared with many organic liquids.

Methodology: The object was suspended on a thin metal thread and weighed twice - measuring the force of pull on the thread when suspended in air and immersed in the liquid.

Figure 6.15: Triple beam Balance for hydrostatic weighing of samples

If a balance from which the thread can be suspended is not available, a modification of the method is to simply weigh the object on a top loading balance followed by weighing the container with the liquid with and without the object immersed (suspended) in the liquid. The puddled earth samples were first coated by paraffin wax and then suspended into a beaker of known volume.

6.5.4. Water drop Absorption

The water drop absorption rate is defined as the absorption time of a limited and definite amount of water by the surface of the material. The resistivity of the puddled earth samples from Chiripa was tested according to the CRATerre Water Drop test originally developed to determine the effects of impacting water on the surfaces of compressed earthen blocks.

Adapting this test for evaluation of puddled earth cubes can similarly indicate the resistance of earth to erosion and leakage when exposed to the direct impact of falling water. Although no published standard for this test method exists, the procedure has been described in detail in previous laboratory testing programs arranged for material testing at the University of Pennsylvania and is easily adapted to this program. The original samples of earth were cut using wet saw, band saw and hex saw to a dimension roughly of 2-inch square surface. Three samples of were tested by this procedure. The results of this test are primarily qualitative in nature, because they are based on visual observation of the damage done to the specimens over the course of their exposure to the falling water. It was, therefore, imperative to have three specimens of the sample that would almost certainly sustain significant damage to use as a basis of comparison in the rating of the resilience of each formulation to impacting waterfall.

Methodology: Three laboratory ring stands were outfitted with burette clamps and three prong extension clamps. The extension clamp on each stand held a Plexiglas plate. A water bottle with a spigot at the base was set on each of the plates and a length of flexible rubber tubing attached to the spigot. A burette stopcock was fitted to the output end of the tube and fed into the barrel of the burette held to the stand by the clamp. The assemblies were then placed on a tall cabinet and the burettes adjusted to the recommended height of 2.5

Figure 6.16: Placement of the Set Up at the height of 2.5 meter above ground

meters (8 feet 2 ½ inches) above the floor. Samples were arranged at the floor level in groups of three beneath the overhanging burettes. Each sample was supported by a test-tube rack nested inside of a bucket to catch run off water. The bottles in the assemblies were then filled with deionized water and both stopcocks in each assembly were adjusted to distribute one drop of water per second. The burettes were thus filled at the same rate as they drained. The samples were exposed to the falling water across an approximately 1 inch area in the center of their exposed surfaces at the rate of one drop per second for a period of one hour (approximately 3600 drops), after which time the maximum depth of erosion was recorded with a digital caliper accurate to 0.01 cm. The samples were photographed after the hour of exposure. The depths of erosion for the three samples were averaged and divided by the amount of elapsed time in minutes to determine the rate of erosion in cm/minute. The knowledge of the resistance of earth to this type of deterioration is useful in evaluating the strength from its endurance against one of the more damaging types of water exposure. Because of the erosive capabilities of falling water, this test is also useful in the determination of the water absorption potential of the puddled earth. This value will help in the determination of the properties of grout to be used with particular earth type.

6.5.5. Water Absorption by Capillary Action

The water absorption potential of the earthen material is an important factor to determine before the design of grout for its repair. This factor will account for determination of the amount of water absorbed by the earthen masonry on the application of the grout. The water absorption rate is also a good indicator of the porosity of the material, which is an important property of porous materials.

Principle: Water rises into the materials by capillary action. Capillary action is a type of suction, occurring because the forces of attraction of the water particles to the material's particles are greater than the gravitational force.

Figure 6. 18: Unburnt and Burnt Puddled Earth Samples after test

It has been proven that the smaller the diameter of the capillaries, or pores, the greater the capillary force. For earthen materials, these physical properties largely determine durability and are dependent on composition, compaction, and the condition after deterioration.

Methodology: The two puddled earth samples (burnt and unburnt) from Chiripa were obtained roughly of the same dimensions (0.85”(22 mm) x 0.85” (22 mm) x 1.5” (40 mm)). These were placed upright in a container. Deionized water was added to the container on a bed of glass beads covered with filter paper on top. It is necessary that only the face of the filter paper is wet from the water to save any disintegration of the earthen sample on contact with water. The height (H) of the rising damp was recorded every 30 seconds for 10 minutes until the water reached the top of the sample. The measurements were taken by placing a ruler next to the sample and recording the height on the face of the sample. Care was taken that the bottom of the filter paper is always in contact with water.

6.5.6. Flexural Strength

The modulus of rupture, or flexural strength, of the two puddled earth samples was tested according to ASTM Standard D1635-00[84]. Sample sizes used were based on the availability of the bulk sample and the minimum length required between the lower knives of the machine. It was specified that rectangular prisms of 3 inch in length, 1/2 inch in width and 1/2 inch in depth would be sufficient to run the test.

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[84] Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading (This test was modified for the use of Four-Point Bending)

Principle: In a Bending test, the specimen is subjected to tension along its top surface and compression along its bottom surface, or vice versa. A three- or four-point bending fixture of older design is capable of pushing from one side only, so that it can bend the specimen in one direction only; that is, it can induce either tension or compression (but not both) on the top or bottom surface. The specimen is placed between two pairs (for a four-point test) or one pair (for a three-point test) of knife-edge load applicators that are anchored on a base plate. One load applicator is fixed; the other three are adjustable. Pairs of convex knife-edge supports on a movable support fixture are also positioned in gentle contact (while in the zero-applied-stress condition) with the specimen near the ends of the specimen.

Methodology: Samples for this test were cut using wet saw, band saw and hex saw from the bulk sample. Two samples each of the burnt and the unburnt puddled earth were tested. This test calls for the placement of the test specimen in a machine-mounted bending apparatus.

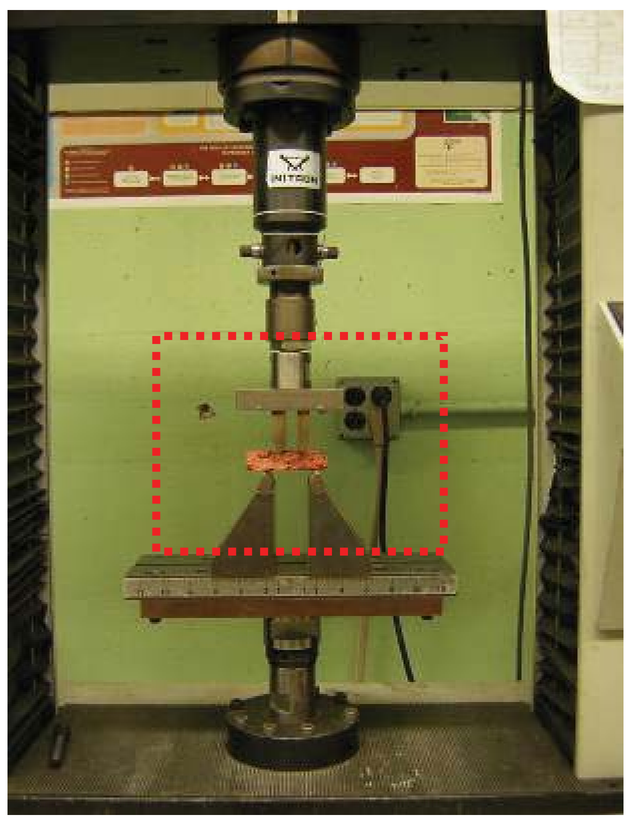

Figure 6.19: Four-Point Bending Set Up

The specimen's width and depth were measured at the center of each specimen prior to the test. The beam-shaped samples were placed with each end on one of two raised seating points. The space between the points at the top gauge was 0.85 inches (22 mm) and the distance between the points at the bottom gauge was 2 inches (50 mm) (specified as three times the depth of the sample). Pressure was then applied through a blunted fulcrum from above the specimen at its middle continually and with increasing load strength. The loading was recorded at the specimen's breaking point, as was the maximum deflection of the sample before breaking. The test is intended to determine the flexibility of the puddled earth as well as its resistance to bending.

The test was conducted at the Laboratory for Research on the Structure of Matter (LRSM) at the University of Pennsylvania using an Instron testing machine model 4206 electro mechanical testing machine).

6.6. Durability

6.6.1. Ultimate Bending Strength

The strength of soils is the property that determines their behavior under external mechanical forces. It is the resultant of the mineralogical components and of the intra-crystalline connections. This behavior is to be expressed by the critical stress causing failure or cracking of the specimen.

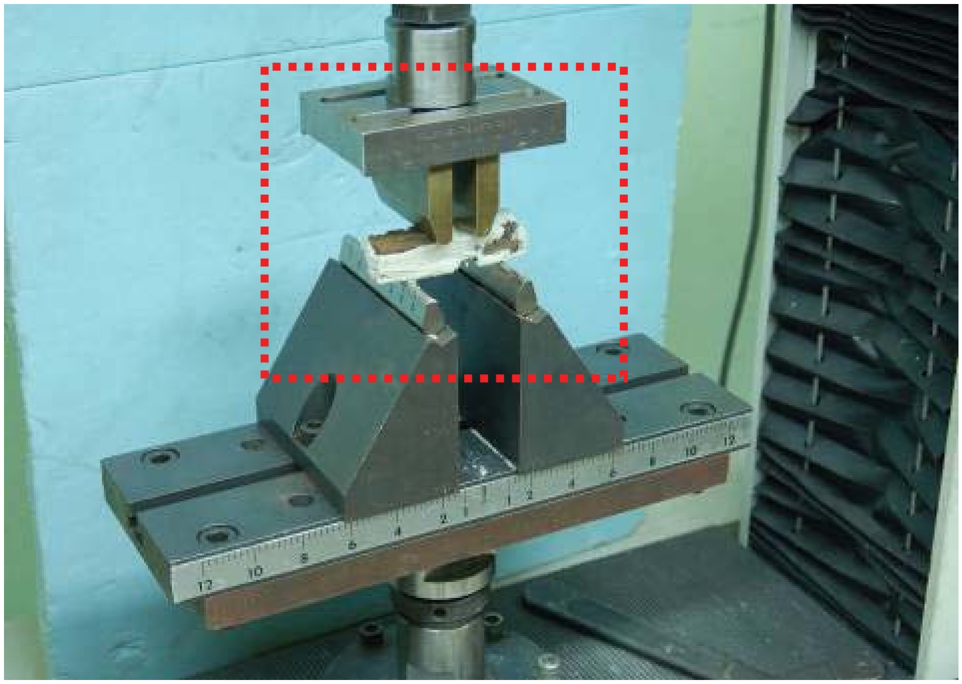

Figure 6.20: View of grouted sample on Four Point Bending

Principle: Strength (ultimate stress) detects the nature of the critical component (the faulty element) in the intrinsic structure of the soil. Strength varies with stress, which exerts mechanical stress on the specimen observed. The flexural test determines a heterogeneous stress field, and defines the bending strength. The flexural strength is an indication of a grout's resistance to bending stress, or tensile stress, resulting from structural settlement, thermal cycles, and fluctuations of humidity or seismic vibrations. Uniform lateral pressure, under displacement control is applied to a squarely cut specimen 0.85" (22 mm) x 0.85" (22 mm) x 3.0" (75 mm) placed between two rigid planes. The prescribed displacement to the sample and the load required are monitored and recorded by a computer-operated data acquisition system, which are later converted to stress versus strain curves. The specimen deflects as a result of combined bending and shear deformation.

With four-point bending fixture a constant bending moment is achieved between the two indenters. In three-point bending the moment increases linearly from support to the indenter. The strain (and stress) in four-point bending varies linearly across the test specimen.

Bending Stress

$$\sigma_b = \frac{3PL}{2wt^2}$$

Where,

P= Normal Force (35 pounds for Unburnt and 25 pounds for burnt puddled earth sample)

L= Length of prism (3 inches)

w= width of prism (0.85 inches)

t= Thickness of prism (0.85 inches)

When the reliability of grouted joints is to be tested, then 4 point bending test is an appropriate test because the grouted crack/ joint, which is 5 mm in this case, between the indenters is under equal loading.

Methodology: The grouted samples were subjected to a Four Point Bending Test. The samples for this test were grouted using the prepared grout. Two samples each of the burnt and the unburnt puddled earth were tested. This test calls for the placement of the test specimen in a machine-mounted bending apparatus. The grouted prism is simply supported on rollers, sitting at a fixed distance G.L (Gauge Length) = 0.85 inches (22 mm) at top and 2.0” (50 mm) at the bottom. Continuous load was then applied to the specimen through blunted fulcrum points at the speed of 0.005 min/second. The loading was recorded at the specimen’s breaking point, as was the maximum deflection of the sample before breaking The output parameters recorded during the experiments are the load F and the bottom fiber deflection (displacement) of the prism middle-span section. The test was conducted at the Laboratory for Research on the Structure of Matter (LRSM) at the University of Pennsylvania using an Instron testing machine model 4206 (electromechanical testing machine).

7.0 RESULTS AND DISCUSSIONS

7.1. Material Characteristics

7.1.1. Soil Characterization

7.1.1.1. Visual Observation

Seventeen soil samples obtained from the Temple Mound at Chiripa were observed under reflected light with a Nikon SMZ-U stereomicroscope at low magnifications (30 x to 75 x) to make general observations about sample fabric and texture. This data is presented in the Appendix B.1. The visual analysis indicates that the soils are predominantly reddish browns to yellow brown soils to dark brown in color, coarse (substrate) to smooth (finish) in texture and possess high sand fraction. The color is a significant factor in classifying soils. Typically darker soils absorb more sunlight than brighter soils (sometimes redder). The darker soils, representing floors of the houses at Chiripa have an evidence of the presence of ash, charcoal and decayed organic matter. The decaying organic material renders the soil unstable by increasing the soil porosity and increasing acidity causing the clays to flocculate and weakening the compressive strength[85]. It was found that the structural puddled earth used in the walls was of two kinds, burnt and unburnt. The burnt puddled earth samples showed different conditions

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[85] Alva, Alejandro and Teutonico, J M, "Notes on the Manufacture of Adobe Blocks for the Restoration of Earthen Architecture" in Adobe: International Symposium and Training Workshop on the Conservation of Adobe, Lima- Cusco, Peru, Sept 10-22, 1983, 48

on the exterior face than the interior face. The exterior surface is harder than the inner and had use of plant fiber material as casts. The unburnt showed an even distribution of the particles with decayed organic material and hair rendering voids and cracks in the matrix of the soil. The burnt soil showed larger voids than the unburnt and cracks in the matrix. Plasters showed coarse base layers with topcoats of finer clay and clay wash. The soils are composed of small aggregates. There are coats of fine riverbed silt over the particle aggregates, which are visible under the microscope providing a cementitious matrix to the soil particles, indicating the strength of the material. There are cracks in several dimensions and orientations and generally the surfaces are compact and dense.

7.1.2. Cross and Thin Sectional Analysis

Optical microscopy was used to identify the microstructure of the earthen masonry by the use of thin sections. The cross section analysis was useful supplemental information to the thin sections for closely examining the structure and physical composition of the samples. Various puddled earth and plaster samples were embedded in Bioplastic polyester resin and prepared on slides for microscopic analysis. The Thin sections are 30 microns thick and act as a tool for identifying aggregates, additives, and other phases of the material. It can also be used to identify the mineralogical composition of the aggregate with the use of polarized light. The sections of the two plaster samples illustrated the composition and stratigraphy of the samples. The sections of masonry were used to study pores, voids, micro-cracks, and apparent porosity. The sectional study is illustrated in the Appendix B.2 and B.3. The analysis shows that the soils are dense matrices of yellow sand with nodules of clay in them. The puddled earth from the walls has pseudomorphic voids, while the wall plaster show a dense yellow birefringent fabric sandwiched between a darker organic-rich fabric. The floor appears to be laid in a single layer. There is decayed plant matter used in the preparation of the floor.

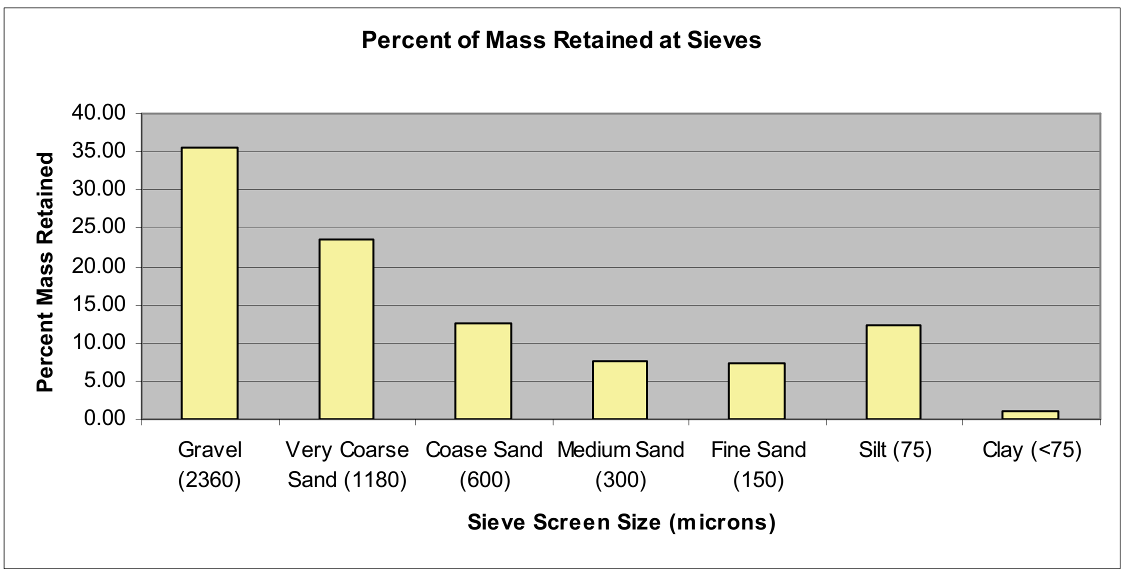
7.1.3. Gravimetric Analysis

Grain Size Distribution

The results from the particle size analysis inform about the behavioral characteristics of the sample. The distribution of the particle size tells about the texture of the soil, whether it is predominantly sandy, clayey or loamy soil. The results reflect on the durability and response to moisture of the samples examined. The percentages show that the puddled earth samples have a higher percentage of fine and very fine sand in the unburnt sample and higher percentages of coarse and very coarse sand in the unburnt soil. The silt and clay together form almost 3 percent of the soil sample and keeps the soil together by creating a cementitious matrix in which the sand particles are embedded. The results show that in the case of Chiripa the clay is only 3.18% of the gross sample, which is very less than the desired quantity. Clay is the only active component of the soil, and the strength is imparted by presence of clay. Strength is required to avoid cracks and resist major earthquakes.

Particle Size Analysis: Sample No. 8547, Chiripa							
Table4: Results of Dry Sieve							
Sieve Number	Screen Size (microns)	M_c (g)	M_2 (Sample+Container) (g)	M_r (M_2 - M_c) (g)	% M_r (M_r / M_s) * 100	% M_{rt} ?% $M_{r\ (on\ or\ above)}$	% M_{pt} 100%-M_{rt} %
8.00	2360	4.55	39.23	34.68	35.43	35.43	64.57
16.00	1180	4.50	27.53	23.03	23.53	58.97	41.03
30.00	600	4.57	16.95	12.38	12.65	71.62	28.38
50.00	300	4.61	12.08	7.47	7.63	79.25	20.75
100.00	150	4.57	11.68	7.11	7.26	86.51	13.49
200.00	75	4.51	16.52	12.01	12.27	98.78	1.22
Pan	<75	4.60	5.70	1.10	1.12	99.91	0.09
			M_s= 97.87				

Table 7.1: Particle Size Analysis of Sample No. 8547 (Burnt Puddled Earth)



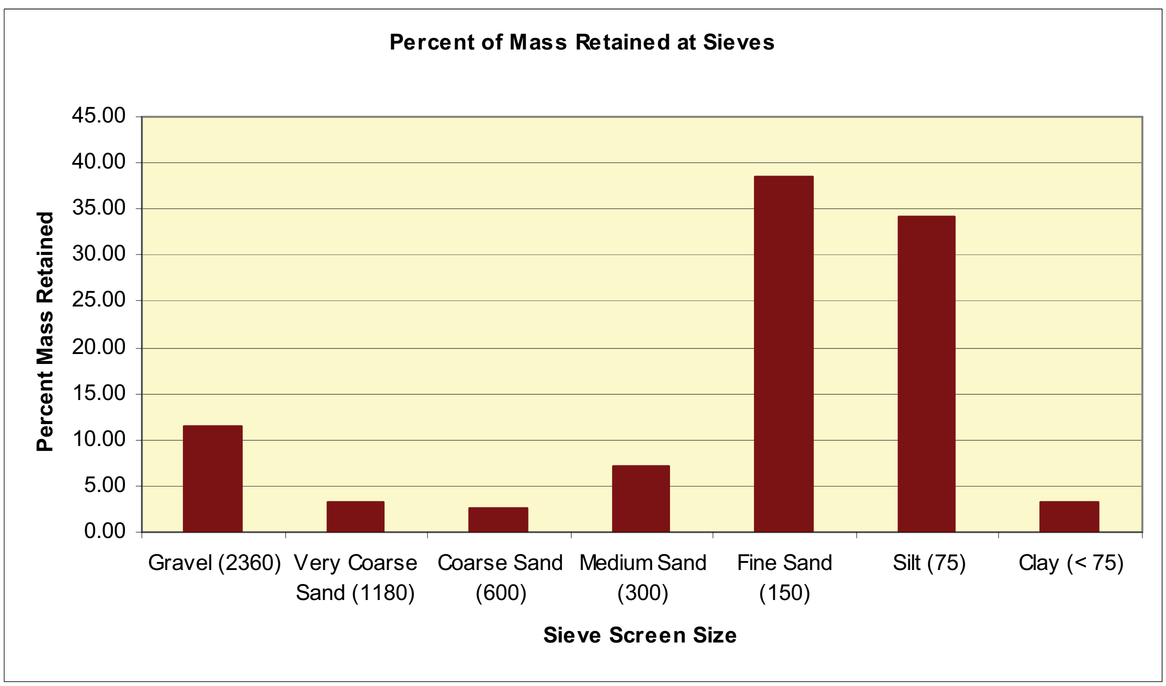
Graph 7.1: Percent Mass Retained at Sieves for Sample 8547

The results of the experiment on the two puddled earth samples are illustrated in Appendix B.4. These show that coarse sand component of the burnt soil sample is23% of the whole. Fine and Very Fine Sand were 7.26% and 12.27% respectively, silt and clay component was 1% of the gross sample. Particle sphericity was between medium to high.

Particle Size Analysis: Sample No. 8573, Chiripa							
Table4: Results of Dry Sieve							
Sieve Number	Screen Size (microns)	M_c (g)	M_2 (Sample+Container) (g)	M_r (M_2 - M_c) (g)	% M_r (M_r / M_s) * 100	% M_{rt} ?% $M_{r\ (on\ or\ above)}$	% M_{pt} 100%-M_{rt} %
8.00	2360	1.85	5.11	3.26	11.53	11.53	88.47
16.00	1180	1.91	2.81	0.90	3.18	14.71	85.29
30.00	600	1.87	2.58	0.71	2.51	17.22	82.78
50.00	300	1.85	3.84	1.99	7.04	24.26	75.74
100.00	150	1.92	12.78	10.86	38.40	62.66	37.34
200.00	75	1.89	11.55	9.66	34.16	96.82	3.18
Pan	<75	1.83	2.73	0.90	3.18	100.00	0.00

M_s= 28.28

Table 7.2: Particle Size Analysis of Sample No. 8573 (Unburnt Puddled Earth)



Graph 7.2: Percent Mass Retained at Sieves for Sample No. 8573

The results from the unburnt sample indicate that the coarse sand component of the soil is 11.53%; Fine and Very Fine Sand component of the soil is 38.40% and 34.16% respectively. The Clay and Silt component is 3.18%.

Based on the above data the Chiripa soils can be categorized as Loamy sand and Sandy loam for burnt and unburnt puddled earths respectively.

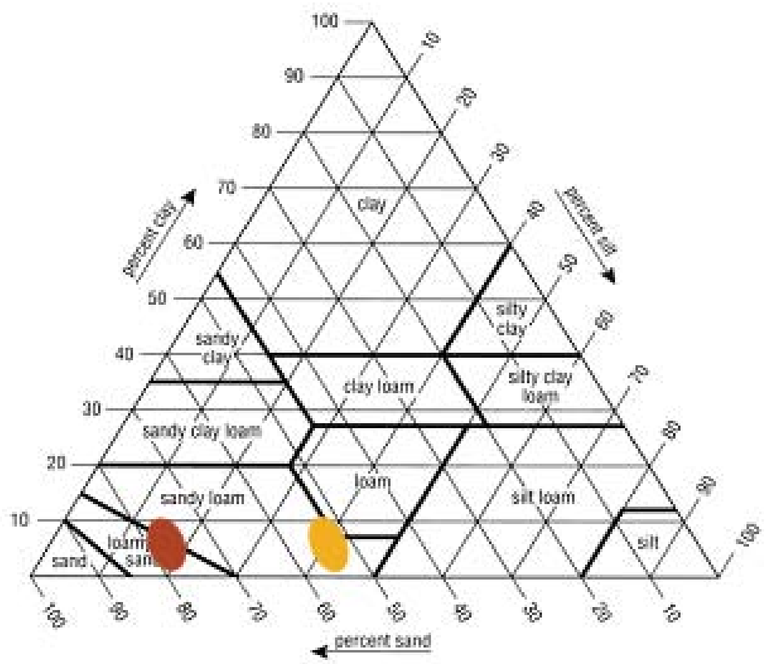


Figure 7.1: Soil Grain Size Distribution on a Triangular grid

Burnt Puddled Soil   Unburnt Puddled Soil

Sedimentation Analysis

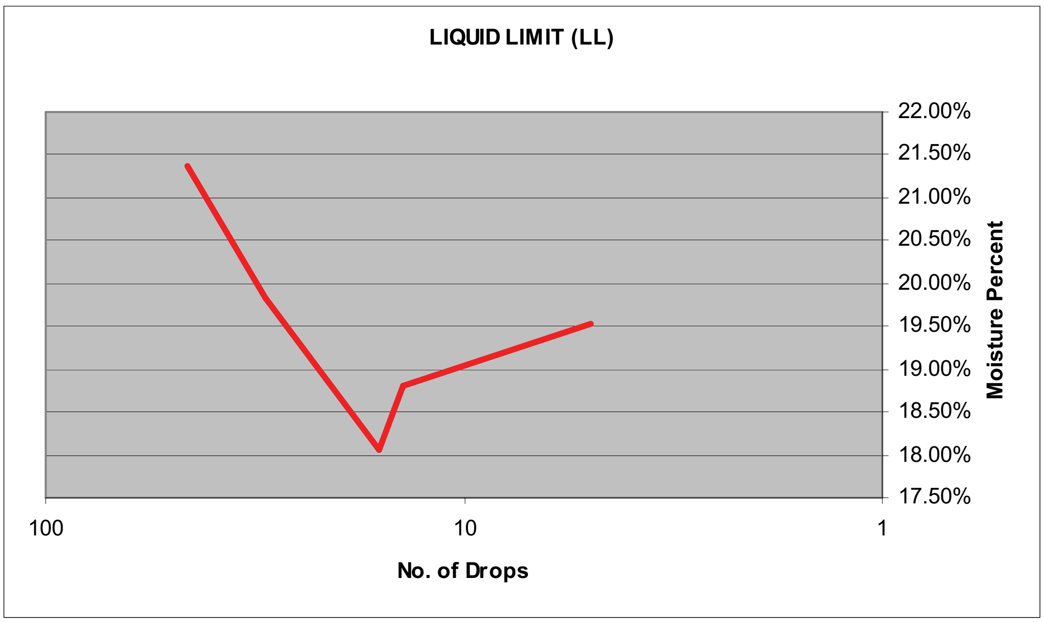
The proportion of the coarse, medium and fine sand are likewise determined by sieving, thus separating them from the clay and silt fractions of the soil. The latter cannot be separated from one another by sieving. Instead they are separated by a process known as sedimentation, which is based upon the fact that larger particles fall more quickly through water than smaller ones. Thus, if a suspension is made up of clay and silt in water, the silt will settle out more quickly than the clay and by measuring the speed at which the suspension as a whole settles out, it is possible to determine the distribution of particle sizes. The sedimentation analysis determines the particle settling velocity by allowing particles to settle in a water-filled column. In sedimentation theory particle-settling velocity is converted to sedimentation diameter by comparing the measured velocity to that of reference sediment of known size and density. Thus, the sedimentation diameter is expressed in terms of hydraulic equivalence, or the equivalent spherical settling velocity of the reference sediment.

The fraction passing 75 microns from sieve analysis of the two puddled earth samples was subjected to a sedimentation analysis and the data is presented in Appendix B.4. Sedimentation analysis employs Stokesian particle settling theory, and is guided by the realization that most sediment is deposited in the process of hydraulic transport. Thus, it is desirable that a characteristic measure related to this depositional process be universally used. The burnt sample showed that the Coarse Silt Fraction is 27 %, Medium and Fine Silt Fraction is 10%, Clay Fraction is 3 % while the unburnt sample showed that the Coarse Silt Fraction is 54 %, Medium and Fine Silt Fraction is 47 %, Clay Fraction is 27 %. The clay percent is higher in the unburnt than the burnt sample. But in terms of the gross sample, the mineralogical clay percent is quite less.

7.1.4. Atterberg Limits

Plastic Limit: 24.28 %; Liquid Limit 19.52 %; Plasticity Index: 4.77 %

Plasticity Index conveys important information about the dimensional response of clay to moisture and vibrations in dynamic environments. The plastic and liquid limits are helpful in characterizing the particles lesser than 425um. This data is presented in the Appendix B.5.



Graph 7.3: Plot illustrating the Liquid Limit of Unburnt Puddled Earth

The plasticity index for the sample is about 5, which is less than 10 and implies that the clay will expand only 4-10 percent when wet[86]. It provides enough cohesive strength but the value does not necessarily reflect the actual plasticity since the

[86] Clifton, R. James, Brown, Paul Wencil and Robbins, Carl R., "Methods for characterizing adobe building materials". Prepared for U.S. Dept. of the Interior, National Park Service, p- 26

mineralogical clay fraction of the soil is less than 3 %. The burnt sample did not exhibit any plasticity and hence this experiment could not be conducted on that. It can be implied that since the burnt puddled earth has a lesser fraction of clay than the unburnt puddled earth and the percent mineralogical clay present has become inert due to the burning event. Atterberg Limits are very useful to find the appropriate consistency and of soils to perform different earth building techniques like puddled earth or adobe, but a good correlation of the limits of the soils with walls strength during seismic vibrations has not been well established yet[87]. So this information is an interesting reference but not a very important tool in this case of relying on this data.

7.1.5. Clay Mineral Identification by X-Ray Diffraction

The data from XRD analysis is located in Appendix B.6. Analysis of the two soils by X-ray diffraction yielded important results: The burnt puddled soil and the unburnt puddled soil produced spectra that were identical, suggesting that these soils contain similar clays and their associated mineralogical parent materials. Both had varying amounts of Albite ($NaAlSi_3O_8$) and Quartz (silica sand - silicon dioxide, SiO_2). Albite is generally consistently associated with the presence of lower clay content. The presence of muscovite indicates presence of phyllosilicates. The usefulness of this study lies in the detection of the clay species, which is found to be Illite. It is a non-reactive and stable

87 As understood from email communication with Prof. Julio Vargas Neumann (2007)

clay. Illite is a phyllosilicate or layered silicate, micaceous mineral. Structurally illite is quite similar to muscovite or sericite with slightly more silicon, magnesium, iron, and water and slightly less tetrahedral aluminium and interlayer potassium. It occurs as an alteration product of muscovite and feldspar in weathering and hydrothermal environments. It is common is sediments, soils, and argillaceous sedimentary rocks as well as in some low grade metamorphic rocks. Rich clay will produce high strength walls and moderately dimensionally stable and non-reactive clay will not swell or contract in contact with the grout. Therefore the key is to find rich clay to get good soils, to build or repair walls with grouts.

7.2 Physical Characteristics

7.2.1. Drying Shrinkage Limit

The shrinkage limit is the water content dividing the semisolid and solid states of a soil. It is quantified for a given soil, as the water content that is just sufficient to fill the voids when the soil is at the minimum volume it will attain on drying. Restated, the smallest water content at which a soil can be completely saturated at this dry volume is called the shrinkage limit. Below the shrinkage limit (SL), any water content change will not result in a volume change of the soil. Above the shrinkage limit, any water content change will result in accompanying volume change. The higher the dry density of a fine-grained soil, the more expansion it can see when exposed to water.

The Shrinkage Limit of the soil is particularly useful in assessing the expansiveness of fine-grained soils with changes in water content. The shrinkage ratio gives an indication of how much volume change may occur as changes in water content above the shrinkage limit occur. A shrinkage limit test is performed on a soil (1) To obtain a quantitative indication of how much change in moisture can occur before any appreciable volume changes occur, and (2) To obtain an indication of change in volume. The shrinkage limit is useful in areas where soils undergo large volume changes when going through wet and dry cycles, which is an important factor to determine when considering the repairs by grouts. It depends on many factors; the percent and the clay species, inherent moisture content of the material. The shrinkage limit of the grout needs to match the original.

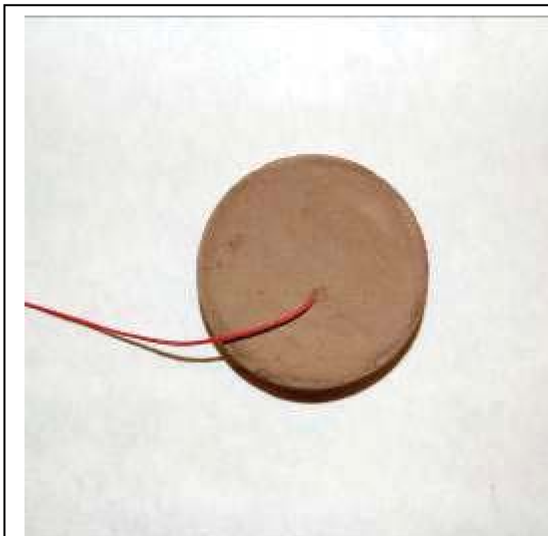


Figure 7.2: View of Soil Pat in Shrinkage Dish Before (Left) and After (Right) drying

The Table of Data is indicated in Appendix B.7. It elaborates the calculations conducted during the experiment. The soil pats were casted in a pre weighed and waxed shrinkage dish. Three samples were obtained from the unburnt puddled earth after it was sieved through a 425µm sieve and 20% deionized water was added according to the Liquid Limit of the soil. The Shrinkage Limit observed is 27.72%; while the Shrinkage Ratio is 1.80 and Volumetric Shrinkage of the soil is computed to be 3.52.

The results suggest that the soil has a fairly low shrinkage and will remain dimensionally stable in contact with water.

7.2.2. Pore Structure

The pore structure of the soils is an indication of the structural integrity of the soils. The use of Petrographic Thin Sections as a method for determining the ratio of the open voids to the mass could not determine the volumetric distribution of the open pores, or porosimetry, which is recommended for future research. The pore space is inversely related to bulk density; for soils with same particle density, the higher the bulk density, the lower the percent pore space[88]. The use of high-resolution digital image interpolation was carried out for the two puddled earth samples.

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[88] Brady, N and Weil, R, "The Nature and Properties of Soils" Eleventh Edition. Macmilan Publishing Co. 1996

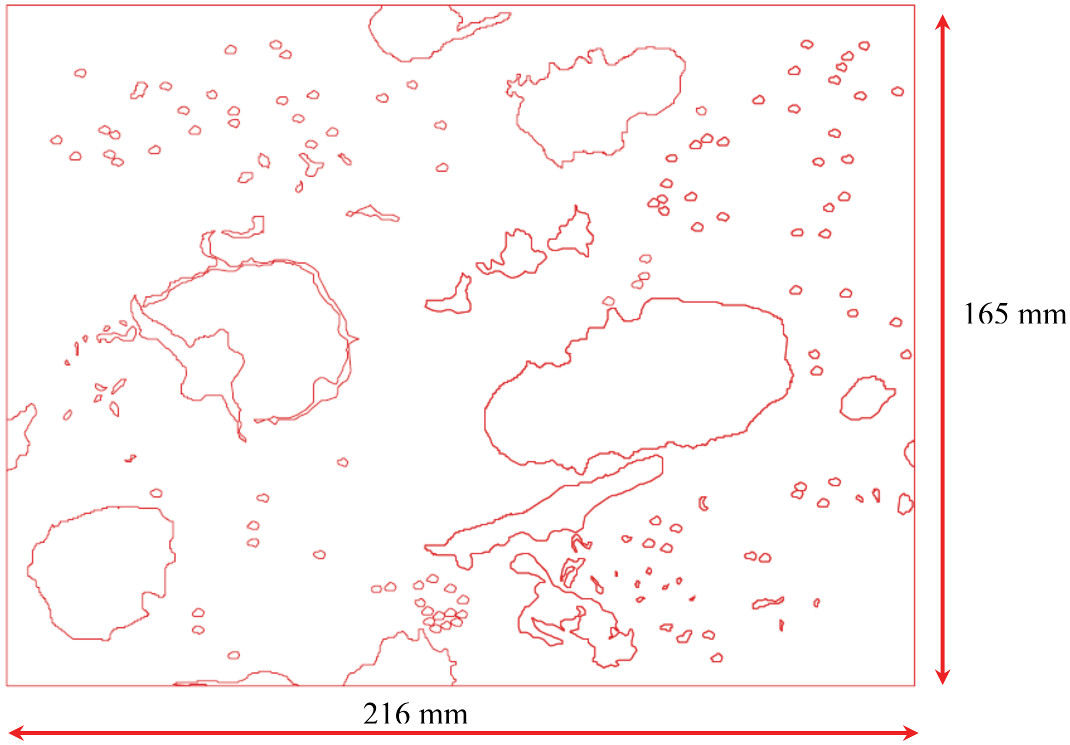


Figure 7.3: Vectorized pore space of Burnt Puddles Earth after Digital Image Analysis

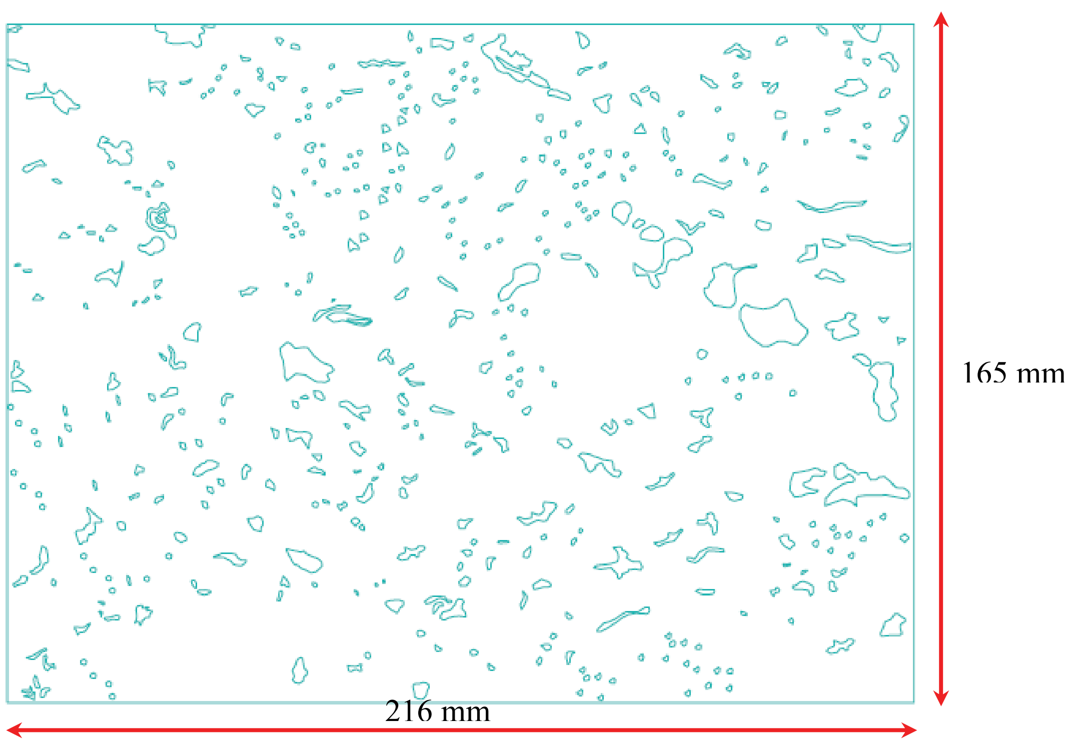


Figure7.4: Vectorized Pore space of the Unburnt Earth

7.2.3. Density of Earth

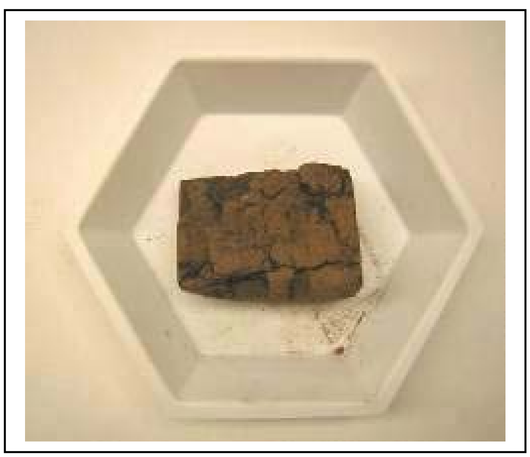
The density of earth is an essential property to determine and together with the water absorption potential and pore structure gives an overall picture of the physical characteristics of the soil. It is useful in estimating the bulk or the weight of the soil and to a certain degree it is also an indication of the internal voids and hence the original strength of the earthen wall. This is because the strength of the material is directly proportional to the density. One of the main reasons of calculating density is that this value can be used to calculate pore structure. To prepare or produce a compatible grout mixture it is essential that the density of the material remains more or less the same or less. This can be understood at the interface of the puddled earth-grout assembly. If the assembly becomes too dense and hence stronger, in case of a seismic vibration it will detach from the substrate. The resultant volume change also plays an important role. The density permits the reversibility of the fill by mechanical means and has a potentially faster rate of deterioration than the original puddled earth. A possible direct correlation between the density of the filler and its resulting composite can also be investigated in future. It is important to know here that all natural soils have specific gravities between 2.6 and 2.8. The particle density can be assumed to be 2.65 for most silicate dominated soils.

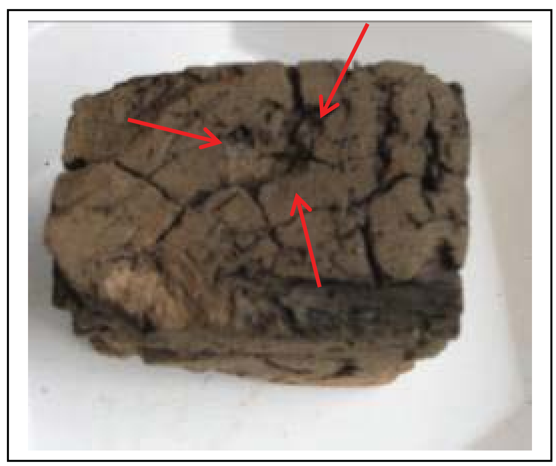
The Bulk Density calculations are illustrated in Appendix B.9. The experiment was conducted on three samples each of the burnt and the unburnt puddled earth and then averaged for each type. The samples were cut using band saw and hex saw from the bulk sample available of each type. The burnt puddled earth has a density of 7.08 g/cm3 and the unburnt puddled earth sample had a much higher density of 14.47 g/cm3.

The higher density of the unburnt sample is an indication of higher mass per volume ratio and hence higher integrity and better strength.

7.2.4. Water drop Absorption

All samples tested in this procedure were exposed over an area of about 1inch to a steady and direct waterfall at the rate of 1 drop per second (from a standard burette) over a distance of 2.5 m (8.20 feet) for a period of one hour. The table indicating all depths of penetration for each sample tested as well as the average depth of penetration for each sample group is included in Appendix B.10.





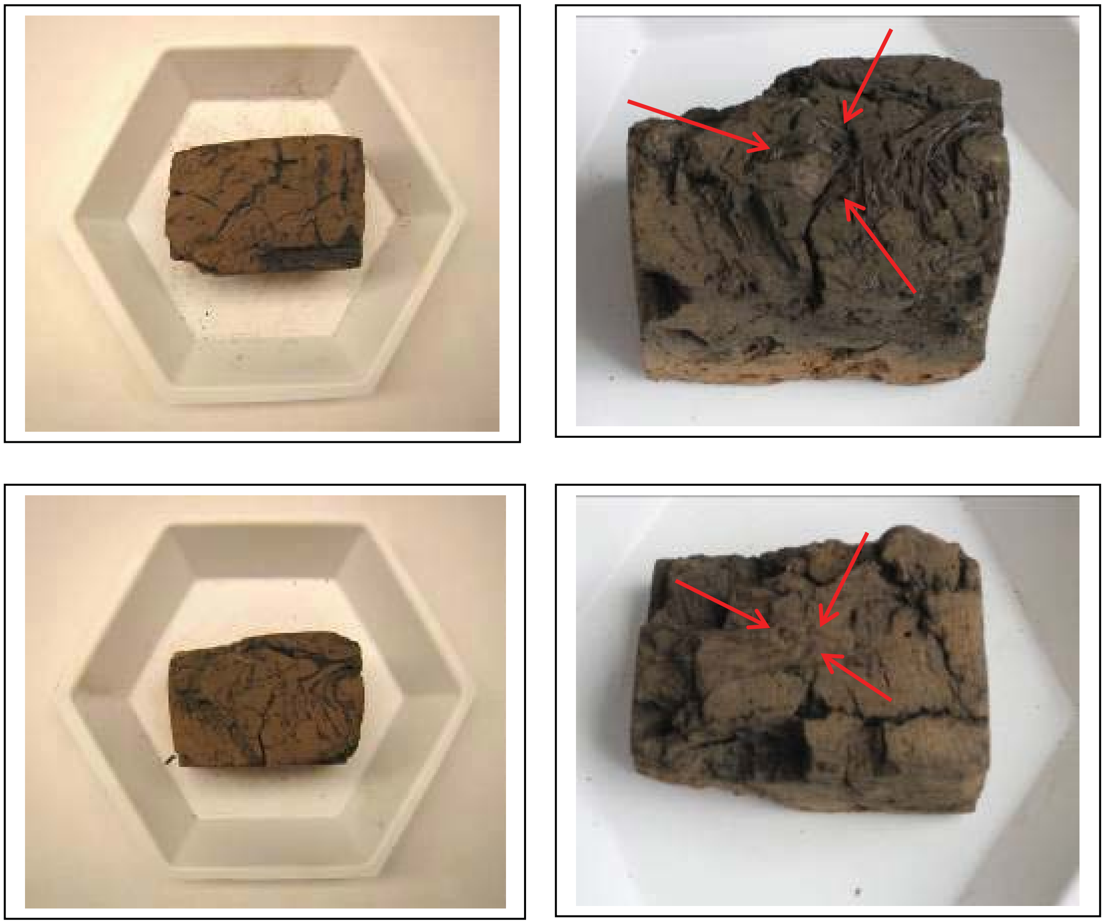


Figure 7.5: View of Samples A, B and C Before (Left) and After (Right) the test.

The soil tested in this procedure exhibited excellent resistance to erosion. The visual or measurable damage to the soil was averaged by the use of three samples. These samples, however, were also the most absorptive and, though the cubes did not lose their basic shape during their exposure to water fall, they were far more malleable following exposure. The water absorption and drying rate of a fill should be close to that of the object, so that a wet fill does not introduce moisture and therefore potential decay in the original puddled earth. A fill should also follow the changing hues of the wet-dry cycle of the object. Although a 48-hour water immersion test is extreme relative to normal ambient external conditions on stone surfaces, such a test will indicate comparative wetting and drying patterns of parent masonry and fills. Considering that such a test will be extremely intrusive to the puddled earth samples, such a test was avoided in this testing program. The data collected illustrates the water absorption potential of the puddled earth samples, was found to be between 1mm-2mm taking into account the average of erosion from three samples. This is an extremely good value for its use towards the walls of Chiripa.

7.2.5. Water Absorption by Capillary

The water absorption by capillary action was carried out to estimate the time of travel of water in the porous structure of the two types of puddled earth. It was also intended that this would provide data for the similarity or difference in behavior of the two types of earth. One sample (0.85” (22 mm) x 0.85” (22 mm) x 1.5” (40 mm)) of each type was obtained for the test and placed upright in a container on a bed of glass beads covered with filter paper on top. The data from the burnt puddled earth sample can be easily compared with the unburnt. It took 6 seconds for the water to reach a height of 30 mm in the burnt sample while the unburnt absorbed water to height of 21 mm in the duration of 6 seconds. A more precise method could have been a longer duration of exposure of the samples to water but in case of puddled earth could have been destructive to the samples. Qualitative results from the test were also helpful in determining the behavior of the samples. The burnt sample although was quicker in absorbing water but stayed unaffected, while the unburnt sample showed a greater time elapse but a quicker disintegration. Hence the sample could not be subjected to water absorption till the asymptomatic reading.

7.2.6. Flexural Strength

The modulus of rupture is an expression of the maximum load-carrying capacity of the soil samples in bending. It is directly proportional to the maximum load (moment) borne by each sample and is a representation of the tensile strength of the soils. During testing, all samples were seated atop two blunt-edged bearing blocks (mounted on the Instron 4206 testing machine) with a Gauge Length of 0.85 inches at the top and 2.0 inches at the bottom. Force was applied to each sample from above via a blunted knife blade until the sample broke. The samples were stored in a dry environment prior to testing.

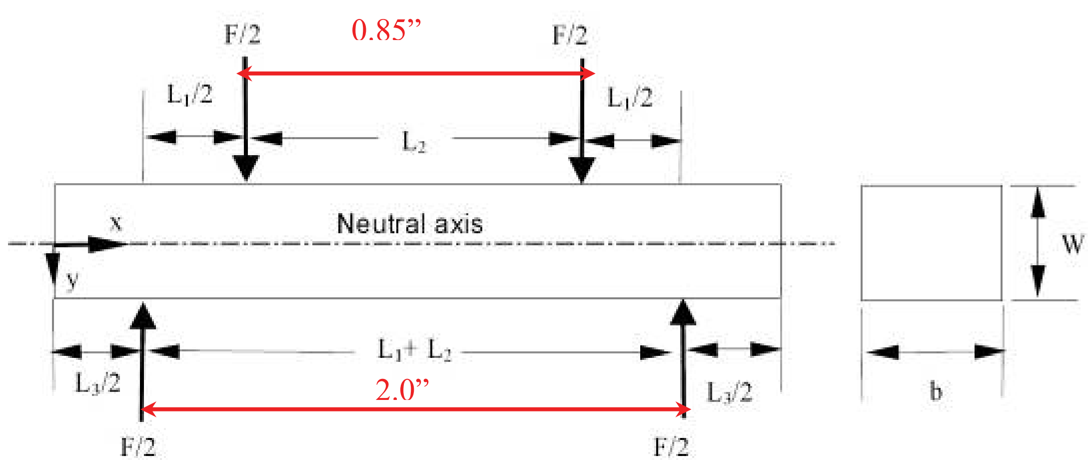


Figure 7.6: Four-Point Bending test Figure

When bending a material, one surface of the material stretches in tension while the opposite compresses. It follows that there is a line or region of zero stress between the two surfaces, called the neutral axis.

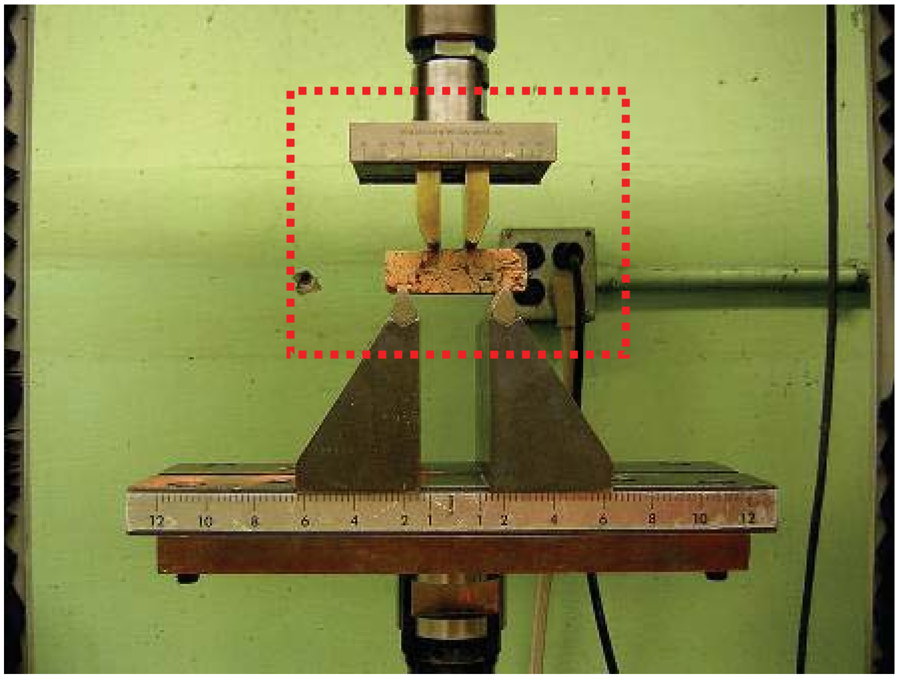


Figure 7.7: Development of diagonal cracks in the Unburnt Puddled Earth prism

The tensile strength is calculated from the ultimate load assuming a linear stress distribution over the section of the sample. The maximum stress a material withstands when subjected to an applied load is called as Ultimate Tensile Strength. Dividing the load at failure by the original cross sectional area determines the value. When in bending a prism of puddled earth, one surface of the material stretches in tension while the opposite surface compresses. It follows that there is a line of zero stress between the two surfaces, called the neutral axis. Using the classic beam formulas and section properties, the following properties can be derived:

The stress strain curves for each of the samples tested is located in Appendix B.12. The load calculations from the samples give the maximum load and the ultimate tensile strength of the particular type of the material.

Bending Stress:

$$\sigma_b = \frac{3PL}{2wt^2}$$

P= Normal Force (35 pounds for Unburnt and 25 pounds for burnt puddled earth sample)

L= Length of prism (3 inches)

w= width of prism (0.85 inches)

t= Thickness of prism (0.85 inches)

The Bending Stress as calculated for the unburnt puddled earth sample is 1.76 MPa (MegaPascals[89]) (256.10 psi) and, the Bending Stress for the burnt puddled earth sample is calculated to be 1.26 MPa (182.75 psi).

Bending Modulus:

$$E_b = \frac{PL^3}{4wt^3y}$$

F= Normal Force (35 pounds for Unburnt and 25 pounds for burnt puddled earth sample)

L= Length of prism (3 inches)

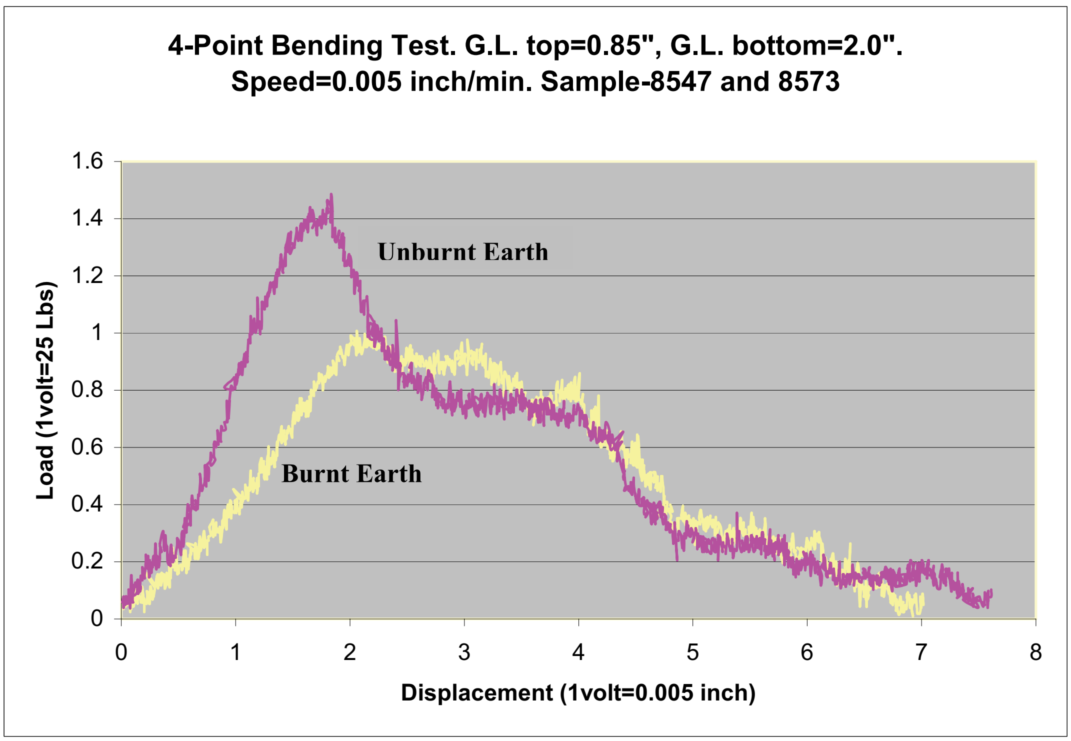
w= width of prism (0.85 inches)

[89] The use of MegaPascals from Pounds per square inch employs a conversion factor of $0.6894\text{x } 10^{-2}$

t= Thickness of prism (0.85 inches)

y= Deflection at Load Point (0.0385 inches for Unburnt and 0.035 inches for burnt puddled earth sample)

The Bending Modulus as calculated for the unburnt puddled earth sample is 77.56 MPa, and, for the burnt puddled earth sample is calculated to be 63.75 MPa.



Graph 7.4: Comparative Analysis of Stress-Strain Behavior of Burnt and Unburnt Sample

The graph from the test conveys information on the heterogeneity of the material. The Strain in the material develops as a result of the applied stress and it stays constant till the material is able to accommodate a maximum stress applied and then there is a drop in the stress although the strain keeps developing. This is because of the occurrence of the first crack in the masonry prism. The strain keeps developing and the prism accommodates two more cracks before it breaks. Crack initiation follows the pore size and distribution in the sample but generally develops in the tension zone of the material. Cracks propagate to the top of the prism between the applied load points.

7.3. Durability

7.3.1. Ultimate Bending Strength

This test was carried out to estimate the adhesion of the grout and the change in the flexure and hence the flexural strength of the assembly.

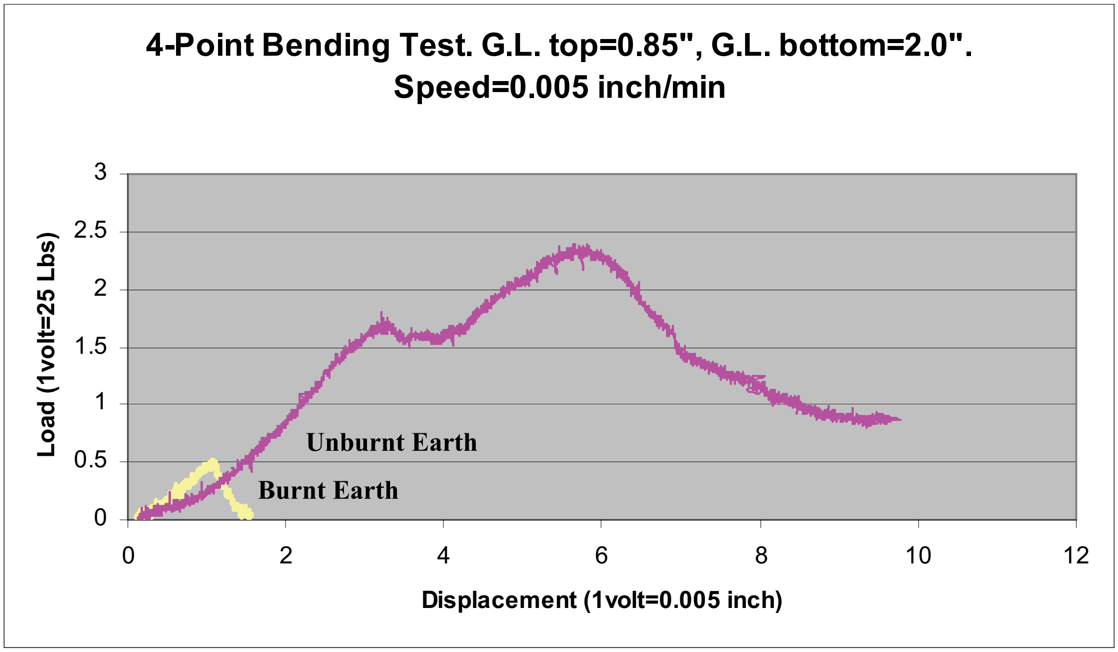
This test is used for the evaluation of composite or heterogeneous materials as that the moment between the two points where load is applied is constant and that therefore understanding of the heterogeneity of the material is gained. A four point bending machine avoids stress concentration at one point. The high anisotropy of the material can also produce high stress concentration. The four-point test is favored over a three point bending test due to a larger portion of the test specimen that is subjected to maximum stresses, therefore allowing more accurate statistical data.

A four point bending fixture was used with each loading point positioned uniformly along the test specimen. The distance between each loading points was 1/3 of the outer support load span. An XY plane recorder was used to simultaneously plot the respective load and extension during the testing process. The test rate was determined to be approximately 0.005 mm/sec. This was chosen so that the rate of the grouted sample is the same as the ungrouted sample for comparison.

The burnt sample registered a load of 12 pounds, which is almost half than that of the ungrouted sample. This can be attributed to the unsuccessful bond. Although the grout was weak and showed cohesion but it was unable to generate any adhesion with the parent masonry. The assembly broke in the grouted area.

The unburnt grouted sample showed a considerable increase in the maximum load uptake. The maximum load on the grouted assembly was 60 pounds, which was almost double than the ungrouted sample. The Strain in the material develops as a result of the applied stress and it stays constant till the material is able to accommodate a maximum stress applied and then there is a drop in the stress although the strain keeps developing. Crack initiation happens at a load of 43.75 pounds but the specimen keeps developing a strain and yields at the Ultimate Load of 60 Pounds. The continuous strain in the material results in the maximum deformation of 5 inches in the assembly. This showed that the sample had developed a capability to resist a sudden rupture and collapse. This behavior can be attributed to the development of a post elastic stage in the grouted assembly.

The results and the graphs from this experiment are illustrated in the Appendix B.13. The load calculations from the samples give the maximum load and the ultimate tensile strength of the particular type of the material.



Graph 7.5: Comparative Analysis of the Burnt and Unburnt grouted assemblies

Bending Stress:

$$\sigma_b = \frac{3PL}{2wt^2}$$

P= Normal Force (60 pounds for Unburnt and 12 pounds for burnt puddled earth sample)

L= Length of prism (3 inches)

w= width of prism (0.85 inches)

t= Thickness of prism (0.85 inches)

The Bending Stress as calculated for the unburnt puddled earth sample is 3.02 MPa (MegaPascals[90]) (439.02 psi).

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[90] The use of MegaPascals from Pounds per square inch employs a conversion factor of $0.6894x\ 10^{-2}$

The Bending Stress for the burnt puddled earth sample is calculated to be 0.605 MPa (87.80 psi).

Comparative Values for Burnt and Unburnt Puddled Earth Samples:

Property Tested	**Burnt Puddled Earth**		**Unburnt Puddled Earth**	
	Ungrouted	Grouted	Ungrouted	Grouted
Max. Load	25 pounds	12 pounds	35 pounds	60 pounds
Ultimate Stress	1.26 MPa (182.75 psi)	0.605 MPa (87.80 psi)	1.76 MPa (256.10 psi)	3.02 MPa (439.02 psi)
Max. Displacement	0.035 inches	0.008 inches	0.0385 inches	5 inches

Table 7. 3: Comparative Strength Values for Burnt and Unburnt Puddled Earth Samples

8.0. DEVELOPED GROUTS AND EXPERIMENTAL QUALIFICATION

8.1. Grouting Requirements at Chiripa

In the earthen masonry of Chiripa, the grout destination is actually not the joints between the outer cobbles with each other (as is the case of full masonry) but the strategic locations between the layers:

- The cracks that separate the internal from the two external leaves and
- The discontinuities at the interior of the matrix forming the inner core, including cracks between the various components (cobbles, aggregate, small chert stones) of this layer.
- Pseudomorphic voids of the inner puddled earth matrix.

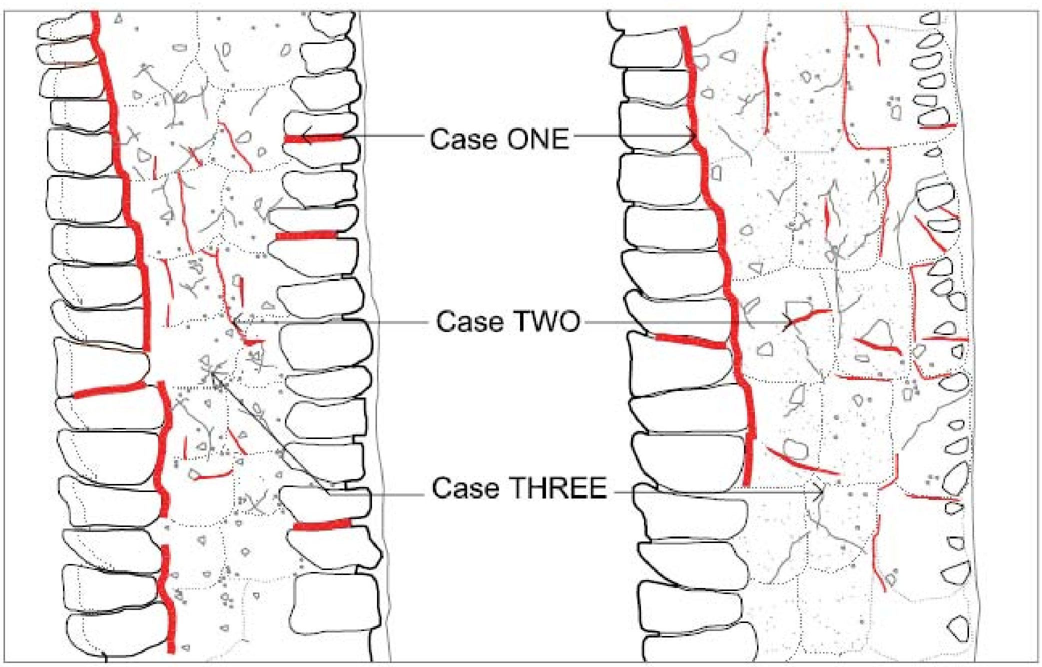

Figure 8.1: Illustration of the walls indicating locations of grouts (Chaudhry' 07)

Concerning the first location, the role of the grout is clear: it has to penetrate those cracks, which could be considered to belong to a surface roughly parallel to both the external and the internal layer. However, a good penetration is not sufficient from a mechanical point of view. The grout must remain in contact with those vertical surfaces and create a continuum as much as possible, in order to enable the lateral stresses to be distributed uniformly (horizontally and vertically) to all the three parts of the wall. It is clear, that in order that the grout functions in this way, good bonding is a requirement of primary importance. The grout addresses the adhesion of the grout between the inner earth core and the outer cobbles. This grout therefore requires a high tensile bonding capacity. It should be noted that the tensile strength of the grout should be equal to or lower than the parent masonry in question. On the other hand, the size of the cross-section occupied by the grout itself is not expected to be significant; therefore the grout is not expected to play any role in terms of "compressive" capacity. These observations point out the importance of the various interfaces inside masonry and the bond issues[91].

Considering the second case, the needs of the grout design are a bit more complex; the grout needs to penetrate the cracks and other discontinuities ranging from 0.05 mm to 5.0 mm, parallel or perpendicular to the external layers. The continuity is required on the vertical and the horizontal axes. The bond requirements are mainly between the puddled earth particles with each other and the grout introduced. The grout

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[91] E. Toumbakari. "Lime-Pozzolan-Cement grouts and their Structural effects on composite masonry walls." PhD Dissertation, Katholieke Universiteit, Leuven, 2001

therefore, requires a strong cohesive property to over bridge the discontinuities successfully.

Considering the third case, the grout needs to bulk the voids inside the matrix. These voids are amorphous and range from 1.0 mm to 50 mm in their dimensions. The grout needs to be stable to fill the voids locally and flow to the next void and fill the subsequent one. This case requires the grout with strong bulking properties and stability. It should be realized here that although voids are variable in their dimension and location but a typical void area is as low as 1.81 mm^2 in the unburnt earth while it is 6.75 mm^2 in the burnt earth.

Considering the above discussion on the masonry composition and condition of the walls at Chiripa, a reflection on the grout design will reveal the requirement of:

- Strong grout to bond the fragmented outer core to the inner layers
- Weak grout to regenerate the bond by filling the cracks and the voids in the inner clayey matrix and to avoid the bonding of the in-between areas.

Compatibility and stability are two major issues in the design of grouts for the above-discussed situations, because it is the condition for achieving the same properties (porosity, strength etc) at every location inside the material the fresh to the hardened state of the grout is of par amount importance.

Research indicated that the intrinsic mechanical properties of the grout do not necessarily influence the final strength of a deteriorated masonry wall. Instead comparable rheological properties are likely to provide more homogenized behavior. The required strength improvement is easy to derive from the structural analysis. Fact is that filling the cracks and the voids will cause the masonry to behave monolithically.

Durability, however, requires the development of microstructure as close to the original materials. Besides the experimental qualification, the current research looks into the projected performance of the previously tested grouts for the earthen masonry at Chiripa by a comparative analysis of the properties.

Three most influential parameters of the Chiripa masonry, as identified by the study are compared with the previously well developed grouts to project compatibility and feasibility of use:

Porosity- 27.83 % for the Unburnt Puddled and Earth37.5 % for the Burnt

Density- 14.47 g/cm^3 for Unburnt Earth and 7.08 g/cm^3 for Burnt Earth

Tensile Strength- 1.76 MPa for Unburnt and 1.26 MPa for Burnt Puddled Earth

8.2. Developed Grouts

The evaluation of the grouts is based on the parameters of the physio-chemical and mechanical compatibility as per the requirements.

Rheological requirements include (a) injectability (penetrability into fine cracks and voids, according to the design and (b) sufficient fluidity for the grout to be diffused into masonry, and (c) stability.

Physical requirements comprise (a) low hydration heat (as high temperatures may adversely affect the bond with the substrate), (b) limited shrinkage (that may cause microcracking along the grout and *in situ* materials interfaces, before the application of any load) (c) adequate hardening time, (d) hygroscopic properties (such as, limited volume changes due to humidity variations, water insoluble grout, etc.).

Chemical requirements (related to both durability and mechanical properties of the grouted masonry) refer, for example, to (a) resistance to expansion: some hydration products (e.g. ettringite and portlandite), (b) to the chemical stability of the products of chemical reactions, taking place between the grout and the *in situ* materials.

Mechanical requirements are related to the desirable mechanical properties of the grouted masonry (i.e. strength and deformability characteristics), depending on the actual state of masonry, the actions to be imposed, the overall scheme of interventions, etc.
For a grout to be injectable to a cracked or porous material, the maximum grain size of the mix, as well as the distribution of various grain sizes (grading curve) should be compatible with the size of the cracks and voids to be filled.

- Grout Formulation[92]:

1 Microspheres: 1 Sand: 2 Riverton Natural Hydraulic Lime with 10% acrylic emulsion This grout was previously developed at the University of Pennsylvania for large-scale detachments repairs for Casa Grande Ruins Monument. The principle binder is Riverton Natural Hydraulic Lime.

Salient Properties of the formulation:

Flow/ viscosity: low viscosity

Splitting Tensile Strength: 0.84 MPa (122.71 psi)

Compressive Strength: 0.76 MPa (110.40 psi)

Bond Strength in Shear: 14.5 MPa (2103.33 psi)

Water Vapor Transmission (Permeability): 4.25

Lime being compatible to the earthen microstructure will display a similar behavior and hence "compatibility" to the puddled earth substrate. It has been found from the experiments that the clay is mildly stable and hence would not react in the proximity to the lime. It is a viscosifying agent and hence will create a certain friction between the layer of puddled earth and the outer layer of cobbles. It has the ability to deform under shear stress, which is quite advantageous in a seismic area. However, the Penetratability

[92] Cancino, Claudia, "Assessment of Grouting Methods for Cracks and Large Scale-Detachment Repair at Casa Grande Ruins National Monument." *[A Thesis in Historic Preservation]* Philadelphia: University of Pennsylvania (Unpublished)

or good injectability is achieved by the addition of a modifier, acrylic emulsion. The shrinkage control is achieved by bulking the mix with sand of an adequate grain size distribution. It was selected as a major aggregate because of its small size (suitable for injectability), as well as its angular shape, greater surface and good particle distribution that can increase strength. The hollow, inert microspheres composed of a silica-alumina ceramic alloy reduce the weight of the mix, while larger aggregates of sand are contributing to the strength and hardness. The spherical shape of the microspheres improves the rheological properties of the mix. The biggest advantage is the expectation of the compatible strength criteria. It has a high bond strength, which will prevent the separation of the wythes under external vibrations caused by wind loads or earthquakes.

This formulation can be proposed for the detachment i.e., the Case One. High bond strength and high permeability of the grout is required. This is a low viscosity grout

8.3. Experimental Qualification

The experimental qualification looked at developing a grout for the puddled earth matrix and addressing the fine cracks (0.05 mm- 1.00 mm). There is a general lack of any published data on the subject and hence the study looked into developing a grout using ethyl silicate.

Ethyl silicate has an ability to cross link, which has been utilized in consolidation of the siliceous materials hence it has the ability to impart strength by increasing the cohesion of the material by forming a vitreous polymer membrane. With the help of SEM micro pictographs, it has been found that ethyl silicate develops a siliceous matrix over time hence it densifies the material. This would contribute towards the homogenization of the masonry by filling in the cracks and voids as the material ages. In the chemical stabilization of adobe in the Montaro Store, Butterbaugh found that the stabilized mud would not hold to vertical surfaces unless the walls were first consolidated. It was found that while most consolidating chemicals tended to give an outer, hardened layer that water would eventually force to separate, alkoxysilanes such as ethyl silicate and particularly methyltriethoxysilane provided a strengthened adobe that transmitted water vapor and showed neither cracking nor the separation of surface layers[93].

SILBOND® 40 is a concentrated form for obtaining usable silica. It is partially hydrolyzed mixture of monomers, dimmers, trimmers, higher polymers and cyclic polysilicates. Silbond® 40 was successfully used at Fort Selden by the Getty Conservation Institute for consolidation of earthen walls, since the material is highly porous and the pores are very minute and the hence injectability and shrinkage are major issues to be dealt with which are tested for the grout produced. The other advantages by the use of alkoxysilanes are that this is a non- aqueous system and hence would perform good in terms of its diffusion in even the minute cracks, voids and the pores of the earth. The studies in Silbond at Fort Selden were based on the work of Giacomo Chiari[94], who has had more than 20 years of successful results using this material for stabilizing adobe.

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[93] Charles Selwitz; Thomas J. Caperton, "Chemical Stabilization of Adobe in the Restoration of the Montaño Store", In *APT Bulletin*, Vol. 26, No. 2/3. (1995), pp. 37-41.
[94] Ibid.

Silbond® 40, a product of the Silbond Corporation, is 70% poly (ethyl silicate), 27% ethyl silicate and 3ø/O ethanol. This relatively nonvolatile and nontoxic liquid has a viscosity of 3.9 centistokes at 25ºC, which is significantly higher than the 1.0038 centistokes of water and 0.8 centistokes of SSH (ProSoCo's Conservare® OH Stone Strengthener)[95]. It is also a low-density silicate (1.05 gm/cm^3).

It was thought that the use of an ethyl silicate module would aid in densifying the silicate matrix by cross-linking the micro cracks allowing for strength modification. This would also an advantage of the inherent low viscosity of the alkoxysilanes, reducing the need for fluidizing additives to the mix.

The grout formulation selected was 1MS (Microspheres): 1S (Yellow Bar Masonry Sand): 2 NHL (St. Astier's Natural Hydraulic Lime 3.5) (all parts by volume) mixed with Silbond® 40. This is a non-aqueous system for the grout. The ratio of the dry mix to Silbond (2% catalyst Methyl Borate TMB-70) used is 2: 1.5. However, the resultant suspension was very weak to hold the ingredients and resulted in the separation of the components.

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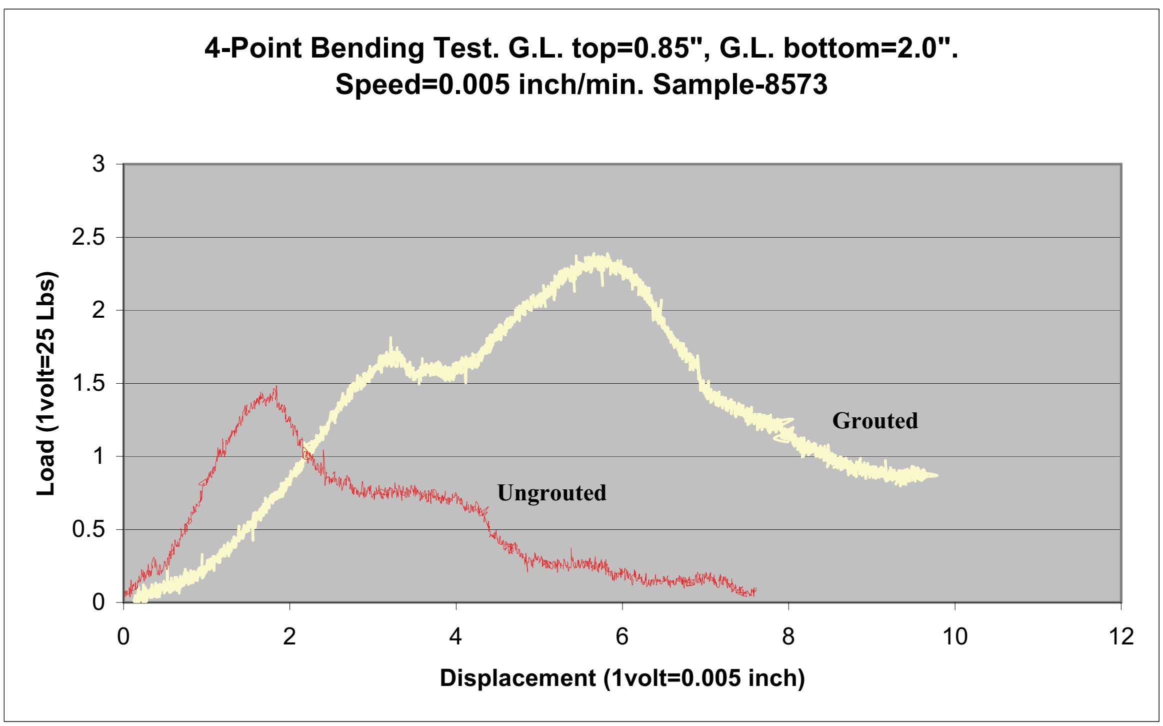
[95] Selwitz Charles, "Continuing Research on the Development of a Composite Treatment for Preserving Historic Adobe". In ICOMOS International Newsletter No. 4, 1994 www.icomos.org/usicomos/Publications/Newsletters/1994_Issues/1994_no_10.htm

9.0. CONCLUSIONS

In the case of a composite masonry like that of Chiripa, the soils are found to be non homogenous, which strongly influences the bearing capacity of the wall. Furthermore, the characteristic strength of a highly non-homogeneous material is quite difficult to determine experimentally. The strength and deformability parameters of the masonry prisms tested in laboratory are not representative of the overall strength and deformability of the whole masonry. It should also be taken into consideration that the global strength of the walls would account for the role of river worn cobbles, which have not been tested in this research.

The worst defect of these masonry walls is that they are not monolithic in the lateral direction, and this can happen, for instance when the wall is made by small pebbles or by two externals layers well ordered but not mutually connected and containing infill material. This makes the wall to become more brittle particularly when external forces act in the horizontal direction.

The results from laboratory tests show that the earth comprising the walls of Chiripa is high in content of sand and silt (particle sizes less than 135 microns). It is rather deficient in the percent of mineralogical clay for an acceptable behavior under a seismic activity. The clay present is also very mildly reactive and quite stable to any dimensional changes. The physical characteristics of the puddled earth showed the soils have a low shrinkage limit, low density and high porosity. Water resistivity potential for the floors was found to be minimal while the results could not be established for the puddled earth comprising the walls due to lack of adequate sample. It could be well assumed that the minute pores of the unburnt earth would demonstrate very high water absorption potential. The mechanical strength of the earth was found to be 1.76 MPa for the unburnt puddled earth and 1.26 MPa for the burnt puddled earth. This value suggests a considerably low existing strength of the walls and a need to reduce this variance. Keeping in mind, the high water absorption potential and the high variance of the strength of the walls, it was imperative to design a treatment with grouts and in specific, non-aqueous grouts to compensate the highly porous material and decrease the variance of the density, porosity and hence strength across the length and the width of the earthen walls.



Graph 9.1: Comparative Strength Analysis of Unburnt Puddled Earth and the grouted assembly

The aim of grouting is to address the injection of binding materials into the masonry with the aim of defining “compatibility” and to improve the adhesion between the various components of the masonry of Chiripa.

The physico-chemical compatibility was attempted by the use of an alkoxysilane grout in accordance with the high silt content of the material. The post grout bending strength of the prisms of the earthen masonry showed enhancement of the mechanical strength for the unburnt puddled earth sample. The Ultimate Bending Stress for the sample increased from 1.76 MPa to 3.02 MPa. The total displacement of the sample increased from 0.0385 inches to 5 inches. The continuous development of the strain even after the yield point showed that the grouted sample was able to develop a post elastic characteristic as opposed to showing a brittle behavior. The cracks and the consequent rupture occurred in the grout, which is a desirable quality. It shows that the grout yielded to save the parent masonry.

However, such results could not be established for the burnt puddled earth sample. It was found that the grout could not successfully over bridge the cracks or display any adhesion to the masonry. The Ultimate Bending Stress for the grouted sample was 0.605 MPa as compared to 1.26 MPa for the ungrouted sample. It suggests that although the grout yielded in case of applied load; it failed to strengthen the parent masonry.

This research acknowledges the experimental ground and the preliminary stage of the grout development and the need to further improve the formulation based on the observations made during this trial. There was a noticeable separation of the components of the grout after the high speed mixing was accomplished. The grout was only able to cure for fourteen days due to limited time at hand. Hence, further research is recommended for the development of the grout.

However, the main limitations of the current research originate from the inaccessibility to the site and availability of a limited amount of samples to work from. Without a site investigation, the specific grout formulation proposed to stabilize the earthen walls at Chiripa cannot be assessed. The existing wall assemblies and their material components have not been documented and hence the correct pathologies of the grouted wall assemblies cannot be fully understood.

Thus the performance of this grout within this structural system cannot be determined or evaluated until a comprehensive laboratory program is devised to improve the formulation and a field survey is conducted.

10.0. RECOMMENDATIONS

The efficacy of this research heavily relies upon a comprehensive documentation and condition assessment of the site. The following recommendations for stabilizing the earthen walls at Chiripa can be presented in defining a methodology for on site work.

10.1. Methodology for On Site Investigation

The on site work must follow the following steps before any treatment with grout. The idea is to lay the parameters of the site as this would govern the grout formulation as well as the grouting technique.

10.1.1. Documentation

- The earthen walls first need to be documented for their correct construction techniques and the vulnerable areas of the walls need to be identified.
- The documentation should also note the layout of the walls at the site. Often the seismic resistance of the architectural components lies in their integrity with the surrounding elements. Hence, the wall assemblies should be identified.

10.1.2. Condition Assessment

The condition of the earthen walls at Chiripa needs to be analyzed in-situ state of the material and assessing the global parameters of strength and deformability. The testing for irregularities in the walls can be done by several techniques depending on the budget, availability and expertise. Electro magnetic resistivity technique has been used at Chiripa before to aid in archaeological digs and the same can be used again for condition assessment of the earthen walls. This technique is non destructive and respects the historic fabric. However, the data obtained should be thoroughly checked with the manual observations made at site. The data collected should include:

- Identification of areas of micro cracking, voids, detachments and loss as different conditions in the walls.
- Identification of the state of elastic stress of the masonry. This can be done by the same technique as above but using density as a parameter for strength. Other tests for instance, Flat Jack tests normally used for this are partially destructive, which cannot be undertaken at Chiripa given the fragile fabric and high historical importance.

10.1.3. In Situ Testing of Grout

The formulated grout should be tested on the earthen walls at Chiripa *in-situ* conditions. The testing should address all the types of conditions identified for grouting as (1) Separation of Masonry leaves, (2) High Porosimetry of the wall due to voids, and (3) Cracks of dimensions varying from 0.05 mm to 5.0 mm.

- The in situ injectability test of the grout must precede the grouting operation. This can be done by creating representative assemblies of the walls in Plexiglass cylinders of appropriate dimensions. The wall models, matching their porosities can be created inside the containers and then grouting can be conducted from the bottom.

- Property of adhesion is very important to be tested in situ, as the samples tested in the laboratory might not be the correct representations for the true inherent moisture content of the material, which is very crucial for designing any treatment for earthen materials. This can be done on the most representative earthen material from the site. This test would be damaging to the original fabric.
- Shrinkage of the grout can be visually assessed by casting the liquid grout into a container of known dimensions and visually assessing for change in the volume in more plastic state.

10.2. Compatible grouts for earthen masonries

This research was not able to delve deeper into the formulation of more grouts for the different needs of the site due to lack of published data on this subject and sufficient time. Future testing needs to be done, in general to develop more high performance grouts for structural strengthening of earthen structures. The major issues identified are penetratability, compatibility and sufficient mechanical strength development of the grout.

These grouts can be:

- Natural Hydraulic Lime grouts: Lime repairs for earthen structures have been a subject of research much preferred in the field of conservation. This is because of a compatible microstructure of the lime with the clays in earthen materials (plate like structures). However, poor penetratability, sedimentation, shrinkage and leaching of the lime have been a concern. Research should be done on superplasticizers for high penetratability and ways of mitigating shrinkage of the grout.
- Non-aqueous grouts: There is a need to develop more grouts, which are non-aqueous; this would eliminate (to a certain extent) the shrinkage in the grout or sedimentation of the binder in the porous material of the earthen walls. This would compensate for the high water absorption potential of most earthen masonries.
- Cement modified grouts: These grouts can be looked into on availability of low-sulphate 'conservation" cement. Many instances in the treatment of the earthen structures require the development of sufficient initial and continuing strength. Such instances might benefit from the use of cement with low-or-no sulphate content[96].

[96] It has been proved from the PhD Dissertation of Toumbakari, E-E at Katholieke Universiteit, Leuven (2001) that a cement phase is necessary for initial strength development of the grout.

10.3. Alternative Methods of Repair

The seismic mitigation of the Chiripan walls must look into strengthening the courses of the walls. The walls have weak mortar and weak bond with the outer wythes, which are made of river worn cobbles.

Stabilizing earthen structures in seismic areas requires a thorough knowledge of the construction materials, their techniques and good craftsmanship. Although, grouts offer minimum impact to the parent masonry, physico-chemical and mechanical compatibility and provide integrity to the disintegrated masonry, their success lies in a skilled operation. A grout may not fill all the all the voids sufficiently when a permeable zone lies parallel to a less permeable zone, simply because the grout will follow the path of least resistance.[97] This will interrupt the process of homogenization.

An alternative method also needs to be explored in case the detachment between the wythes is quite large for the grouts to compensate. Much has been written about the composite repairs for stone and brick masonries than for earthen masonries. However, recently there have been experimental researches in this field are explained below:

- Grouted Anchors:

Nels Roselund demonstrated mechanical pinning using fiberglass rods with modified earthen grout in California in 1984 at Pio Pico Mansion, which failed in successive earthquake in 1987. It was found that this was due to the insufficient bond between the

[97] This finding came out of a PhD Dissertation of Ignoul, S at Katholieke Universiteit, Leuven (2003)

grout and the fiberglass reinforcement. The GSAP (Getty Seismic Adobe Project) looked into grouted anchors for the experimental research in the 1990s to stabilize earthen buildings in seismic areas after the Northridge Earthquake in California in 1987 by using scaled models of the earthen construction. Their further research was done for the Conservation and Seismic Strengthening of Byzantine Churches in Macedonia. Both these researches looked into the use of anchors set in epoxy-grouts.

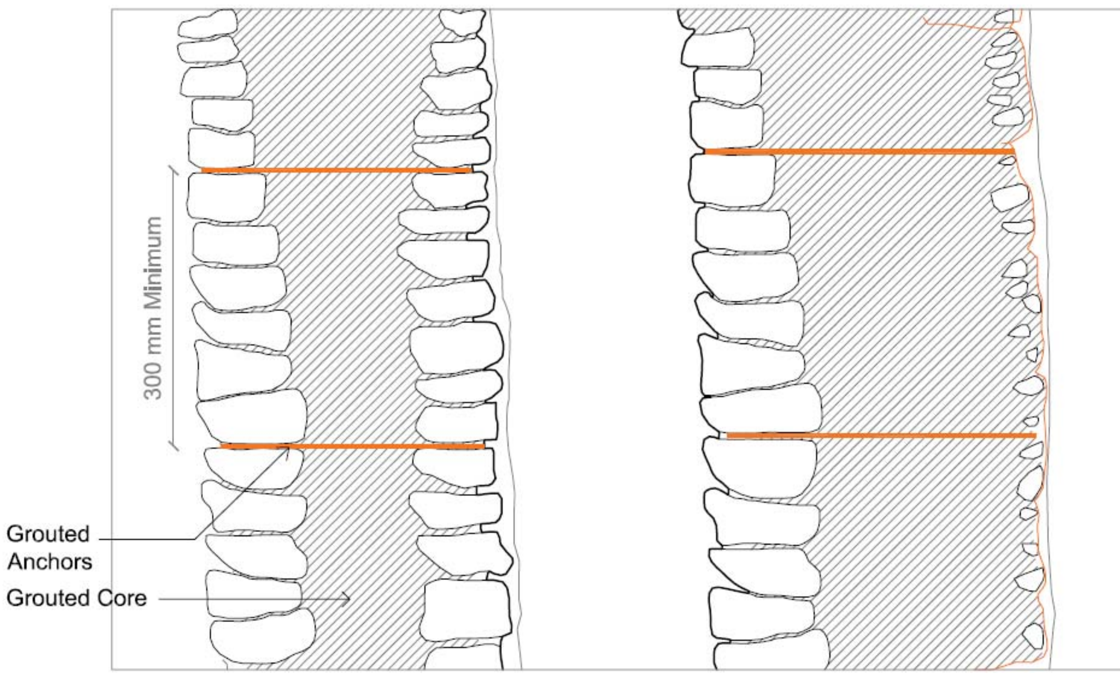


Figure 10.1: Illustration of grouted anchors (Chaudhry' 07)

The role of epoxy or modified mud grout is however speculated for the current research. An ethyl silicate module system was developed for the conservation of Nidaros

Cathedral in Norway[98]. Ethyl silicate is more preferred in this research than epoxy due to the chemical compatibility shown by a silicate with the silica-rich soils of Chiripa. Use of fiberglass or carbon rods can be used for addressing large-scale detachments set in the grout using ethyl silicate module system. Carbon rods have been tested before in the laboratory and are sold for their high flexural strength. This will strengthen the structural system of the walls.

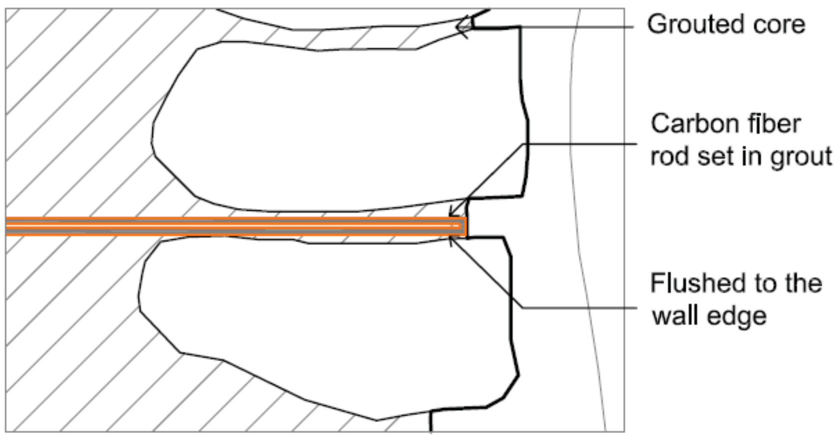


Figure 10.2: Illustration of the Detail of Grouted Anchor (Chaudhry' 07)

- Clay-lime-pozzolan bars:

A new concept towards the treatment of earthen structures or masonries set in earthen mortar has emerged recently and published at the conference of Structural Analysis of Historical Constructions (SAHC) held in New Delhi, India.

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[98] Per Storemyr, Eberhard Wendler & Konrad Zehnde, "Weathering and Conservation of Soapstone and Greenschist Used at Nidaros Cathedral (Norway) Preliminary summary of results - a work document", In *Lunde, Ø. & Gunnarsjaa, A. (eds.) (2001): Report Raphael II Nidaros Cathedral Restoration Trondheim Norway 2000. EC Raphael Programme – European Heritage Laboratory.* Report no. 2/2001, The Restoration Workshop of Nidaros Cathedral, Trondheim, Norway, August 2002

This solution is proposed by Papayianni (2006) for repair or strengthening of adobe structures. Holes are drilled and a (clay-cement or a clay-lime-pozzolan) grout is introduced with the aim not to fill voids but to form "reinforcement bars" like stronger zones within masonry. The up to now available results seem to be promising[99].

This route can be taken for the composite walls of Chiripa in case there are noticeable and unacceptable shrinkage or incompatibility problems of the grout with the earthen masonry.

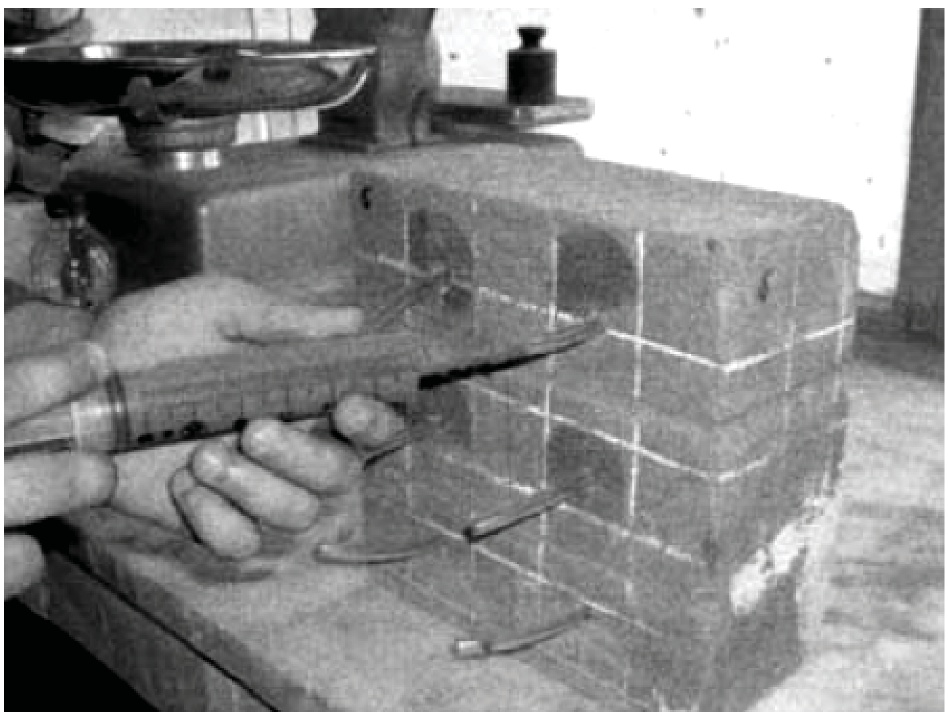


Figure 10.3: View of Clay-Lime-Pozzolan bars to create stronger zones in Masonry. (Vintzileou. E, 2006)

[99] Elizabeth Vintzileou, "Grouting of Three-Leaf Stone Masonry: Types of Grouts, Mechanical Properties of Masonry before and after Grouting". (Editors: PB Lourenco, P. Roca, C. Modena, S. Agrawal). In *Structural Analysis of Historical Constructions*, New Delhi, India Sept 6-8 2006

The authors tested the injectability of this grout using the standard test of the sand column, as well as using cylinders with material taken from the structure to be strengthened. The laboratory tests were successful; the site application was successful, as well. However, for the time being, there are no experimental results measuring the improved mechanical properties of the grouted masonry[100].

10.4. Future Areas of Research for Earthen Constructions

This research delves into grouting as a viable technique for structural strengthening of earthen masonry. However, there were many areas, which remained unanswered:

Earth and Earthquakes:

- Predicting damage to earthen constructions in earthquake regions, i.e., correlating the seismic magnitude to the relative strength of the walls.
- Relationship of plasticity of the material to the seismic performance.
- Water content of the material and the load bearing capacity of earth structures

Grouts for Earthen Structures:

- This study could only cursorily develop a grout for the strengthening of earthen masonry at Chiripa. The grout needs a lot of development in terms of suitable raw materials and testing in terms of physical and mechanical behavior and strength respectively.

[100] Ibid.

- There seems to be relationships that exist between all levels of the structure: what is observed on the micro scale has a direct relationship to what is observed at a macro scale of the grout. The limited time of this research was not able to look into these areas in detail to bridge the gaps in knowledge.
- Earthquake damage itself should be further researched. Shaking tables should be employed for full-scale grouted assemblies of the grouted earthen walls. This would require a systematic survey and intensive use of field instrumentation especially in the case of Chiripa. It has been acknowledged that a great deal of testing data are available, but that there is a lack of analysis and synthesis, and that efforts should be developed to relate lab results to field observations
- Development of compatible grouts for strengthening of earthen structures and their performance in seismic areas.
- Investigation of the chemistry and mechanics of pore structure and water absorption of the grouts is crucial for earthen structures. It should be determined if the pores distribute water and other elements into the adjacent materials and if the pores influence resistance to external weather related deterioration.

APPENDIX A

LITERATURE REVIEW MATRIX

STRUCTURAL REPAIR												
SN	YR	PROJECT/ TITLE	AUTHOR	INTENT	GROUTS USED	PROPERTIES MASONRY	PROPERTIES GROUTS	PURPOSE	COND. ASSESSMENT	TESTS	COUNTRY	REMARKS
1	2006	Grouting of Three-Leaf Stone Masonry: Types of Grouts, Mechanical Properties of Masonry before and after Grouting	Elizabeth Vintzileou	Experimental and In Situ applications and performance of Hydraulic Lime grouts	Hydraulic Grouts	Mechanical Strength, Modulus of Elasticity	Injectability, Viscosity and Stability	Separation of the multiple wythes	N/A	Compressive Strength, Flexural Strength, Modulus of Elasticity, Vertical Strain, Shear Stress	Greece	Experimental/
2	2006	Mechanical Properties of Three Leaf Stone Masonry Before & After Grouting	Miltiadou, A et. al.	Develop a grout for the tensile strength enhancement of the masonry injectable to fill fine voids	Ternary Grout; Hydraulic Lime grout	Mechanical Strength, Modulus of Elasticity	Rheological Properties	Separation of the multiple wythes	Y	Injectability, Compressive and Flexural Strength	Greece	Insitu Operation
3	2005	Design and Appication of Hydraulic grouts of high injectability for the structural restoration of column drums of the Parthenon Opisthodomos	Miltiadou, A et. al.	Describes the restoration of the column drums of the Parthenon Opisthodomos, using hydraulic grouting injections of fine cracks on the column drums, compromising their stability. The authors describe the methodology behind testing cements and grouting	Hydraulic grouting was composed of white cement and pozzolana,	Physical and Mechanical Properties	injectability, bonding strength, microstructure, durability and application.	cracks	Y	Compatibility and Durability	Greece	Insitu Operation
4	2005	NDT-Control of Injection of an Appropriate Grout Mixture for the Consolidation of the Columns Foundations of Our Lady's Basilica at Tongeren (B)	L. Schueremans, F. Van Rickstal and D. Van Gemert	This paper discusses the analysis of the data, obtained during an on site measuring campaign, carried out to evaluate the injections of the columns' masonry foundations of Our Lady's Basilica at Tongeren (Belgium). The selections of the grout composition, as well as the design of an effective injection procedure are based on laboratory and on site tests.	Slaked lime and cement blended grouts	Non Destructive Geo Electrical Survey Physical and Mechanical Properties	Compressive Strength, Bond Strength	Strengthening	Y	Viscosity, Injectability , Yield Stress, Fluidity, Thixotropy	Belgium	Insitu Operation
5	2004	Strategies for the restoration of heritage building with innovative active compatible materials	Asthana, K.K. and Lakhani, Rajni	Attempt to define and describe fundamental criteria for choosing repair materials along with structural and nonstructural treatment options, encompassing the broad acts of repair, rebuilding, strengthening, and reconstruction	White cement	compatibility	Durability	cracks	Y	Physio-Mechanical Compatibility	India	Insitu Operation

6	2003	Conserving the ruins of a Hellenistic farmhouse in Crimea, Ukraine	Jerome et al.	Fieldwork: trials on an limestone building in Ukraine	**LIME-POZZOLAN** Cab-O-Sperse A3875 + Sikament 10 ESL; Ceramic microspheres +/or sand, with possible addition of Rhoplex E-330 or El Rey Superior 200; Ceramic microspheres +/or sand, with possible addition of Rhoplex E-330 or El Rey Superior 200	Not Specified	Physio Chemical and Mechanical Compatibility,	wall caps for limestone walls, cracks	Y	viscosity; setting time; water vapour transmission; water absorption; adhesive bond strength	United States of America	Insitu Operation
7	2003	Application of mineral grouts for structural consolidation of historical monuments	Ignoul et al.	Fieldwork: trials on a church in Belgium	Bentonite + Rheobuild 716	Tensile Strength, Adhesive Bond Strength	Rheological Properties of Grout- Viscosity, Yield strength and Flow time	Separation of the multiple wythes	Y	Injectability, Bond Strength	Belgium	Insitu Operation
8	2003	Evolution of structural consolidation and strengthening of masonry in Belgium: historical overview and case studies.	Van Gemert, D.; Ignoul, S.; Van Rickstal, F.; Toumbakari, E.; and Schueremans, L.	Mass consolidation of stone and brick masonry is considered, with exclusion of pure crack repair. Fieldwork on the consolidation of the tower of the Basilica of Our Lady (1992 94) in Tongeren, Belgium	Blended Lime Cement Pozzolan Grout	Bond Shear Strength	Compressive Strength, Bond Strength	Strengthening, Consolidation and Underpinning	Y	Compressive Strength, Bond Strength	Belgium	Insitu Operation
9	2003	Safety assessment and design of consolidation and strengthening by means of injections.	Schueremans, L. and Van Gemert, D.	The article addresses the need for a reliability-based assessment framework for existing masonry structures. The applications focus on the assessment of existing masonry structures and on the reliability increase obtained by consolidation and strengthening by means of injections.	Blended Lime Cement Pozzolan Grout	Bond Strength	Injectability	Strengthening	Y	Injectability	Belgium	Insitu Operation
10	2002	Heritage: the magazine of the Heritage Canada Foundation	Turner, Susan D	Author warns that the first act of repair should not be the replacement of stone and discusses several kinds of interventions, including reattachment by dowel, Dutchman bond, and plastic fills. She stresses that cracks should be repaired with grout rather than epoxies.	Not Specified	Not Specified	Not Specified	cracks	N/A	Bond Strength	United States of America	Analytical

11	2002	Impermeation of Macedonian tombs in N. Greece using grouting techniques.	Christaras, B et.al	The Macedonian tombs of northern Greece were used as a pilot example for study, given that they are buried in loose sediments where the aquifer overflows their floors. The purpose of this method is to create an impervious shell, which isolates the floor and the walls of the tombs from groundwater.	The grout mixes are colloidal solutions or polymers, such as silica or lignochrome gels, tannins, organic colloids on polyurethane, or pure chemical solutions, such as acrylamides, aminoplast or phenoplast.	Compatibility/ grain size of the soil	Not Specified	waterproofing	Y	Water Absorption	Greece	Insitu Operation
12	2002	Devised grouting admixture for reinforcing the masonry of Pisa Tower	Veniale, F.; Setti, M.; and Lodola, S	A grouting admixture has been devised with appropriate composition, granulometry, and rheological and mechanical properties to avoid "bleeding" and sulfate-alkali attack and to achieve low injection pressure.	"microlite" cement (D-98 ≤ 10 μm) consisting of Fe-clinker (81.5%), silica "fume" (14.5%), and anhydrite (4%) added with 3% of a dispersant (MAC-Rheobuilt 1000) and water (C/W ratio = 1:1)	Compatibility	Rheological Properties of Grout- Viscosity, Yield strength and Flow time	Cracks, voids and detachments	Y	Injectability, Bond Strength	France	Insitu Operation
13	2001	Grout injection of masonry, scientific approach and modeling.	Van Rickstal, F.	DOCTORAL THESIS- experimental program, the results of which provided an enhanced physical understanding of the injection process. New tests have been developed or existing tests have been adapted to the peculiarities of grout.	Cement blended grouts	Shear Strength	Rheological Properties of Grout- Viscosity, Yield strength and Flow time	Cracks, voids and detachments	N/A	Finite element model that simulates the flow of the grout through the masonry.	Belgium	Experimental
14	2000	Technical aspects of stone conservation in Jerusalem	Lobovikov-Katz, Anna.	The report examines some technical aspects of stone conservation concerning the properties of the building material and the technologies involved: stone (limestone) types and grouting and pointing mortars.	Not Specified	Not Specified	Not Specified	cracks and discontinuities	n/a	n/a	Israel	Analytical
15	2000	Research on the formulation of a grout composed of hydraulic binders for the injection in fine cracks and cavities	Paillere, A. M et al.									Experimental
16	1999	Methodology for the design of injection grouts for consolidation of ancient masonry	Toumbakari, E.-E et al.	Testing of multi blend hydraulic grouts for upgrading mechanical properties of ancient masonry	Cement-Lime-Pozzolan- Silica Fume	mechanical and bonding properties, microstructure, porosity, and pore size distribution	Physiochemical Compatibility	Enhanced mechanical properties	N/A	Physiochemical and Mechanical Compatibility	Belgium	Experimental
17	1999	Scientific Design of Grouting as a Repair and Strengthening Technique for Masonry	Van Gemert, D et al	Various Lab tests on grouts as a strengthening technique	Hydrated lime; cement; synthetic polymers	Mechanical Strength	Physiochemical Compatibility	Enhanced mechanical properties	N/A	stability; viscosity; mechanical properties	Belgium	Experimental

18	1998	Criteria for the design of hydraulic grouts injectable into fine cracks and evaluation of their efficiency	Miltiadou-Fezans, Androniki.	criteria for the design of hydraulic grouts of high injectability possessing a broad range of strength values, thus affording the possibility to assure compatibility with the existing materials of the damaged structure.							Greece	Experimenta l
19	1998	Injection grouts for ancient masonry: strength properties and microstructural evidence.	Toumbakari, Eleni-Eva and Van Gemert, Dionys.	DOCTORAL THESIS- experimental program, the results of which provided an enhanced understanding of the ternary grouts (Lime-pozzolan-cement)	nine grout compositions made by 30%-wt ordinary portland cement, natural pozzolans, and hydrated lime to activate the pozzolanic reaction have been investigated.	To enhance early strength development, condensed silica fume has been added in some of the grouts. It is shown that compressive strengths of 15-17 MPa and tensile strengths of 3 MPa at the age of 90 days with W/S as low as 0.85 can be achieved.	Rheological and mechanical properties of the grout a	Compatibility, Enhanced mechanical properties	N/A	Electron microscopy investigation gives further information on the microstructure of the developed grouts.	Belgium	Experimenta l
20	1998	Multiple leaf stone masonry as a composite: the role of materials on its behavior and repair	Anzani, A.; Baronio, G.; and Binda, L.	Systematic research on the mechanical behavior of stonework masonry is a classification of the different cross sections to identify homogeneous groups, both on a geometrical and on a mechanical basis. A procedure is presented, which includes an in situ survey of stonework multiple leaf masonry, the laboratory	various hydraulic grouts	Mechanical Properties	Injectability and Efficacy of Injection	Enhanced mechanical properties	Y	Injectability, Bond Strength	Italy	Insitu Operation
21	1998	Mortars and grouts in restoration of Roman and Byzantine monuments.	Karaveziroglou, M.; Papayianni, J.; and Penelis, g	The authors report results of tests of many characteristics performed at the Aristotle University Laboratory of Reinforced Concrete on ancient and modern masonry and on original and repair mortars.	Cement blended grouts	Not Specified	Not Specified	Repair	Y	Compatibility and Durability	Greece	Insitu Operation
22	1997	In situ investigations of mortars for repairing masonry in historical buildings	Karaveziroglou, Maria; Zombou, Anna; and Magoulas, Thomas	Laboratory and On site, the large amount of fresh mortar or grout for repairing masonry, the time interval between mixing the grout and placing it in situ, and the absorption of its moisture by the existing masonry (old mortar in joints and bricks) are factors that influence the strength of these mixtures.	Cement blended grouts	Insitu non destructive testing Compressive strength and modulus of elasticity	microstructure, strength	Repair	Y	Compatibility and Durability	Greece	Insitu Operation

23	1997	Mortars for repairing masonry in Eptapyrgion fortress.	Karaveziroglou, Maria; Zombou, Anna; and Magoulas, Thomas	filling of cracks by grouting, the replacing of damaged mortar in joints, and the rebuilding of some parts of the masonry must immediately be undertaken. The kind of mortars and grouts to be used depends on the properties of the original materials in the fortress. The authors present results of research to define the composition of mortars and grouts for the repair of the fortress masonry.	lime, pozzolana, crushed brick, and natural sand.	environmental conditions, the durability of mortars and grouts through thermal cycles.	N ot specified	cracks and discontinuities	Y	Environmental condition, Freeze Thaw, Durability	Greece	Insitu Operation
24	1997	Lime-pozzolana-cement injection grouts for the repair and strengthening of three-leaf masonry structures.	Toumbakari, Eleni-Eva and Van Gemert, Dionys.	The repair and strengthening of the interior parts of masonry walls has usually been done by cement or cement-polymer injection grouts	cement-polymer grouts	Physio Mechanical Properties	Rheological Properties	Enhanced mechanical properties	Y	injectability	Belgium	Insitu Operation
25	1997	Interventions for the masonry reinforcements of the "Leaning" Tower of Pisa (Italy).	Macchi, G. and Veniale, F	Good performance has been obtained with the Preliminary tests on a stable section of the tower (north side) have been satisfactory, and the treatment will be implemented as soon as possible.	admixture: Fe-clinker, 81.5% (to avoid the formation of C3A phase); silica fume, 14.5%; anhydrite, 4%, with the addition of 3% of a dispersant (MAC-Rheobuild 1000) and water 1:1; achieving equivalent Na2O=0.38 and granulometry: D98<10 µm.	Pore Structure, shape, size and Voids with GPR and video inspection	Preliminary investigations have been carried out to design a grouting admixture with appropriate composition, granulometry, and rheological and mechanical properties to avoid "bleeding" and sulfate-alkali attack and to achieve low-pressure injection	Enhanced mechanical properties	Y	Injectbility and Strength	Italy	Insitu Operation
26	1997	Consolidation of the Tower of St. Mary's Basilica at Tongeren.	Van Gemert, D.; Ladang, C.; Carpentier, L.; and Geltmeyer, B	Masonry consolidation was realized by injection of both hydraulic and polymeric grout. In combination with the geoelectrical sounding technique, this method allowed a reliable and economical restoration of the monument.	Cement blended grouts	Physical and Mechanical Properties	injection tests	Enhanced mechanical properties	Y	Injectability and Bond Strength	Belgium	Insitu Operation
27	1996	Grouting as a Repair and Strengthening Tchnique	Nuni. P Gil	Grouting efficiency is discussed, regarding the two main parameters involved: the type of grout and the type of masonry. The methods to check the expected efficiency and optimise the technological procedure are described.	microcement and cement blended binary and ternary grouts	Compressive strength, Porosity	injection tests	cracks, discontinuities and detachments	Y	Injectability and Bond Strength	Belgium	Insitu Operation

28	1996	"PMC grouts for structural strengthening of Ashlar masonry structures"	Sharma, R.K.; Maiti, S	For structural stability, load distribution of the truss and to prevent the water ingress into the core of the structure, conservation measures by sealing the joints, surface cracks and grouting the walls with a material which besides meeting the general requirements, would alo be compatible with the structural behaviour of the ashlar masonry structures.	The studies have been carried out with PMC (Polymer modified cementitious) for its use as a grouting material and for sealing of the cracks.	This paper reports the results of polymer loadings in different proportions and other additives on the strength characteristics of PMC.	Not Specified	cracks and discontinuities	Y	Injectability and Compatibility	India	Insitu Operation
29	1996	Investigations on injection grouts to readhere lime mortars to adobe grounds.	Hartmann, A		"Hydraulic Lime Brick dust + Primal AC33 + sodium gluconate (i.e. 'ICCROM grout) Quartz sand + quartz powder + glass bubbles + pyrogen silica gel; KLUCEL E sometimes added (i.e. STROTMANN grout)"					Lab tests: various working properties; tensile strength; modulus of elasticity; water vapour permeability		Insitu Operation
30	1995	Design and evaluation of hydraulic lime grouts for the reattachment of lime plasters on earthen walls.	Matero, Frank and Bass, Angelyn		Hydraulic Lime, Ceramic microspheres +/or sand, with possible addition of Rhoplex E-330 or El Rey Superior 200			minute cracks and voids	Y		United States of America	Insitu Operation
31	1993	Evaluation of injection grouting for structural strengthening of ancient buildings.	Barcellona et al	The author suggests that the biggest problem with structural consolidation is compatibility between the original constituents of the masonry and the products used for its consolidation. Water introduced in walling should be minimized to reduce degradation process related to water presence in porous system, injected product should not release soluble salts and should be stable with regards to the salts already present in wall. Mechanical strength of injected grout should not be excessively greater than the original walling grout.	Hydraulic lime; Portland ASTM Type 1 cement with True Pozzolana 1. EMACO RESTO I (MAC SpA-Italy) 2. Portland ASTMM Type I cement (Italcementi-Italy) 3. Ledan TB1 (Tecno Edile Toscana-Italy) 4. Hydraulic lime (Lafarge-France) 5. "Super-airy" pozzolana (Salone-Italy)	Porosity; Pore Size Distribution; Ion Content; Mechanical Strength; Water Absorption	Strength; Water Absorption; Injectability	discontinuities; structural strengthening	N/A	fluidity/ workability; mechanical strength; Anstett test; water absorption by total immersion; water vapour permeability; porosity; soluble salts; efflorescence formation	Italy	Experimental

)90	Repair of cracked adobe walls by injection of modified mud	Roselund, Nels	It presented the conclusions from a demonstration project designed to develop a procedure for stabilizing the wall of the Pio Pico Mansion California, damaged by an earthquake. The 1987 earthquake generated cracks and left portions of the walls loose and likely to become unstable. The procedure called for filling the cracks with mud that had been modified with lime and fly ash for strength and hardness	Fly ash+ Lime/ Cement; Ledan TB1, Emaco Resto	Shrinkage; Mechanical Strength	qualitative assessment of working properties and performance characteristics	Seismic Strengthening of Pio Pico Mansion	Y	Lab tests: Flow Diameter Test; Shrinkage;Hardness, Breaking Strength;Permeability (Water Absorption); Injectability	United States of America	Insitu Operation
)90	Repair of cracked Unreinforced Brick walls by Injection of Grout	Roselund, Nels	Damage to unreinforced brick buildings caused by earthquakes includes cracks through brick walls due to horizontal offsets in the plane of wall. The repair procedure stabilizes the wall by firmly rebonding loose components	Silica+Sand+ Plastic Portland Cement+ Type S Lime+ Type F Fly Ash	Condition assessment	Fluidity; Water Retention; Shrinkage; Strength; Bond; Injectability	Cracks	Y	Fluidity; Water Retention; Shrinkage; Strength; Bond; Injectability	United States of America	Insitu Operation
)90	Repair of Masonries by injection technique: Effectiveness, Bond and durability problems	Binda, L et al	The results of a previous experimental research carried out by the authors (Binda, Baronio, Fonatana, 1987), have shown that the injections strongly depend on: chemico-physical and mechanical compatibility between the grout and the original material, the penetration and diffusion capacity of the grout, the durability of the grout to frost-defrost actions, thermal cycles, etc.	Resin S (two component epoxy-amine system curing at room temperature, · A-bisphenol epichlorohydrin modified with 1.4 butandioldiglycidylether (ratio 1:4)); Resin M (· Materials not speicfied);	Mechanical Strength	Injectability; Mechanical Strength	Cracks, voids, discontinuities	Y	Injectability; Bond Strength	Italy	Insitu Operation
)87	Durability of decayed brick-masonries strengthened by grouting	Binda, L et al	There has been a considerable amount of study in the last few decades in the retrofitting of old masonry buildings in seismic areas and in historical centers for the conservation and rehabilitation of monumental buildings. Injection grouting has been among the more popular of repair methods, largely used in Italy and other European countries, coupled with reinforcement and prestressing bars.	M1 (Pozzolana: Lime); M2 (Cement: Lime); M3 (High Strength Cement: Acrylic Resin Emulsions)	Salt Crysallization; Compressive strength; deformability; Bond Strength	Injectability; Strength; Bond Strength; Crystallization	Strengthening	N/A	Injectability; Strength; Bond Strength; Crystallization	Italy	Experimental

APPENDIX B

LABORATORY TEST DATA

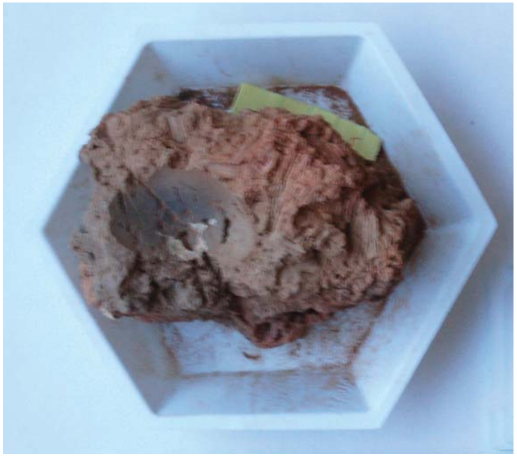
B.1. VISUAL ANALYSIS

	Sample ID: 01-AD-8547
	Name: Adobe
	Locus: 8547
	Weight: 1002.5 g
	Color: 5 YR 7/6 and 7.5 YR 6/6
	Texture: Coarse and Smooth

Description:
The sample is a lump of earth and consists of an outer shell and an inner core. The outer shell seems more brittle than the core. There are casts of straw and organic material visible on the surface. There are holes on the surface and various flat striations where the organic material originally used as casts has long deteriorated. Few hairline cracks are visible on the surface. The sample conists of reddish brown fines.

	Sample ID: 02-AD-8573-1/2
	Name: Adobe
	Locus:8573
	Weight: 331.83 g
	Color: 7.5 YR 7/6
	Texture: Smooth

Description:
The sample was disintegrated into sub angular and sub-rounded particles of varying sizes. The chunks, when observed under Nikon SMZ U Microscope under 1: 0.75 x magnification seem to be covered with reddish brown fines. Plant material is also visible as casts for the puddled earth. Various flat and round holes are present where this organic material has deteriorated.



Sample ID:	03-AD-8573-2/2
Name:	Adobe
Locus:	8573
Weight:	322.31 g
Color:	7.5 YR 7/6
Texture:	Smooth

Description:
The sample is a well integrated chunk of puddled earth. The surface exhibits a darker colored recessed area. It is believed to be in contact with a cobble of the wall masonry. There is a presence of holes on the surface. There are also casts of plant organic material visible on the surface. The holes appear where this plant material has deteriorated. There are few hairline cracks also visible. The sample had a lot of fines, Reddish brown in color as identified with the Munsell Color Chart.

Sample ID:	04-PL-8612
Name:	Plaster
Locus:	8612
Weight:	243.55 g
Color:	7.5 YR 6/4; 7.5 YR 5/4; 7.5YR 4/2
Texture:	Coarse substrate; smooth finish

Description:
The sample is believed to be a wall plaster. It consists of a dark color coarse textured substrate about 80 mm thick. There is a thinner layer of fine plaster over it about 1/4 inch thick. The final layer is extremely thin < 5 mm. It is composed of very fine clay and has a black spotted appearance on top. There are decomposed plant material casts visible as holes. The deteriorated organic fiber is visble at certain places. A few hairline cracks are visible on the surface.

Sample ID:	05-PL-8627/ 15
Name:	Plaster
Locus:	8627
Weight:	256.69 g
Color:	7.5 YR 4/1 Substate; 7.5 YR 5/3 Top
Texture:	coarse substrate; smooth finish

Description:

The sample observed was a floor plaster. It consists of two layers. The substrate is dark colored and extremely coarse about 50 mm thick. This layer seems cracked at various places. There are various thinner and smoother and dark layers on top (< 5 mm thick). There is exidence of plant fiber casts in the substrate. There are wide cracks in the substrate and a few hairline cracks on the top layer.

Sample ID:	06-PL-8627/ 11
Name:	Plaster
Locus:	8627
Weight:	402.43 g
Color:	7.5 YR 4/1
Texture:	coarse substrate; smooth finish

Description:

The sample is believed to be a wall plaster. The bottom most layer is dark colored, coarse textured and about 80 mm thick. The upper layers are thinner, reddish in color and smooth textured. The finish coat applied to the sample is extremely fine and thin (< 5 mm thick) . There are plant fiber casts used in the substrate, which has deteriorated in certain areas leading to flat and round holes and cracks of various sizes.

B.1. VISUAL ANALYSIS

Sample ID:	07-PL-8627/12
Name:	Plaster
Locus:	8627
Weight:	153.7 g
Color:	7.5 YR 4/1
Texture:	coarse substrate; smooth finish

Description:
The sample observed is believed to be obtained from the floor and is suspected to be the top layer of the floor. The substrate is highly coarse and very dark. It is about 60 mm thick. The upper top most layer is extremely fine (about 1-2 mm thick) and same color as the substrate. There are evidences of plant fiber casts which have disintegrated leading to cracks and holes. The sample was also disintegrated into smaller sub angular chunks. The top coat had extremely fine hairline cracks.

Sample ID:	08-PL-8627/16
Name:	Plaster
Locus:	8627
Weight:	304.07 g
Color:	7.5 YR 4/1
Texture:	coarse substrate; smooth finish

Description:
It has a coarse, dark substrate about 75 mm thick and various same color but finer layers on top. Observation under Nikon SMZ U microscope at 1: 0.75x magnification reveals presence of rounded and subrounded black color "ash-like" substance at various places in the matrix of the substrate. The components of the substrate also seem to be covered by extremely fine particles forming a dense matrix. There are 1-2 mm thick cracks in the substrate.

	Sample ID: 09-PL-8625 Name: Plaster Locus: 8625 Weight: 160.69 g Color: 7.5 YR 5/4; 7.5 YR 6/4 Texture: coarse substrate; smooth finish

Description:
The sample obtained is believed to be a wall plaster. The bottom most layer is dark colored, coarse textured and about 80 mm thick. The upper layers are thinner, reddish in color and smooth textured. The finish coat applied to the sample is extremely fine and thin (< 5 mm thick) . There are plant fiber casts used in the substrate, which has deteriorated in certain areas leading to flat and round holes and cracks of various sizes. The observation under Nikon SMZ U microscope at 1: 0.75 x magnification reveals dark lumps or clusters of "ash-like" substances.

	Sample ID: 10-PL-8547 Name: Plaster Locus: 8547 Weight: 17.84 g Color: 5 YR 7/6 Texture: smooth

Description:
The sample obtained is believed to be a wall plaster. It is covered with various layers of thin coats of a fine material believed to be a clay wash. The substrate is about 30 mm thick and very solid and brittle material with a flat surface on which coats of white colored clay wash are applied.

B.1. VISUAL ANALYSIS

	
	Sample ID: 11-PL-8597
	Name: Plaster
	Locus: 8597
	Weight: 140.86 g
	Color: 5 YR 6/6
	Texture: smooth

Description:
The sample under observation was marked as plaster although was highly disintegrated and hence the morphology of the sample cannot be understood. However, observations under Nikon SMZ- U microscope and 1: 0.75 x magnification reveals sub angular and angular nature of the particles.

	
	Sample ID: 12-PL-8654/5
	Name: Plaster
	Locus: 8654
	Weight: 173.93 g
	Color: 7.5 YR 8/4
	Texture: Smooth

Description:
The sample under observation was quite disintegrated into mainly subangular chunks of varying sizes. The plaster chunks has holes and hairline cracks in it. The darker substances observed under SMZ-U microscope at 1: 0.75 x magnification reveals ash-like hard and black substances.The particles are also covered in a very fine matrix of sand or silt.

B.1. VISUAL ANALYSIS

Sample ID:	13- AD- 8620
Name:	Burnt Adobe
Locus:	8620
Weight:	67.05 g
Color:	5 YR 7/6
Texture:	Smooth

Description:
The sample under observation was marked as burnt adobe. It is a round, red, very brittle chunk of earth which does appear to be burnt. There are holes on the surface indicating the decomposition of the organic plant fiber casts.

Sample ID:	14- AD- 8507
Name:	Adobe
Locus:	8507
Weight:	101.86 g
Color:	7.5 YR 6/4
Texture:	Smooth

Description:
The sample under observation was marked as adobe. It is disintegrated into smaller chunks. There is a presence of holes on the surface. There are also casts of plant organic material visible on the surface. The holes appear where this plant material has deteriorated. There are few hairline cracks also visible. Flat striations are also visible on the surface indicative of decomposed straw.

B.1. VISUAL ANALYSIS

Sample ID:	15- PL- 8676
Name:	Plaster
Locus:	8676
Weight:	116.98 g
Color:	7.5 YR 6/4
Texture:	Smooth

Description:

The sample under observation was quite disintegrated into mainly subangular chunks of varying sizes. The plaster chunks has holes and hairline cracks in it. The darker substances observed under Nikon SMZ U microscope at 1: 0.75 x magnification reveal ash-like hard and black substances.The particles are also covered in a very fine matrix of sand or silt. The is also a high presence of quartzitic materials believed to be cobbles from the wall masonry.

Sample ID:	16- PL- 8615/5
Name:	Plaster
Locus:	8615
Weight:	94.3 g
Color:	7.5 YR 6/4
Texture:	Smooth

Description:

The sample under observation was quite disintegrated into mainly ronded and subangular chunks of varying sizes. The chunks has holes in it. The darker substances observed under Nikon SMZ U microscope at 1: 0.75 x magnification reveal ash-like hard and black substances.The particles also appear to be covered in a very fine matrix of sand or silt. The is also a high presence of quartzitic materials believed to be cobbles from the wall masonry.

B.1. VISUAL ANALYSIS

<table>
<tr><td rowspan="6"></td><td>Sample ID: 17- AD- 8666</td></tr>
<tr><td>Name: Plaster</td></tr>
<tr><td>Locus: 8666</td></tr>
<tr><td>Weight: 53.38 g</td></tr>
<tr><td>Color: 7.5 YR 6/4</td></tr>
<tr><td>Texture: Smooth</td></tr>
</table>

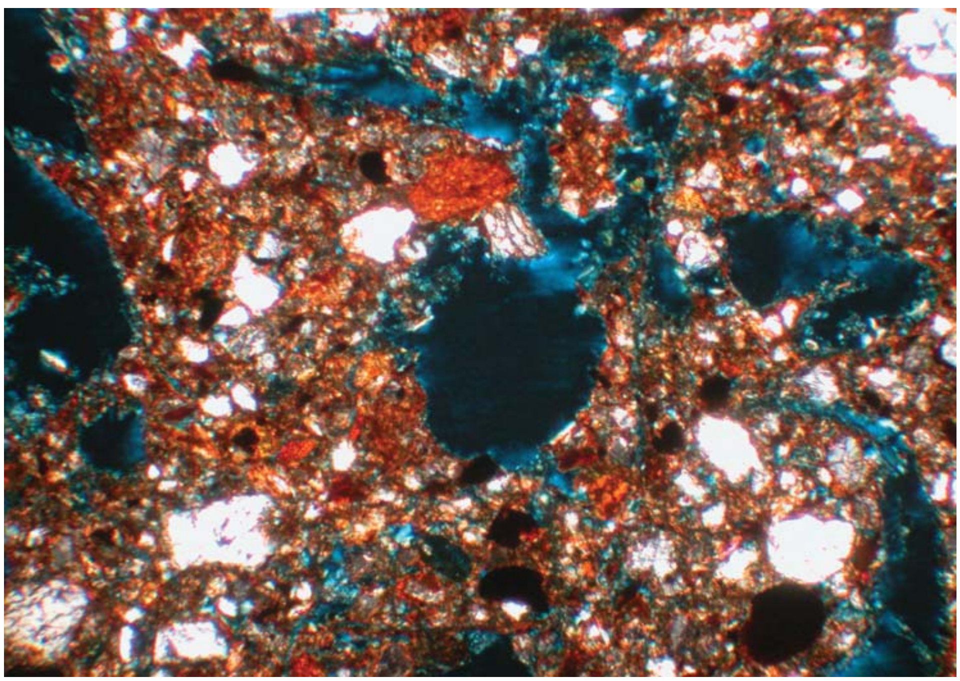
Description:

The sample under observation was marked as plaster although was highly disintegrated and hence the morphology of the sample cannot be understood. However, observations under Nikon SMZ-U microscope and 1: 0.75 x magnification reveals sub angular and angular nature of the particles. There are a lot of fines covering the matrix of the composition. There is a presence of dark “ash-like” substances and reddish particles too.

B.2.THIN SECTION ANALYSIS

	Microscope: Nikon Microflex AFX-DX Magnification: 200 x Type of Illumination: Transmitted cross polarized Projection Lens: 10x Camera: Nikon Coolpix 5000X Exposure Time: 1second

Project Site: Chiripa	
Sample ID: 01-AD-8547	Sample Name: Structural Burnt Puddled Earth
	Analysis by: Charu Chaudhry
	Date: 28 March 2007



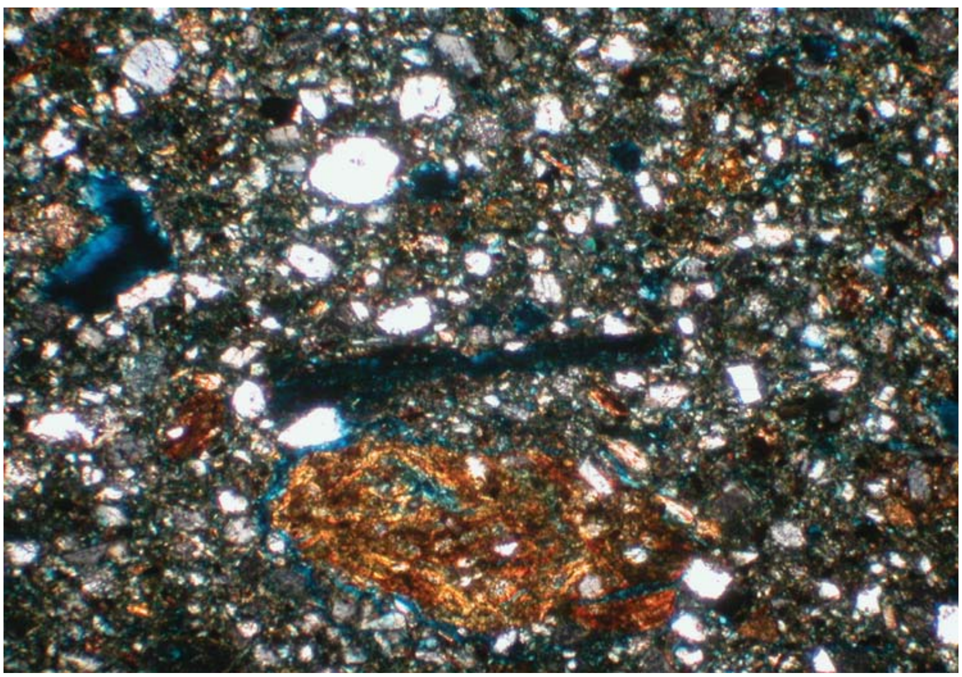
Comments

The general matrix of the soil suggests moderately sorted ground mass of sand (yellow), blebs of clay (red) and quartz crystals (white) interspersed small pores and big pseudo-morphic round to oval shaped voids. There is decayed organic matter visible in the matrix. The sand exhibits light birefringence patterns. The crystal forms range from angular to sub angular. The texture of the mass is fine, and the content of the clay is low. There are no micro artifact inclusions.

B.2.THIN SECTION ANALYSIS

Microscope: Nikon Microflex AFX-DX	
Magnification: 200 x	
Type of Illumination: Transmitted cross polarized	
Projection Lens: 10x	
Camera: Nikon Coolpix 5000X	
Exposure Time: 1second	

Project Site: Chiripa	
Sample ID: 02-AD-8573	Sample Name: Structural Unburnt Puddled Earth
	Analysis by: Charu Chaudhry
	Date: 28 March 2007



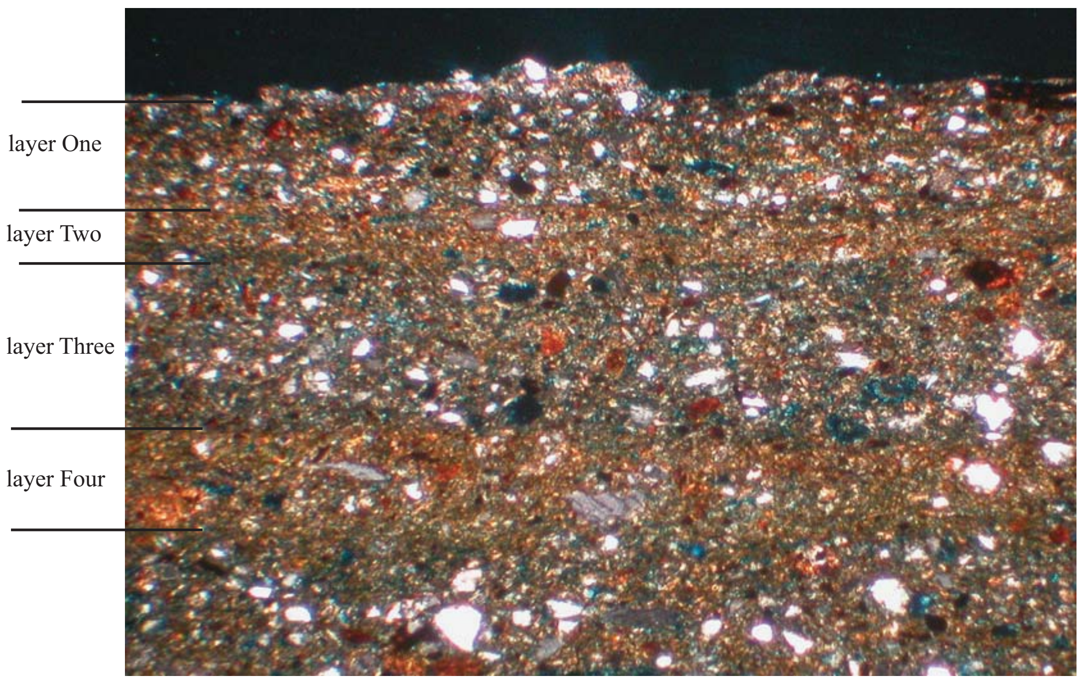
Comments

The ground mass is a well sorted and fine sandy matrix, with angular particles of quartz and nodules of clay of varying sizes. There is light birefringence in the fine ground mass. The pores are extremely minute and the decayed organic matter visible as long and linear voids. There are no microartifact inclusions visible in the matrix.

B.2.THIN SECTION ANALYSIS

	Microscope: Nikon Microflex AFX-DX
	Magnification: 100 x
	Type of Illumination: Transmitted cross polarized
	Projection Lens: 5x
	Camera: Nikon Coolpix 5000X
	Exposure Time: 1/2 second

Project Site: Chiripa	
Sample ID: 02-PL-8625	Sample Name: Wall Plaster
	Analysis by: Charu Chaudhry
	Date: 28 March 2007

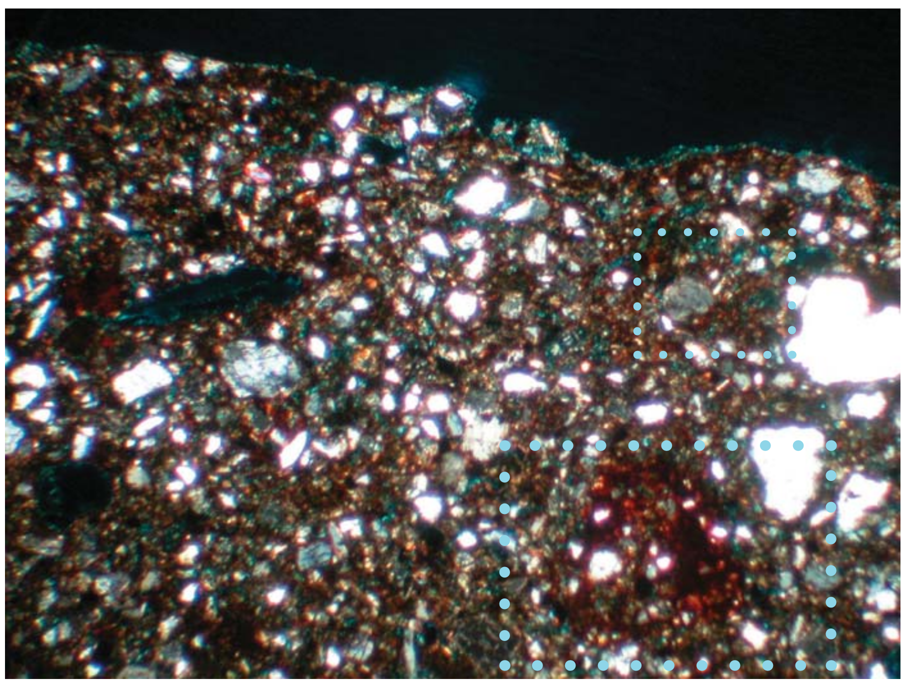


Comments

The wall plaster show a dense yellow birefringent fabric sandwiched between a darker organic-rich fabric. The ground mass is a well sorted dense yellow matrix of sand while there are red nodules of clay interspersed in the matrix.
The top most layers are too fine to be visible under this field and the microscope. It had clay coatings on the sandy plaster suggesting that it was probably water lain. (Goodman 1999)

B.2.THIN SECTION ANALYSIS	
	Microscope: Nikon Microflex AFX-DX
	Magnification: 200 x
	Type of Illumination: Transmitted cross polarized
	Projection Lens: 10x
	Camera: Nikon Coolpix 5000X
	Exposure Time: 1 second

Project Site: Chiripa	
Sample ID: 02-PL-8627/12	Sample Name: Floor Plaster
	Analysis by: Charu Chaudhry
	Date: 28 March 2007

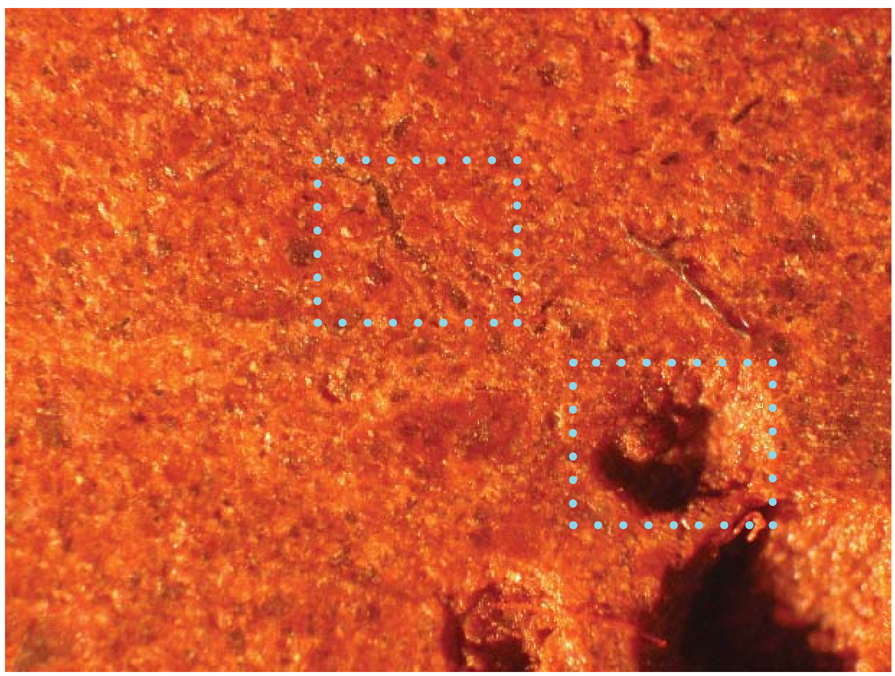


Comments

The floor appears to be laid in a single layer. The ground mass of the soil shows a dense yellow matrix interspersed with angular and sub angular quartz particles. There are nodules of red clay of varying sizes in the matrix. The matrix is abundant in aggregates of charcoal. The pores are very minute and very less. There is decayed plant matter used in the preparation of the floor.

	
	Microscope: Nikon Microflex AFX-DX
	Magnification: 200 x
	Type of Illumination: Reflected light
	Projection Lens: 5x
	Camera: Nikon Coolpix 5000X
	Exposure Time: 1/4 second

Project Site: Chiripa	
Sample ID: 01-AD-8547	Sample Name: Structural Burnt Puddled Earth
	Analysis by: Charu Chaudhry
	Date: 28 March 2007



Comments

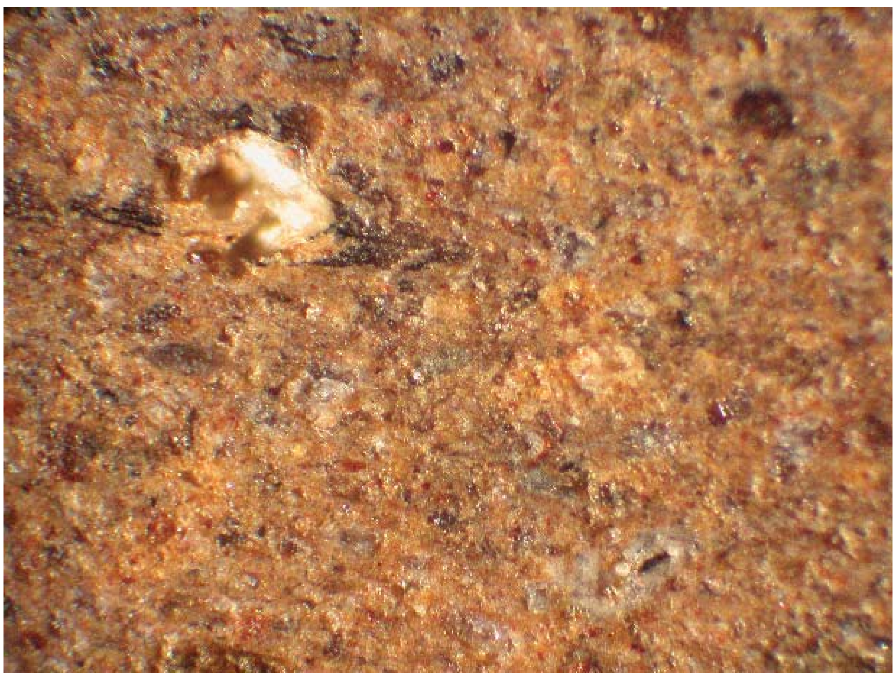
General- The surface of the soil section shows a dense red fabric with plant material, fine cracks.

Color- Overall red

Additional Features- There are minute pores and large open voids.

	
	Microscope: Nikon Microflex AFX-DX
	Magnification: 200 x
	Type of Illumination: Reflected light
	Projection Lens: 5x
	Camera: Nikon Coolpix 5000X
	Exposure Time: 1/4 second

Project Site: Chiripa	
Sample ID: 02-AD-8573	Sample Name: Structural Unburnt Puddled Earth
	Analysis by: Charu Chaudhry
	Date: 28 March 2007



Comments

General- The surface of the soil section shows a dense yellow fabric interspersed with small red nodules of clay.

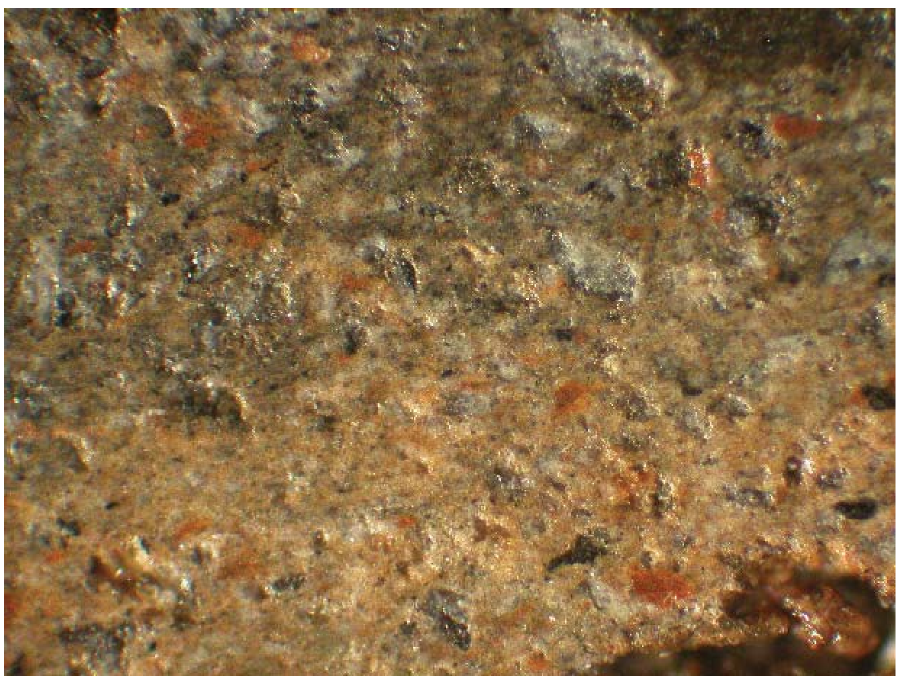
Color- Overall yellow

Additional Features- There are minute pores.

B.3. CROSS SECTION ANALYSIS

	
	Microscope: Nikon Microflex AFX-DX
	Magnification: 200 x
	Type of Illumination: Reflected light
	Projection Lens: 5x
	Camera: Nikon Coolpix 5000X
	Exposure Time: 1/4 second

Project Site: Chiripa	
Sample ID: 02-PL-8612	Sample Name: Wall Plaster
	Analysis by: Charu Chaudhry
	Date: 28 March 2007



Comments

General- The surface of the soil section shows a dense yellow fabric interspersed with small red nodules of clay.

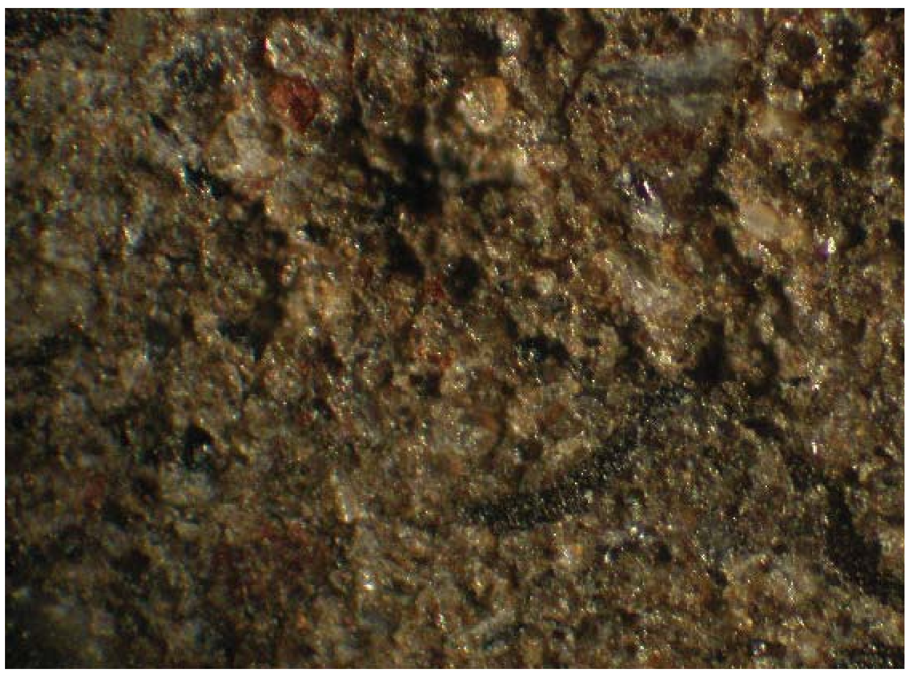
Color- Overall yellow

Additional Features- There are minute pores.

B.3. CROSS SECTION ANALYSIS

	Microscope: Nikon Microflex AFX-DX
	Magnification: 200 x
	Type of Illumination: Reflected light
	Projection Lens: 5x
	Camera: Nikon Coolpix 5000X
	Exposure Time: 1/4 second

Project Site: Chiripa	
Sample ID: 02-PL-8627/12	Sample Name: Floor Plaster
	Analysis by: Charu Chaudhry
	Date: 28 March 2007



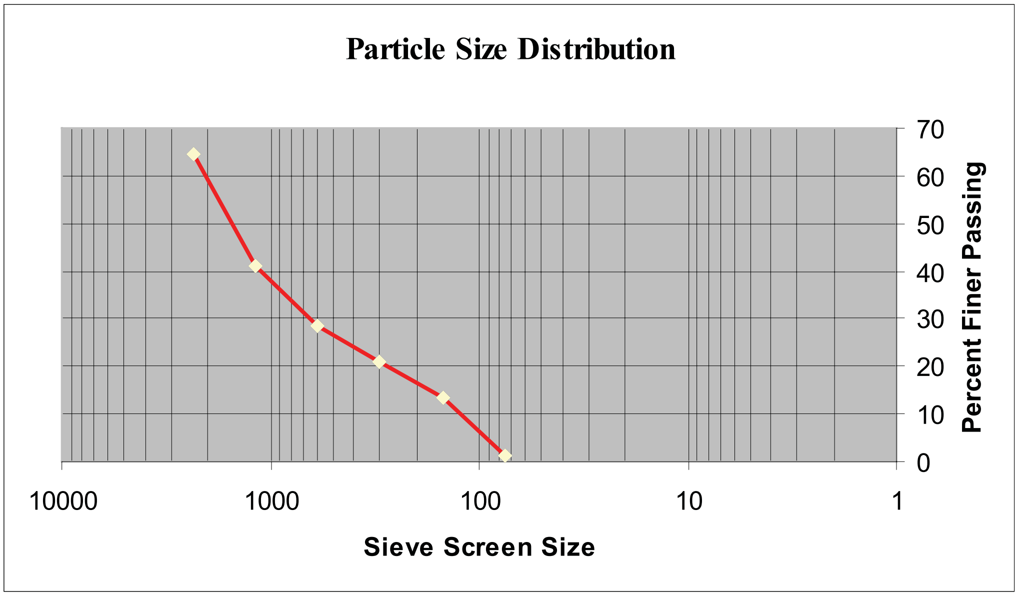
Comments

General- The surface of the soil section shows a dense yellow fabric interspersed with small red nodules of clay. There are aggregates of charcoal in the soil.

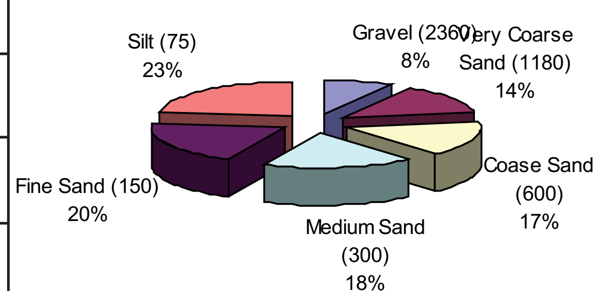
Color- Overall dark brown

Additional Features- There are minute pores.

B.4 SOIL CHARACTERIZATION DATA SHEET: SAMPLE 8547



Plastic Limit	N/A
Liquid Limit	N/A
Plasticity Index	N/A
Munsell Color	7.5 YR 6/6
Texture	Smooth
Mass of Dried Sample	97.87 g



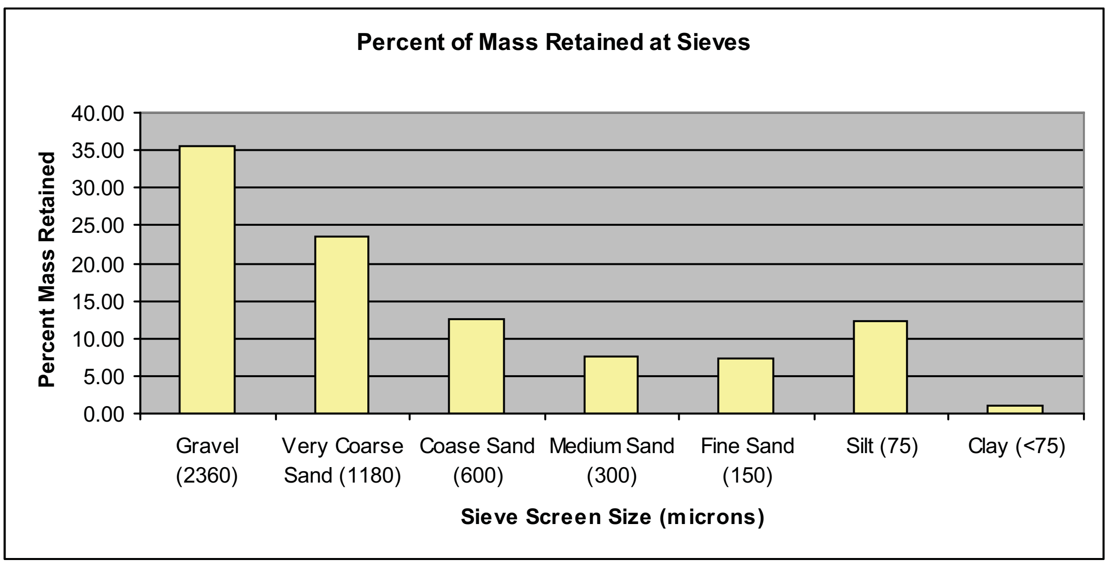
Particle Description	(> 75 microns)
Particle Size	Dominates in various fractions of sand and 8 % Gravel
Particle Shape	Predominantly sub angular with a notable quantity of rounded particles
Notes	Very fine soil with noticeable amounts of organic material as casts

Particle Size Analysis: Sample No. 8547, Chiripa

Table4: Results of Dry Sieve

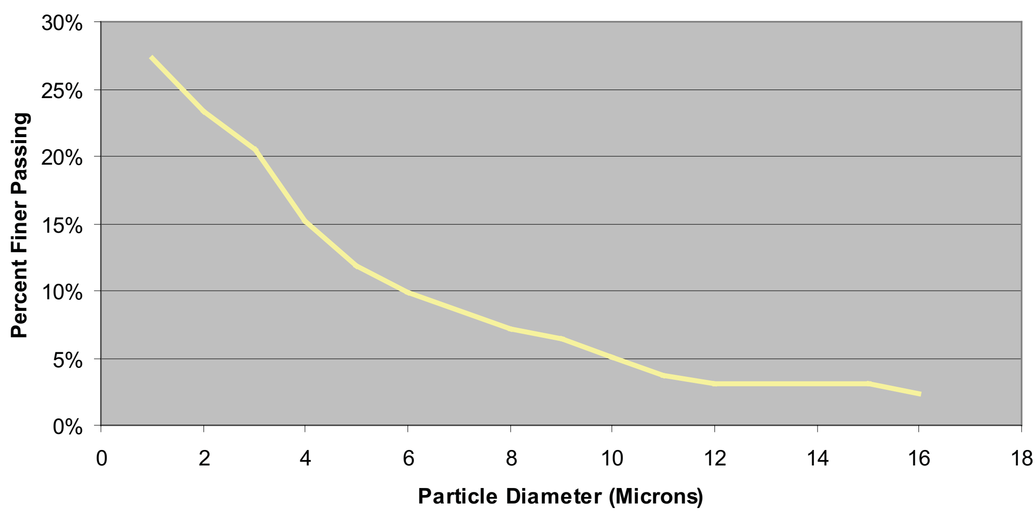
Sieve Number	Screen Size (microns)	M_c (g)	M_2 (Sample+Container) (g)	M_r (M_2 - M_c) (g)	% M_r (M_r / M_s) * 100	% M_{rt} ?% M_r (on or above)	% M_{pt} 100%-M_{rt} %
8.00	2360	4.55	39.23	34.68	35.43	35.43	64.57
16.00	1180	4.50	27.53	23.03	23.53	58.97	41.03
30.00	600	4.57	16.95	12.38	12.65	71.62	28.38
50.00	300	4.61	12.08	7.47	7.63	79.25	20.75
100.00	150	4.57	11.68	7.11	7.26	86.51	13.49
200.00	75	4.51	16.52	12.01	12.27	98.78	1.22
Pan	<75	4.60	5.70	1.10	1.12	99.91	0.09

M_s= 97.87



Date	Time of Reading	Elapsed Time (min)	Temp (C°)	Hydrometer Reading (R_a)	Corrected Reading (R_R)	Meniscus correction (R)	% finer	L (from Table 4)	L / t	Sq Rt L / t	K (from Table 3)	D (mm)	D (μ)
1/14/2007	8:30am	0	21	41	40.6	40.5	27%	9.58	n/a	n/a	0.0133	0	0
1/14/2007	8:30am	0.5	21	35	34.6	34.5	23%	10.85	21.7	4.658	0.0133	0.062	61.96
1/14/2007	8:31am	1	21	31	30.6	30.5	21%	11.59	11.59	3.404	0.0133	0.045	45.28
1/14/2007	8:32am	2	21	23	22.6	22.5	15%	12.98	6.49	2.548	0.0133	0.034	33.88
1/14/2007	8:34am	4	21	18	17.6	17.5	12%	13.89	3.4725	1.863	0.0133	0.025	24.78
1/14/2007	8:38am	8	21	15	14.6	14.5	10%	14.5	1.8125	1.346	0.0133	0.018	17.91
1/14/2007	8:45am	15	21	13	12.6	12.5	8%	14.89	0.9927	0.996	0.0133	0.013	13.25
1/14/2007	9:00am	30	21	11	10.6	10.5	7%	15.44	0.5147	0.717	0.0133	0.010	9.54
1/14/2007	9:30am	60	21	10	9.6	9.5	6%	15.62	0.2603	0.51	0.0133	0.007	6.79
1/14/2007	10:30am	120	21	8	7.6	7.5	5%	16.28	0.1357	0.368	0.0133	0.005	4.90
1/14/2007	12:30pm	240	21	6	5.6	5.5	4%	17.05	0.071	0.267	0.0133	0.004	3.54
1/14/2007	4:30pm	480	20	5	4.6	4.5	3%	17.55	0.0366	0.191	0.0134	0.003	2.56
1/15/2007	12:30am	960	18	5	4.6	4.5	3%	17.55	0.0183	0.135	0.0138	0.002	1.87
1/15/2007	4:30pm	1920	18	5	4.6	4.5	3%	17.55	0.0091	0.096	0.0138	0.001	1.32
1/17/2007	12:30am	3840	18	5	4.6	4.5	3%	17.55	0.0046	0	0.0138	0.000	0.00
1/17/2007	8:30am	5760	18	4	3.6	3.5	2%	18.43	0.0032	0	0.0138	0.000	0.00

Sedimentation Analysis for Sample 8547

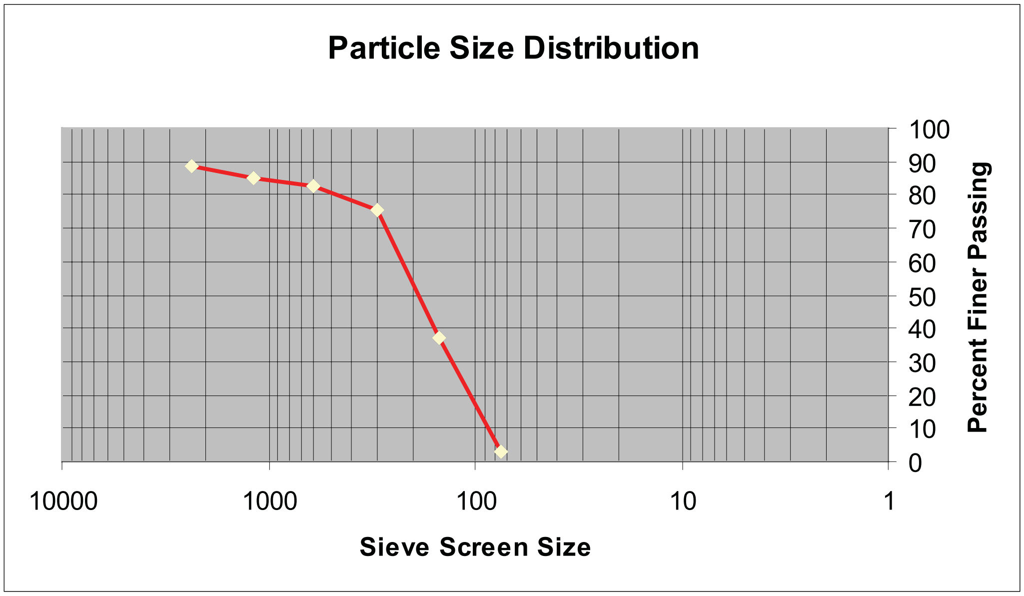


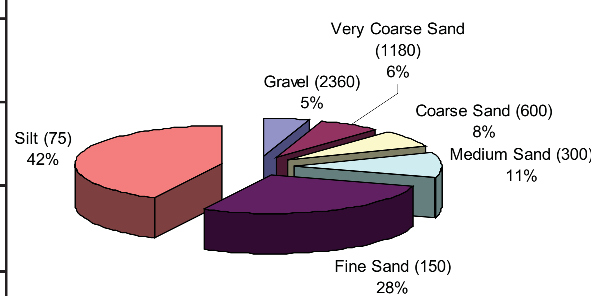
Additional Information:

Mass of Dried Sample (including coarses): 147.11g
Hydrometer # 152 H 68ºF
G_s of solids = 2.70 g/cm^3
a = .99
Dispersing agent: $NaPO_3$
Zero Correction (x) = 0.1
Meniscus Correction = .5

Coarse Silt
Medium and Fine Silt
Clay

B.4 SOIL CHARACTERIZATION DATA SHEET: SAMPLE 8573



Plastic Limit	24.28 %	
Liquid Limit	19.52 %	
Plasticity Index	4.77 %	
Munsell Color	7.5 YR 7/6	
Texture	Smooth	
Mass of Dried Sample	28.37 g	

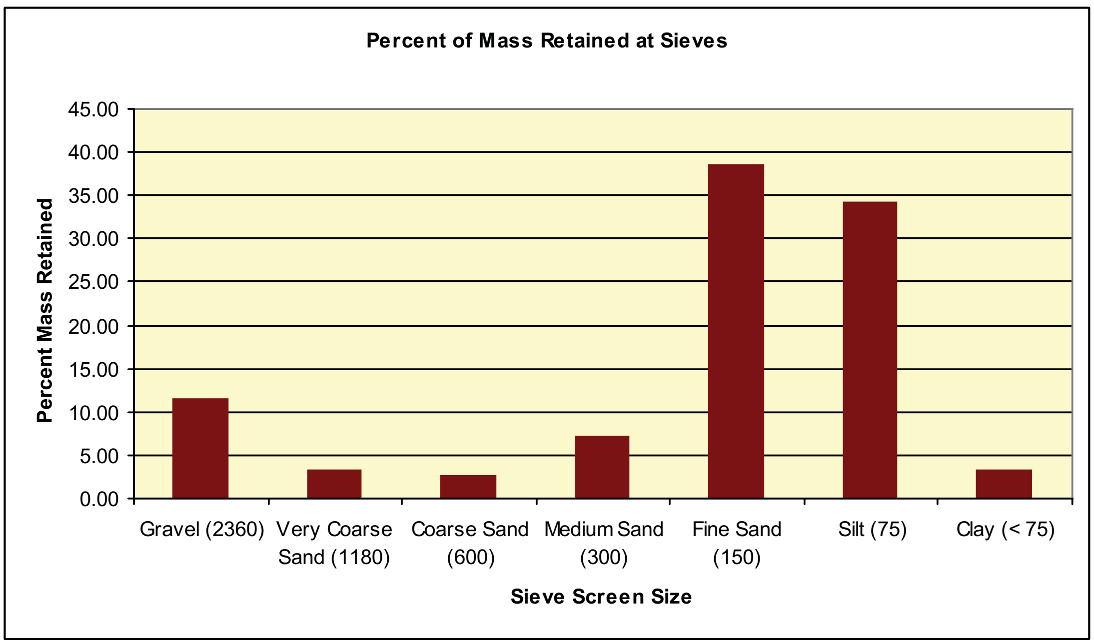
Particle Description	(> 75 microns)
Particle Size	Dominates in various fractions of sand and 5 % Gravel
Particle Shape	Predominantly sub angular with a notable quantity of rounded particles
Notes	Very fine soil with noticeable amounts of organic material as casts

Particle Size Analysis: Sample No. 8573, Chiripa

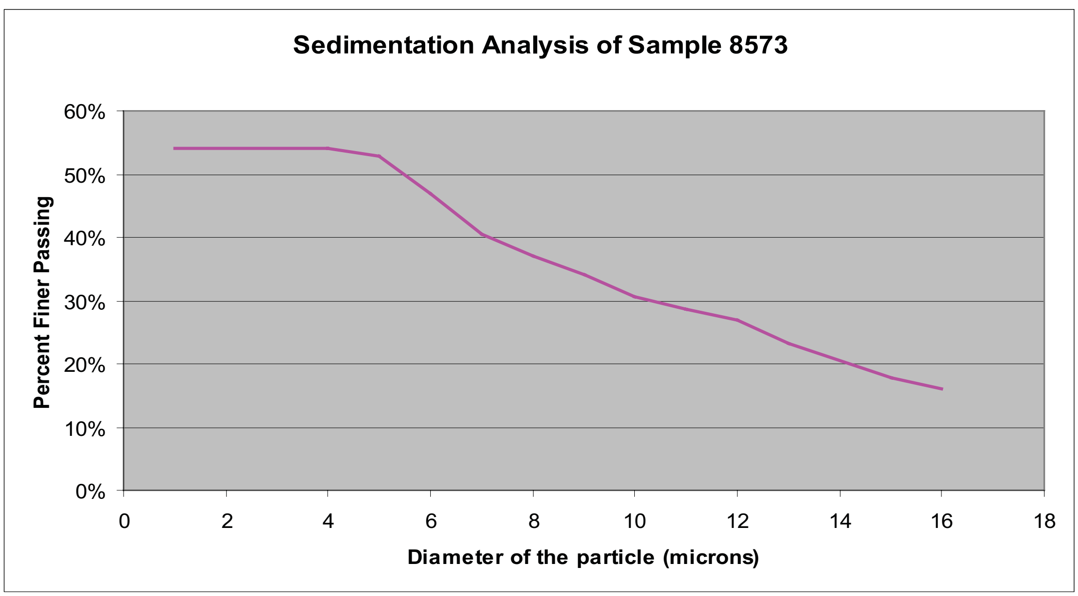
Table4: Results of Dry Sieve

Sieve Number	Screen Size (microns)	M_c (g)	M_2 (Sample+Container) (g)	M_r (M_2 - M_c) (g)	% M_r (M_r / M_s) * 100	% M_{rt} ?% $M_{r \text{(on or above)}}$	% M_{pt} 100%-M_{rt} %
8.00	2360	1.85	5.11	3.26	11.53	11.53	88.47
16.00	1180	1.91	2.81	0.90	3.18	14.71	85.29
30.00	600	1.87	2.58	0.71	2.51	17.22	82.78
50.00	300	1.85	3.84	1.99	7.04	24.26	75.74
100.00	150	1.92	12.78	10.86	38.40	62.66	37.34
200.00	75	1.89	11.55	9.66	34.16	96.82	3.18
Pan	<75	1.83	2.73	0.90	3.18	100.00	0.00

M_s= 28.28



Date	Time of Reading	Elapsed Time (min)	Temp (C°)	Hydrometer Reading (R_a)	Corrected Reading (R_R)	Meniscus correction (R)	% finer	L (from Table 4)	L/t	Sq Rt L/t	K (from Table 3)	D (mm)	D (μ)
1/14/2007	8:30am	0	21	41	40.6	40.5	27%	9.58	n/a	n/a	0.0133	0	0
1/14/2007	8:30am	0.5	21	35	34.6	34.5	23%	10.85	21.7	4.658	0.0133	0.062	61.96
1/14/2007	8:31am	1	21	31	30.6	30.5	21%	11.59	11.59	3.404	0.0133	0.045	45.28
1/14/2007	8:32am	2	21	23	22.6	22.5	15%	12.98	6.49	2.548	0.0133	0.034	33.88
1/14/2007	8:34am	4	21	18	17.6	17.5	12%	13.89	3.4725	1.863	0.0133	0.025	24.78
1/14/2007	8:38am	8	21	15	14.6	14.5	10%	14.5	1.8125	1.346	0.0133	0.018	17.91
1/14/2007	8:45am	15	21	13	12.6	12.5	8%	14.89	0.9927	0.996	0.0133	0.013	13.25
1/14/2007	9:00am	30	21	11	10.6	10.5	7%	15.44	0.5147	0.717	0.0133	0.010	9.54
1/14/2007	9:30am	60	21	10	9.6	9.5	6%	15.62	0.2603	0.51	0.0133	0.007	6.79
1/14/2007	10:30am	120	21	8	7.6	7.5	5%	16.28	0.1357	0.368	0.0133	0.005	4.90
1/14/2007	12:30pm	240	21	6	5.6	5.5	4%	17.05	0.071	0.267	0.0133	0.004	3.54
1/14/2007	4:30pm	480	20	5	4.6	4.5	3%	17.55	0.0366	0.191	0.0134	0.003	2.56
1/15/2007	12:30am	960	18	5	4.6	4.5	3%	17.55	0.0183	0.135	0.0138	0.002	1.87
1/15/2007	4:30pm	1920	18	5	4.6	4.5	3%	17.55	0.0091	0.096	0.0138	0.001	1.32
1/17/2007	12:30am	3840	18	5	4.6	4.5	3%	17.55	0.0046	0	0.0138	0.000	0.00
1/17/2007	8:30am	5760	18	4	3.6	3.5	2%	18.43	0.0032	0	0.0138	0.000	0.00



Additional Information:

Mass of Dried Sample (including coarses): 147.11g
Hydrometer # 152 H 68ºF
G_s of solids = 2.70 g/cm^3
a = .99
Dispersing agent: $NaPO_3$
Zero Correction (x) = 0.1
Meniscus Correction = .5

Coarse Silt
Medium and Fine Silt
Clay

B5. ATTERBERG LIMITS

ATTERBERG LIMITS

TABLE01- PLASTIC LIMIT

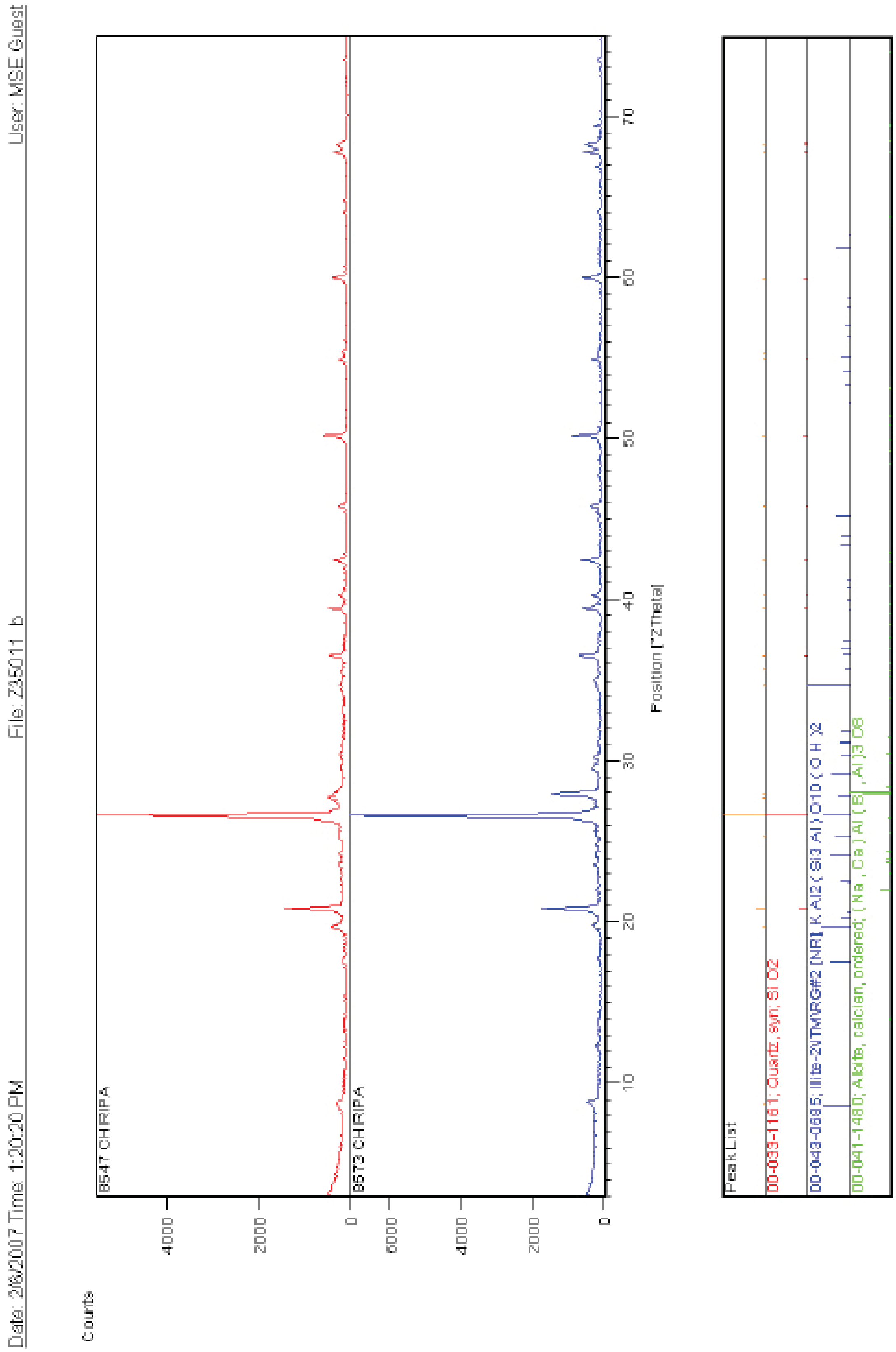
TEST NO.	1	2	3	4	MEAN
CONTAINER NO.	1	2	3	4	N/A
WEIGHT OF WET SOIL + CONTAINER (M_2) (g)	11.59	11.61	11.62	11.69	11.63
WEIGHT OF DRY SOIL + CONTAINER (M_3)	9.43	9.59	9.62	10.07	9.68
WATER LOSS (M_2-M_3) (g)	2.16	2.02	2	1.62	1.95
WEIGHT OF CONTAINER (M_1) (g)	1.61	1.62	1.62	1.62	1.62
WEIGHT OF DRY SOIL (M_3-M_1)	7.82	7.97	8	8.45	8.06
PLASTIC LIMIT (M2-M3)/(M3-M1) * 100	27.62%	25.35%	25.00%	19.17%	24.28%

TABLE 02- LIQUID LIMIT

TEST NO.	1	2	3	4	MEAN
CONTAINER NO.	1	2	3	4	N/A
NUMBER OF DROPS	46	30	16	14	26.5
WEIGHT OF WET SOIL + CONTAINER (M_2) (g)	27.15	27.97	27.07	26.52	27.18
WEIGHT OF DRY SOIL + CONTAINER (M_3) (g)	24.13	25	24.5	24.08	24.43
WATER LOSS (M_2-M_3) (g)	3.02	2.97	2.57	2.44	2.75
WEIGHT OF CONTAINER (M_1) (g)	13.02	13.00	12.84	13.54	13.10
WEIGHT OF DRY SOIL (M_3-M_1) (g)	14.13	14.97	14.23	12.98	14.08
MOISTURE PERCENT (M2-M3)/(M3-M1) * 100	21.37%	19.84%	18.06%	18.80%	19.52%

TABLE 03- PLASTICITY INDEX

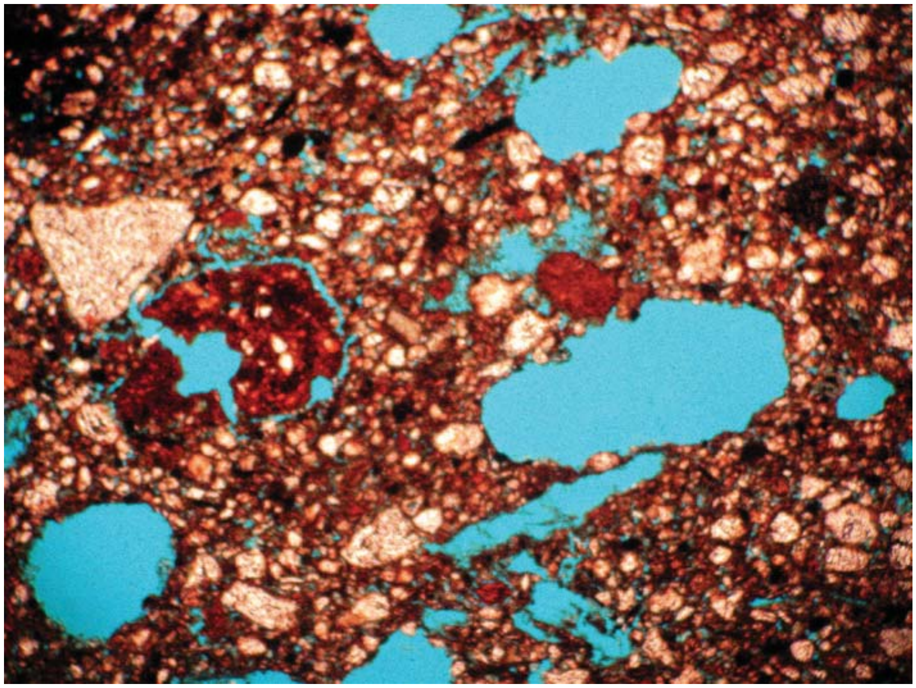
PLASTIC LIMIT (PL)	24.28%
LIQUID LIMIT (LL)	19.52%
PLASTICITY INDEX (PL-LL)	4.77%

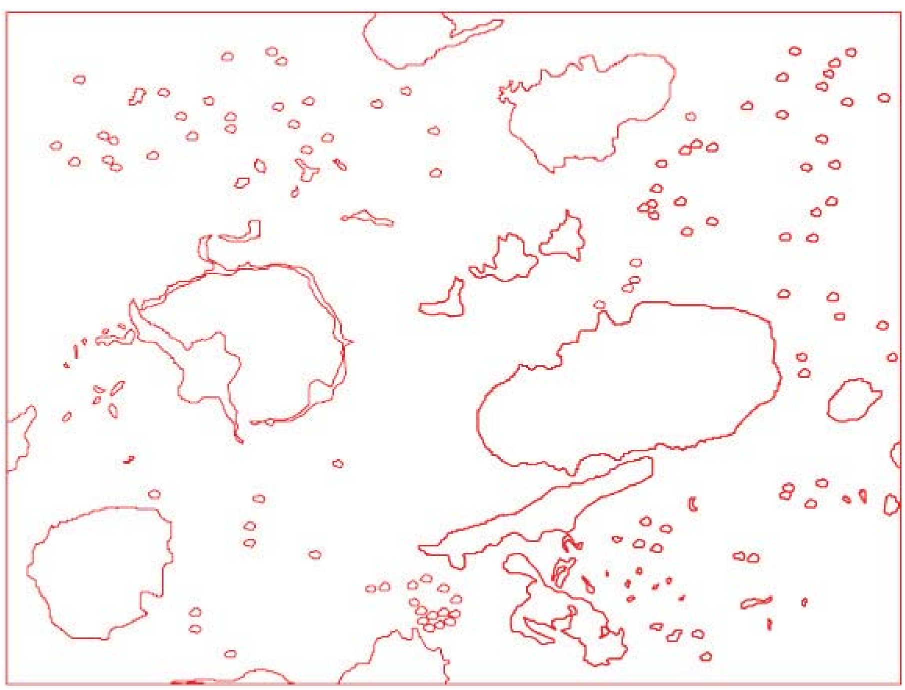


Date: 2/6/2007 Time: 1:20:20 PM
File: Z35011_b
User: MSE Guest
Counts
8547 CHIRIPA
8573 CHIRIPA
Position [°2Theta]
Peak List
00-033-1161; Quartz, syn; Si O2
00-043-0685; Illite-2\ITM\RG#2 [NR]; K Al2 (Si3 Al) O10 (O H)2
00-041-1480; Albite, calcian, ordered; (Na , Ca) Al (Si , Al)3 O8

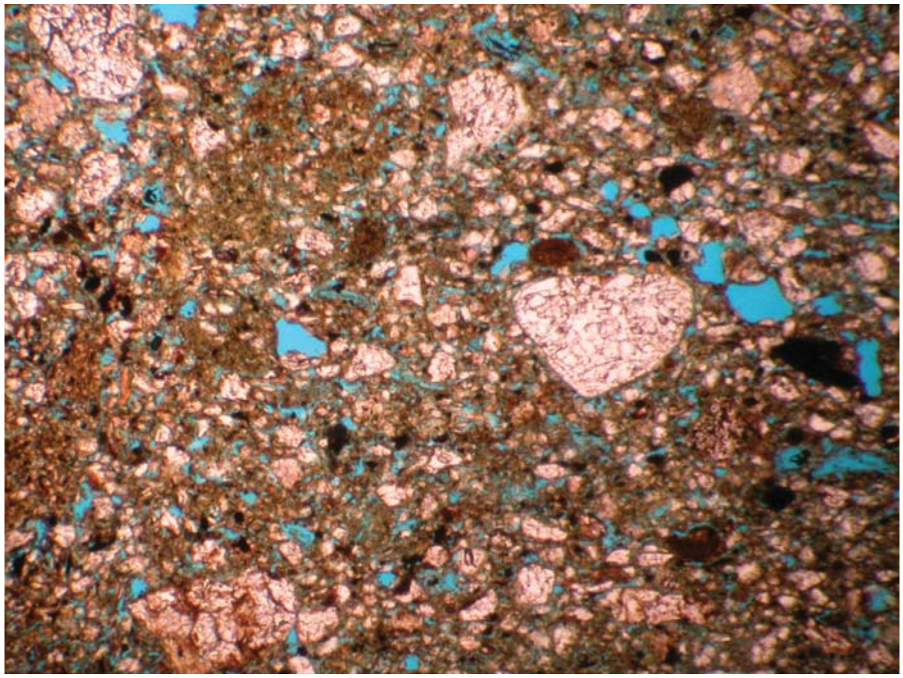
B 7. DRYING SHRINKAGE LIMIT

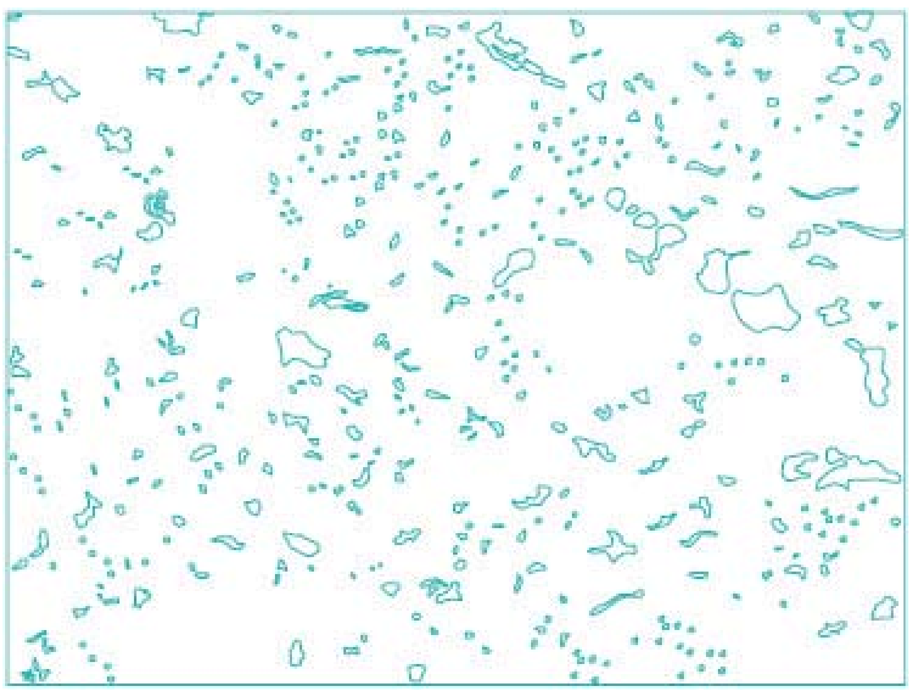
SHRINKAGE LIMIT OF SOIL 8573				
1. Mass of Dry Soil				
TEST NO.	1	2	3	MEAN
SHRINKAGE DISH NO.	1	2	3	N/A
MASS OF WET SOIL + SHRINKAGE DISH (M_w) (g)	112.43	119.45	114.45	
MASS OF THE SHRINKAGE DISH(m) (g)	13.19	13.27	13.25	
MASS OF DRY SOIL PAT + SHRINKAGE DISH (m_d) (g)	90.79	96.55	92.45	93.26
MASS OF DRY SOIL PAT (m_s) (g)	77.6	83.28	79.2	80.03
MASS OF THE WET SOIL (g)	99.24	106.18	101.2	102.21
2. Moisture Content of the Soil				
MOISTURE CONTENT OF THE SOIL AT TIME IT WAS PLACED IN THE DISH $w = \left[\frac{(m_w - m_d)}{m_s}\right] \times 100$	27.89%	27.50%	27.78%	27.72%
3. Volume of Dry Pat Soil				
MASS OF DRY SOIL IN AIR (m_{sxa}) (g)	80.8	87.88	81.3	
MASS OF DRY SOIL IN WATER (m_{sxw}) (g)	33.2	36.6	35.4	
$V_{d_s} = \frac{(m_{sxa} - m_{sxw})}{\rho_w}$ VOLUME OF THE DRY SOIL (cm^3)	47.6	51.28	45.9	
MASS OF THE WAX (m_w) (g)	3.2	4.6	2.1	
DENSITY OF PARAFFIN WAX	0.85	0.85	0.85	
VOLUME OF THE WAX (V_x) (cm^3)	3.76	5.41	2.47	
VOLUME OF THE DRY SOIL PAT (V_d) (cm^3)	43.84	45.87	43.43	44.38
VOLUME OF THE SHRINKAGE DISH (V) (cm3)	45.25	45.25	45.25	
4. Shrinkage Limit				
$SL = w - \left[\frac{(V - V_d)\rho_w}{m_s}\right] \times 100$	26.06	25.81	25.48	25.78
5. Shrinkage Ratio				
$R = \frac{m_s}{(V_d \times \rho_w)}$	1.77	1.82	1.82	1.80
6. Volumetric Shrinkage				
$V_s = R(w_1 - SL)$	3.24	3.08	4.186	3.502





Pore Space Calculation for Burnt Puddled Earth: Sample No. 8547
Through Digital Image Analysis at 1536 x 2048 pixels





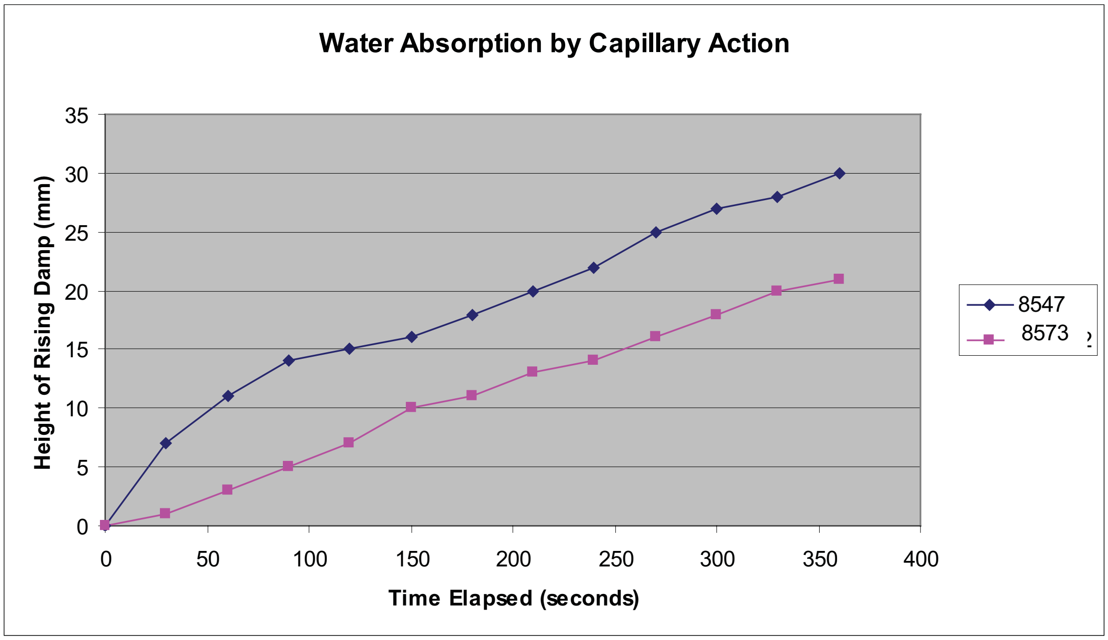
Pore Space Calculation for Burnt Puddled Earth: Sample No. 8573
Through Digital Image Analysis at 1536 x 2048 pixels

B 9. BULK DENSITY

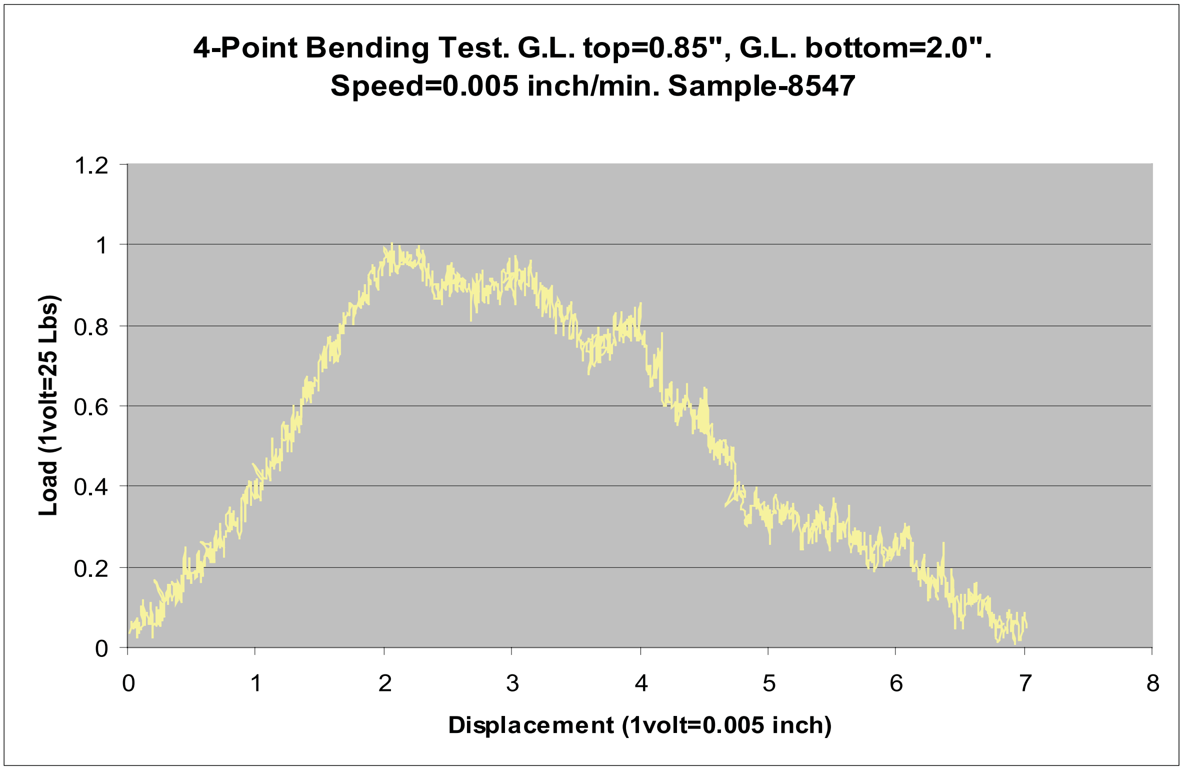
		8547				8573			
SN	Property	A	B	C	Mean	D	E	F	Mean
1	Dry Mass of the Sample in Air (M_1) (g)	8.32	6.43	10.35		10.27	6.59	8.89	
2	Dry Mass of Coated Sample in Air with wire (M_2) (g)	12.31	10.35	15.32		14.94	11.38	13.41	
3	Weight of the wire (M_w) (g)	3.25	3.25	3.25		3.25	3.25	3.25	
4	Mass of the Sample (M_s) (g)	9.06	7.1	12.07		11.69	8.13	10.16	
5	Mass of the wax (M_x) (g)	0.74	0.67	1.72		1.42	1.54	1.27	
6	Mass of the Dry Sample (M_d= M_s-M_x) (g)	8.32	6.43	10.35		10.27	6.59	8.89	
7	Hydrostatic Mass of the coated sample (M_{sxw}) (g)	6.55	4.9	7.15		8.05	4.48	7	
8	Volume of the water displaced (V) (ml)	6	4	9		7	5	7	
9	Specific Gravity of Paraffin Wax (G_x)	0.9	0.9	0.9		0.9	0.9	0.9	
10	Density of Paraffin Wax (g/ cm3)	0.85	0.85	0.85		0.85	0.85	0.85	
11	Volume of the wax (V_x) (cm^3)	0.967	0.876	2.248		1.856	2.013	1.66	
12	Volume of the sample (V_{dx}) (cm3)	2.082	1.8	3.765		2.612	2.482	2.224	
13	Volume of the Dry Sample (V_d= V_{dx}-V_x) (cm3)	1.12	0.92	1.52		0.76	0.47	0.56	
14	Density =M/V (g/ cm3)	7.46	6.96	6.83	7.08	13.59	14.04	15.78	14.47

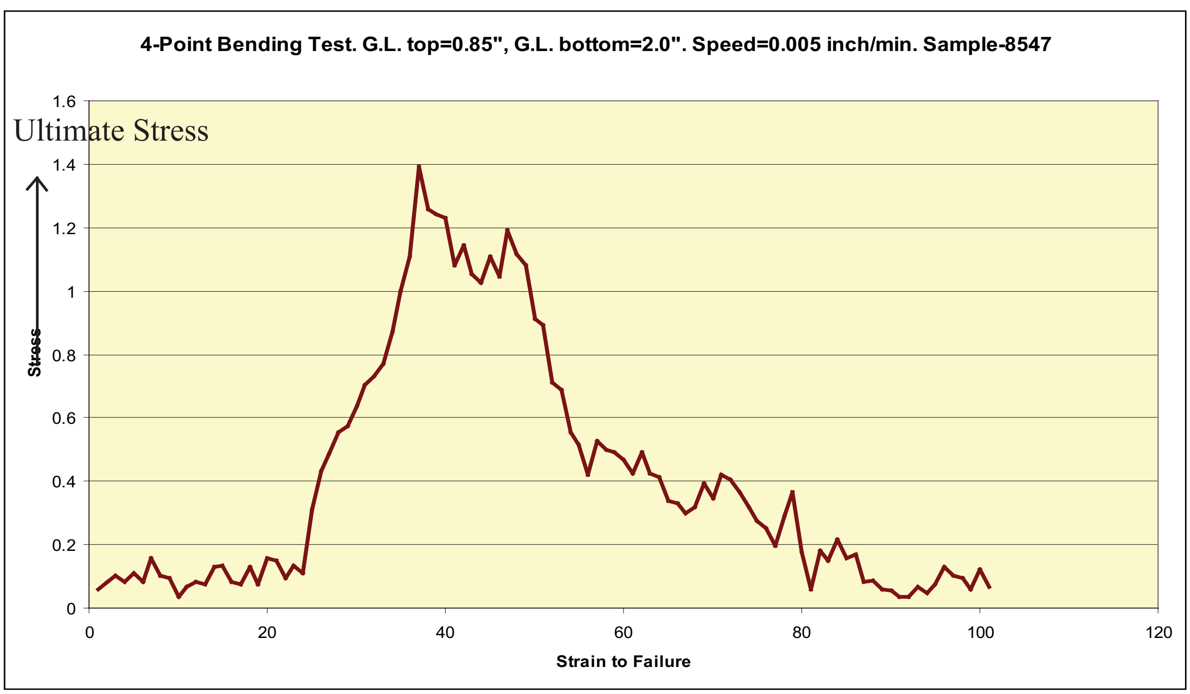
Penetrative Damage From Falling Water				
Sno	Sample	Time Elapsed (sec)	Depth of Penetration (mm)	Average Depth of Penetration
1	8627 A	15 min	0	0
2	8628 B	15 min	0	0
3	8629 C	15 min	0	0
1	8627 A	30 min	1	1
2	8628 B	30 min	0.5	0.5
3	8629 C	30 min	0	0
1	8627 A	45 min	1.5	1.5
2	8628 B	45 min	1	1
3	8629 C	45 min	0	0
1	8627 A	60 min	3	3
2	8628 B	60 min	1	1
3	8629 C	60 min	0	0

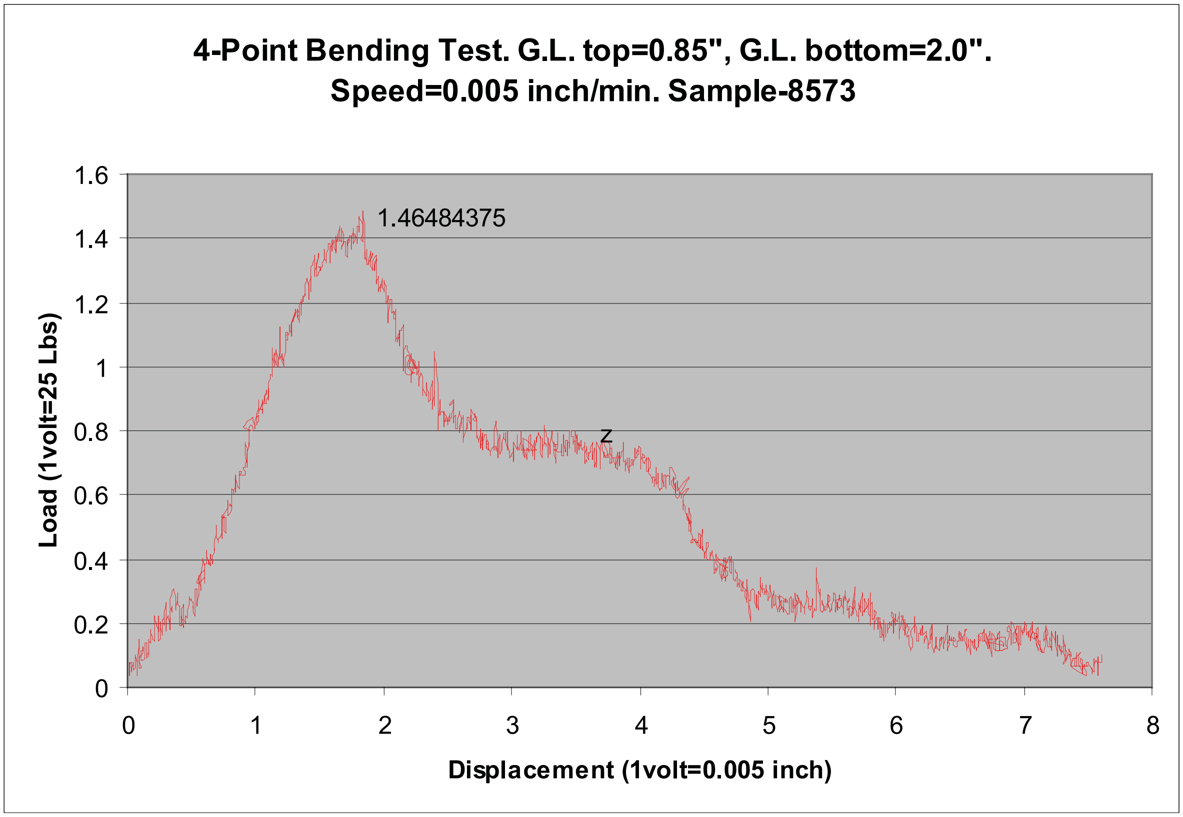
B 11. WATER ABSORPTION BY CAPILLARY

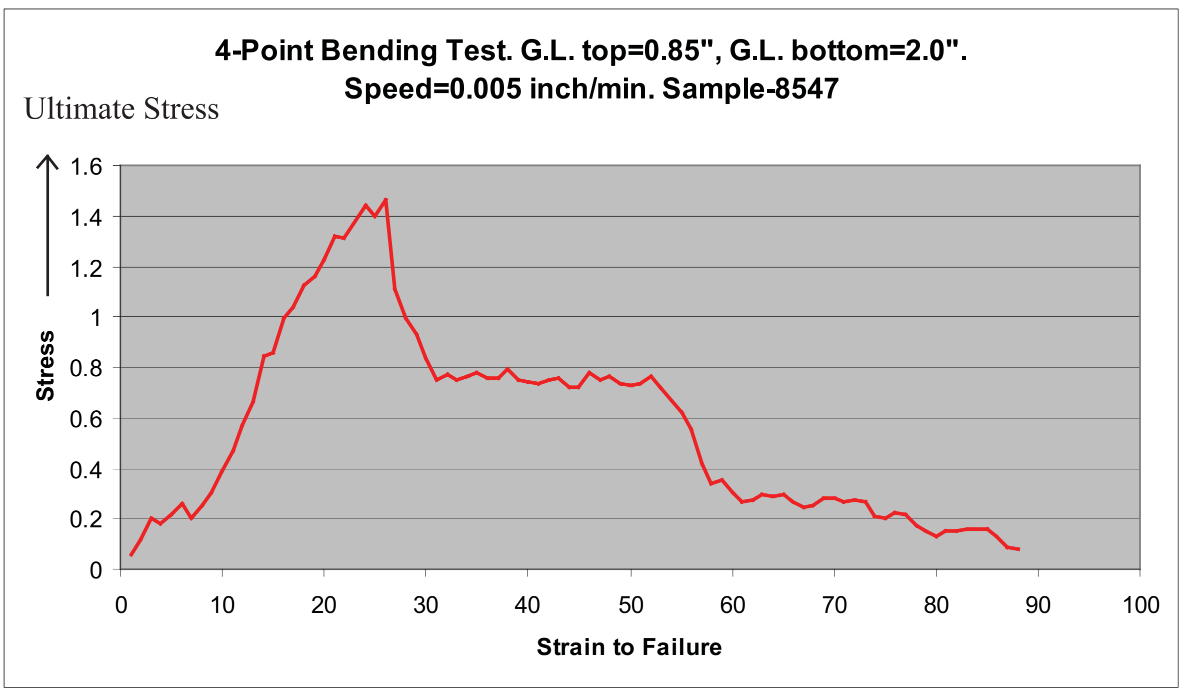


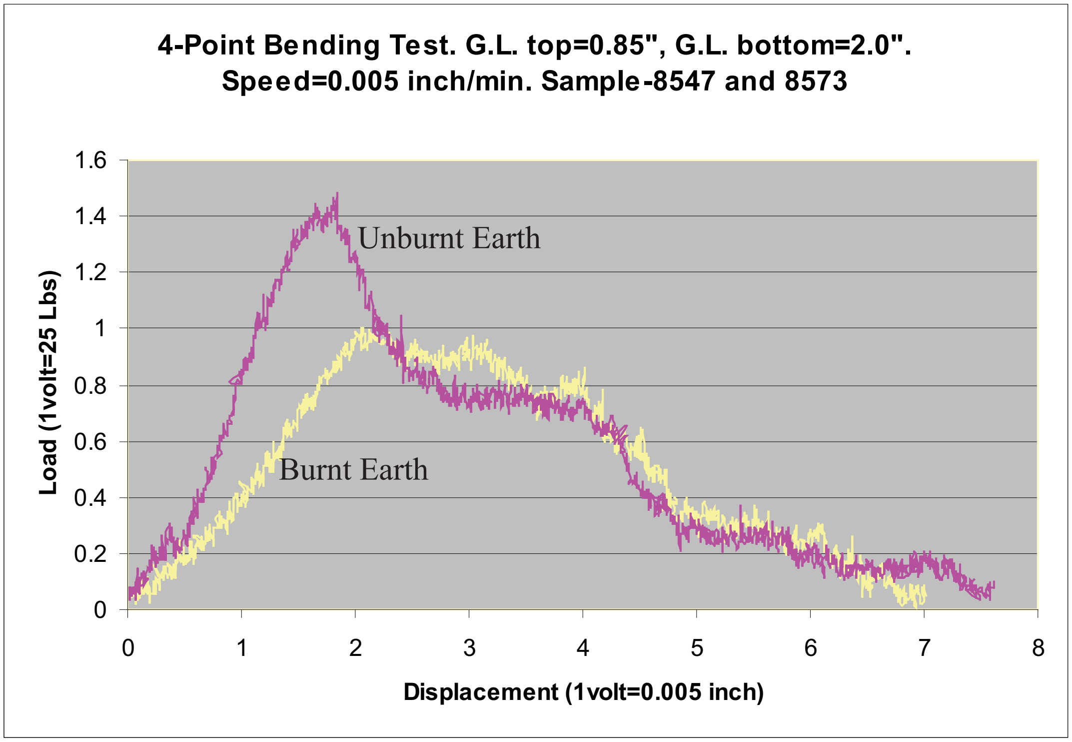
Water Absorption by Capillary Action			
S.N	Time Elapsed (seconds)	Ht. Of Rising Damp (mm)	
		8547	8573
0	0	0	0
1	30	7	1
2	60	11	3
3	90	14	5
4	120	15	7
5	150	16	10
6	180	18	11
7	210	20	13
8	240	22	14
9	270	25	16
10	300	27	18
11	330	28	20
12	360	30	21

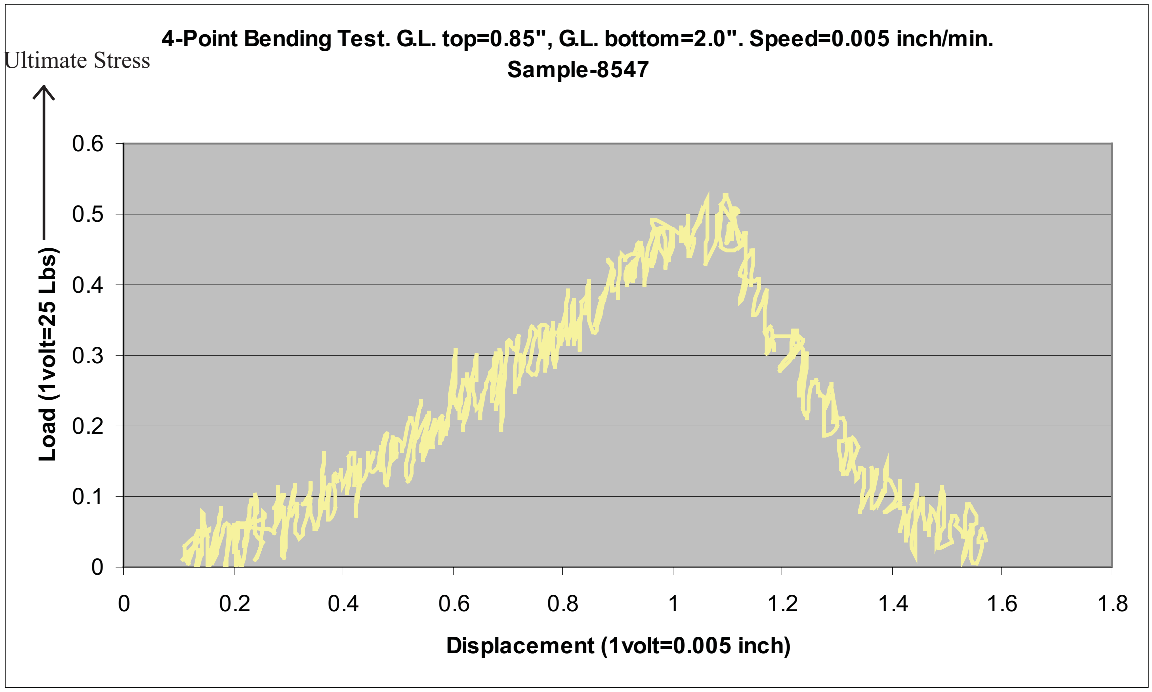

4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0".
Speed=0.005 inch/min. Sample-8547
Load (1volt=25 Lbs)
Displacement (1volt=0.005 inch)
0
0.2
0.4
0.6
0.8
1
1.2
0
1
2
3
4
5
6
7
8

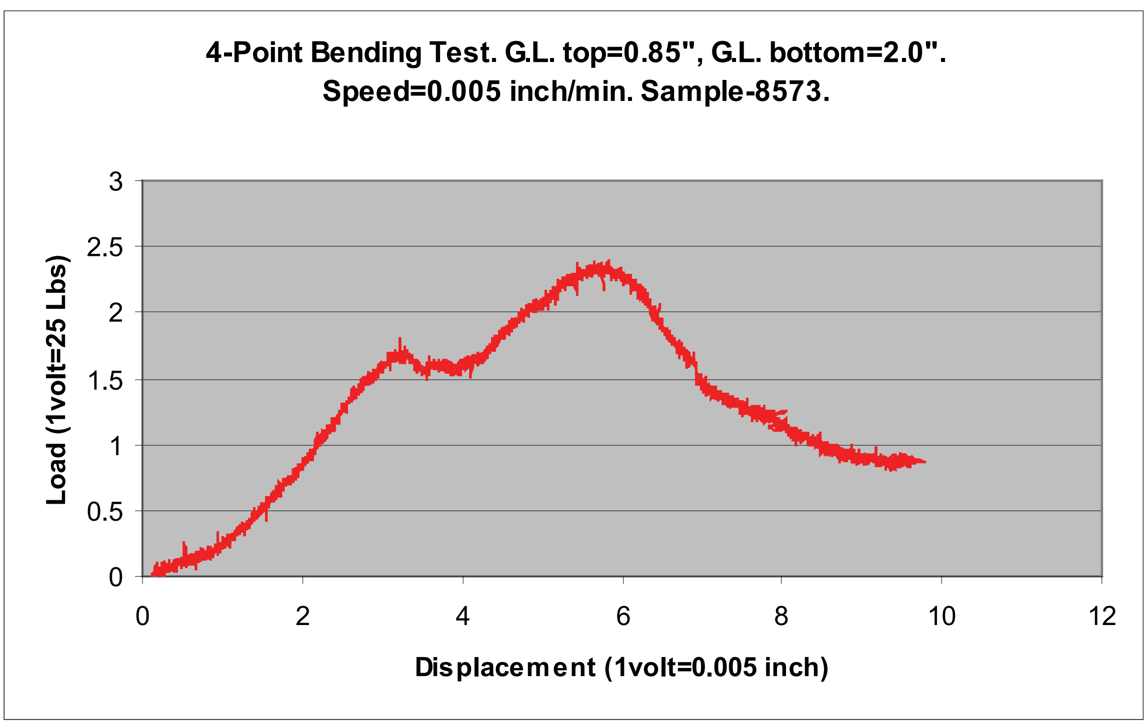

4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0". Speed=0.005 inch/min. Sample-8547
Ultimate Stress
Stress
Strain to Failure
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
20
40
60
80
100
120

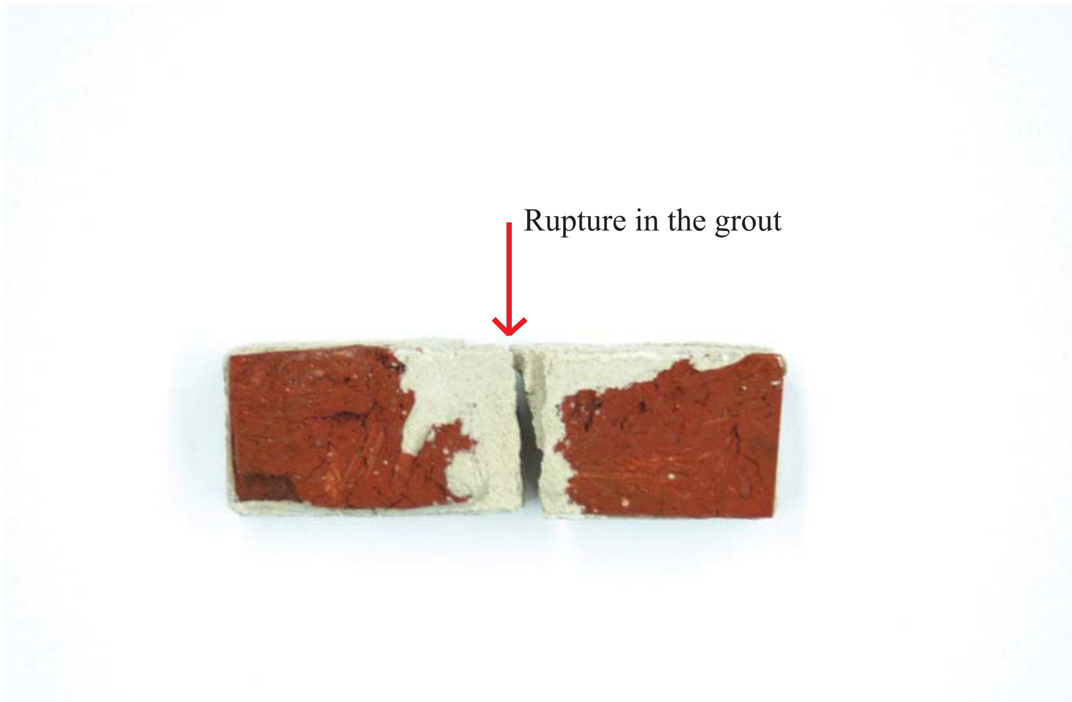

4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0".
Speed=0.005 inch/min. Sample-8573
1.46484375
z
Load (1volt=25 Lbs)
Displacement (1volt=0.005 inch)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
1
2
3
4
5
6
7
8


4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0".
Speed=0.005 inch/min. Sample-8547
Ultimate Stress
Stress
Strain to Failure
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
10
20
30
40
50
60
70
80
90
100


4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0".
Speed=0.005 inch/min. Sample-8547 and 8573
Load (1volt=25 Lbs)
Displacement (1volt=0.005 inch)
Unburnt Earth
Burnt Earth
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
1
2
3
4
5
6
7
8

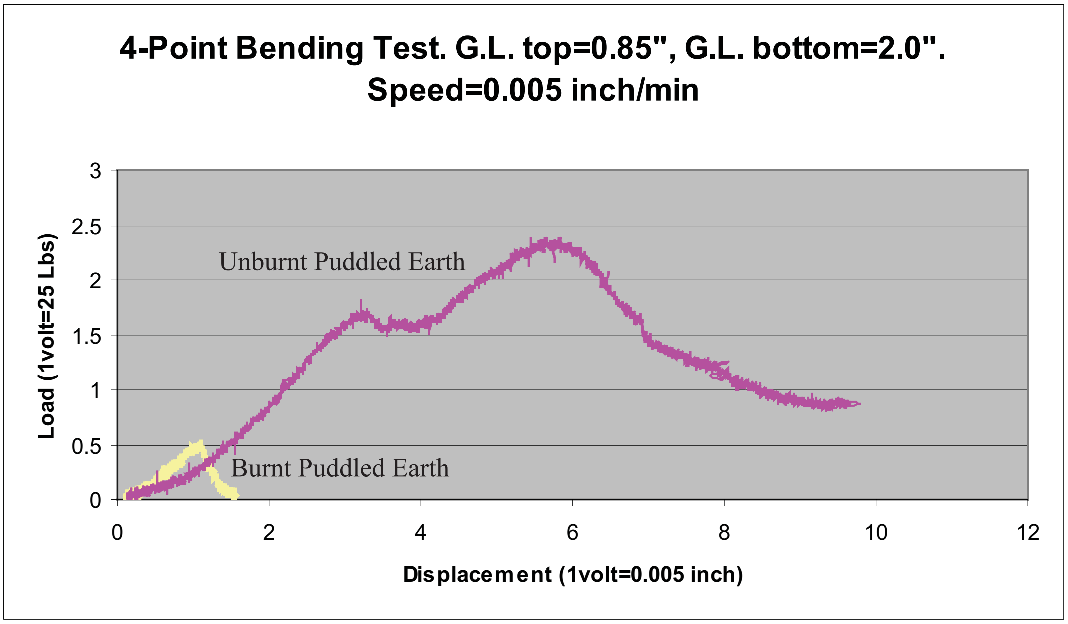

4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0". Speed=0.005 inch/min.
Sample-8547
Ultimate Stress
Load (1volt=25 Lbs)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Displacement (1volt=0.005 inch)


4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0".
Speed=0.005 inch/min. Sample-8573.
Load (1volt=25 Lbs)
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
Displacement (1volt=0.005 inch)



Sample 8547: Burnt Puddled Earth

Sample 8573: Unburnt Puddled Earth


4-Point Bending Test. G.L. top=0.85", G.L. bottom=2.0".
Speed=0.005 inch/min
Load (1volt=25 Lbs)
3
2.5
2
1.5
1
0.5
0
Unburnt Puddled Earth
Burnt Puddled Earth
0
2
4
6
8
10
12
Displacement (1volt=0.005 inch)

APPENDIX C

Silbond CORPORATION

Material Safety Data Sheet

PAGE 1
MSDS NO. 004

SECTION 1. CHEMICAL PRODUCT & COMPANY INFORMATION

PRODUCT NAME
SILBOND® 40

CHEMICAL NAME
Alkyl Silicate

SYNONYM
Alkyl silicate binding material

CHEMICAL FORMULA
Mixture

CAS # MIXTURE

CHEMICAL FAMILY
Alkyl Silicate

PRODUCT USE
Binding agent

MANUFACTURERS NAME
Silbond Corporation

ADDRESS
9901 Sand Creek Highway
Weston, MI 49289

EMERGENCY CONTACT
Carl McLaughlin

COUNTRY
U.S.A.

EMERGENCY TELEPHONE #1
1-517-436-3171

EMERGENCY TELEPHONE #2
CHEMTREC USA 1-800-424-9300
OUTSIDE USA **703-527-3887**

ISSUE DATE
2/01/2002

SECTION 2. COMPOSITION /INFORMATION ON INGREDIENTS

SUBSTANCE DESCRIPTION	PERCENT	CAS#
Ethyl Silicate	~20.000	78-10-4
Ethanol	<3.000	64-17-5
Ethyl Polysilicates	~77.000	11099-06-2

SECTION 3. HAZARDS IDENTIFICATION

APPEARANCE & ODOR
Clear liquid with a sweet odor.

STATEMENT OF HAZARDS
WARNING!
FLAMMABLE LIQUID AND VAPOR
KEEP AWAY FROM HEAT SPARKS AND FLAME
KEEP CONTAINER CLOSED
USE ADEQUATE VENTILATION

FIRE AND EXPLOSION HAZARDS
This product is a flammable liquid. Vapors are heavier than air and may travel to a source of ignition and flash back. Vapor mixtures are explosive above the flash point. Drums have nylon closures and should vent during fires.

Silbond Corporation • 9901 Sand Creek Highway • P.O. Box 200 • Weston, MI 49289 • (517) 436-3171 • silbond@silbond.com

Material Safety Data Sheet

SECTION 3. HAZARDS IDENTIFICATION (Continued)

PRIMARY ROUTE OF EXPOSURE
Skin contact and inhalation are the principal routes of exposure to this product.

INHALATION ACUTE EXPOSURE EFFECTS
Inhalation of vapor may irritate the respiratory tract and may cause central nervous system depression with dizziness, headache, or confusion.

SKIN CONTACT ACUTE EXPOSURE EFFECTS
Skin contact is not expected to cause irritation.

EYE CONTACT ACUTE EXPOSURE EFFECTS
Eye contact is not expected to cause irritation.

INGESTION ACUTE EXPOSURE EFFECTS
This product has a low order of toxicity. No significant toxic effects are expected.

NFPA HEALTH RATING
1

NFPA FLAMMABILITY RATING
3

NFPA REACTIVITY RATING
0

NFPA OTHER
NA

SECTION 4. FIRST AID MEASURES

INHALATION
Remove to fresh air. If breathing becomes difficult, oxygen may be given, preferably with a physician's advice. If not breathing, give artificial respiration. Get medical attention.

SKIN CONTACT
Remove contaminated clothing and equipment. Wash all affected areas with plenty of soap and water for at least 15 minutes. Do not attempt to neutralize with chemical agents. Wash any contaminated clothing and shoes before reuse. Obtain medical advice if irritation occurs.

EYE CONTACT
Flush eyes with large quantities of running water for a minimum of 15 minutes. If the victim is wearing contact lenses, remove them. Hold the eyelids apart during flushing to ensure rinsing of the entire surface of the eye and lids with water. DO NOT let victim rub eye(s). Do not attempt to neutralize with chemical agents. Oils or ointments should not be used at this time. Get medical attention if eye irritation occurs.

INGESTION
Give several glasses of water. DO NOT induce vomiting. If vomiting occurs keep head below hips to reduce risk of aspiration. Give fluids again. Seek medical attention if health effects occur. Never give anything by mouth to a person who is unconscious or convulsing. If victim is unconscious, monitor pulse, breathing, and airway. If breathing stops, begin artificial respiration immediately. If the heart has stopped, give cardiopulmonary resuscitation (CPR). Get medical attention immediately.

SECTION 4. FIRST AID MEASURES (Continued)

MEDICAL CONDITIONS AGGRAVATED
Persons with pre-existing kidney or liver disease may be at an increased risk from exposure to this material.

NOTE TO PHYSICIAN
No specific antidote is known. Based on the individual reactions of the patient, the physician's judgment should be used to control symptoms and clinical conditions.

SECTION 5. FIRE FIGHTING MEASURES

FLASH POINT
81.00 °F 27.22 °C

FLASH METHOD
Tagliabue Closed Cup

AUTO IGNITION TEMPERATURE
685.00 °F 362.77 °C (for ethyl alcohol)

UPPER EXPLOSION LIMIT
19 % (For ethyl alcohol)

LOWER EXPLOSION LIMIT
3.3 % (For ethyl alcohol)

EXTINGUISHING METHOD
Use water fog, dry chemical powder, "alcohol resistant" foam or carbon dioxide extinguishing agents.

FIRE FIGHTING PROCEDURES
As in any fire, prevent human exposure to fire, smoke, fumes or products of combustion. Only properly trained personnel should be involved in firefighting. Evacuate non-essential personnel from the fire area. Firefighters should wear full-face, self-contained breathing apparatus and impervious protective clothing. If possible, move containers from the fire area. High pressure water may spread product from broken containers increasing contamination of fire hazard. Dike fire water for later disposal. Do not allow contaminated water to enter waterways.

FIRE AND EXPLOSION HAZARDS
This product is a volatile, flammable liquid. Vapors may travel to a source of ignition and flash back.

OTHER FIRE AND EXPLOSION HAZARDS
Decomposes under fire conditions to give off oxides or silicon and carbon.

HAZARDOUS PRODUCTS/COMBUSTION
Oxides of silicon and carbon may be produced by the combustion of this product.

SECTION 6. ACCIDENTAL RELEASE MEASURES

CLEAN-UP
A comprehensive spill response plan should be developed. If material is spilled, all ignition sources in the area should be extinguished and the leak stopped at the source. For large spills dike ahead of spill to contain. For small spills, absorb with sand, clay or other inert absorbent. Place in containers for disposal. Personnel involved in spill control and cleanup should follow the recommended exposure controls in SECTION 8 of this MSDS. All non-essential personnel should be evacuated from the immediate spill area.

Material Safety Data Sheet

SECTION 6. ACCIDENTAL RELEASE MEASURES (continued)

WASTE DISPOSAL
The characteristic of Ignitability per RCRA could apply to the unused product if it becomes a waste material. The EPA hazardous waste number D001 could apply. It is the responsibility of the waste generator to evaluate whether his wastes are hazardous by characteristics or listing.

CONTAINER DISPOSAL
Containers should be cleaned of residual product before disposal. Empty containers should be disposed of in accordance with all applicable laws and regulations.

SECTION 7. HANDLING/STORAGE/TRANSPORTATION

HANDLING
Electrically grounded tanks and containers should always be used as should non-sparking, electrically grounded hand tools and appliances. Ground or bond to ground all vessels when transferring to prevent the accumulation of static electricity. See National Electric Code.

STORAGE
Because the product is a flammable liquid, storage should meet the requirement of 29 CFR 1910.106, Flammable and Combustible Liquids Code. Store in a cool, dry, well-ventilated area away from sources of heat, ignition, direct sunlight, oxidizers and alkalis. Keep container closed when not in use. Remove closures carefully; internal pressure may be present.

MAXIMUM STORAGE TEMPERATURE
Store below flashpoint if possible

SECTION 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

GENERAL COMMENTS
This product may be slightly acidic and may attack certain plastics and corrode carbon steel over extended periods of time.

RESPIRATORY PROTECTION
Use NIOSH-approved organic vapor respirators with dust, mist and fume filters to reduce potential for inhalation exposure if use conditions generate vapor, mist or aerosol and adequate ventilation (e.g. outdoor or well ventilated area) is not available. Where exposure potential necessitates a higher level of protection, use a NIOSH-approved, positive-pressure/pressure-demand, air-supplied respirator. When using respirator cartridges or canisters, they must be changed frequently (following each use or at the end of the workshift) to assure breakthrough exposure does not occur.

SKIN PROTECTION
Skin contact with liquid or its aerosol should be prevented through the use of suitable protective clothing, gloves and footwear selected with regard for use condition exposure potential. Viton® gloves and boots are not recommended.

EYE PROTECTION
If the possibility of splashing or spraying of this material exists, chemical goggles and/or a full face shield should be worn.

VENTILATION PROTECTION
Local exhaust ventilation, enclosed system design, continuous monitoring devices, process isolation and remote control are traditional exposure control techniques which may be used to effectively minimize employee exposure.

Material Safety Data Sheet

SECTION 8. EXPOSURE CONTROLS/PERSONAL PROTECTION (Continued)

OTHER PROTECTION
All food and smoking materials should be kept in a separate area away from the storage/use location. Eating, drinking and smoking should be prohibited in areas where there is a potential for exposure to this material. Before eating, drinking or smoking, hands and face should be thoroughly washed.

APPLICABLE EXPOSURE LIMITS
Other than any exposure limits which may be displayed in Section 15, there are no other known exposure limits applicable for this product or its components.

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

VAPOR PRESSURE (mm Hg)
21
@ 50 °F 10 °C

EVAPORATION RATE
N/D

BOILING POINT
172 °F 78 °C
(at 760 mm Hg)

SPECIFIC GRAVITY
1.06
@ 68 °F 20 °C

SOLUBILITY IN WATER
Hydrolyzes in water

COEFFICIENT OF OIL/WATER
N/D

MELTING POINT
-130 °F -90 °C

CLOUD POINT
N/D

VAPOR DENSITY (Air = 1.0)
N/D

VOLATILE %
~34 (ASTM D-2369-93)

ODOR THRESHOLD (ppm)
AP 85
ppm (ethanol & ethyl silicate)

BULK DENSITY
N/D

SOLUBILITY IN OTHER SOLVENTS
Miscible with organic solvents

POUR POINT
N/D F N/D C

PH FACTOR
N/D

OTHER
Viscosity 5.0-6.5 @ 68 °F 20 °C

SECTION 10. STABILITY AND REACTIVITY

STABILITY
This product is stable at ambient temperatures and atmospheric pressures. It is not self-reactive and is not sensitive to physical impact.

INCOMPATIBILITIES
This product hydrolyzes slowly and nonviolently under moist alkaline or acidic conditions at ambient temperatures and atmospheric pressures to form silicon dioxide and ethanol. It reacts with oxidizing agents such as nitrates and hypochlorites. The product may attack certain plastics and corrode carbon steel over extended periods of time.

POLYMERIZATION
Hazardous polymerization is not expected to occur.

Material Safety Data Sheet

DATE PRINTED: 8/3/2004
SILBOND 40

PAGE 6
MSDS NO. 004

SECTION 10. STABILITY AND REACTIVITY (continued)

DECOMPOSITION
Thermal decomposition products include oxides of carbon and silicon.

CONDITIONS TO AVOID
Under wet alkaline or acidic conditions, prolonged storage at elevated temperatures should be avoided to assure product integrity.Store away from foodstuffs, animal feed and incompatibles such as oxidizers, acids and alkalis.

SECTION 11. TOXICOLOGICAL INFORMATION

INHALATION EFFECTS
The acute inhalation LC50 is greater than 4.8 mg/L in both male and female rats. A single 4-hour inhalation exposure of 4.8 mg/L (greater than 95 percent respirable) produced a 4 to 7 percent decrease in body weights in male and female rats. No mortality was observed.

INHALATION CHRONIC EXPOSURE EFFECTS
Prolonged and/or repeated inhalation may cause severe respiratory irritation, pulmonary edema and possible kidney and liver damage.

DERMAL EFFECTS
The acute dermal LD50 is greater than 1000 mg/kg in rabbits. A single dermal application of 4640 mg/kg did not produce signs of toxicity in rabbits. Local effects included mild edema.

This product was non-irritating to rabbit skin following a 4-hr. exposure.

SKIN CONTACT CHRONIC EXPOSURE EFFECTS
Chronic dermal exposure effects for this product are not known.

EYE EFFECTS
This product did not produce irritation when tested in rabbits eyes.

EYE CONTACT CHRONIC EXPOSURE EFFECTS
Chronic eye exposure effects for this product are not known.

INGESTION EFFECTS
The oral LD50 for this material is >5000 mg/kg in rats. A single oral dose of 5000 mg/kg did not produce signs of toxicity in male rats.

INGESTION CHRONIC EXPOSURE EFFECTS
Health effects as a result of chronic ingestion are not known.

CARCINOGENICITY/MUTAGENICITY
Neither this product nor its components have been classified as a carcinogen by IARC, NTP, OSHA, or ACGIH.

REPRODUCTIVE EFFECTS
The reproductive toxicity of this product is not known. Reproductive toxicity of the components of this product are as follows:

> **ETHYL ALCOHOL**
> Ethyl alcohol has been shown to affect male fertility. It is not clear from the literature if exposures which are solely occupational and clearly within the exposure limits are sufficient to be a reproductive risk.

Material Safety Data Sheet

DATE PRINTED: 8/3/2004 PAGE 7
SILBOND 40 MSDS NO. 004

SECTION 11. TOXICOLOGICAL INFORMATION (Continued)

NEUROTOXICITY
The neurotoxic effects of this product are not known.

OTHER EFFECTS
No other toxic effects for this product are known.

TARGET ORGANS
Overexposure to this product may affect the skin and respiratory system. Overexposure to ethyl silicate may cause damage to the liver, kidneys and cause anemia.

SECTION 12. ECOLOGICAL INFORMATION

ECOLOGICAL TOXICITY
The ecological toxicity of this product is not known. However, the following data exists for ethanol:
Toxicity threshold (cell multiplication inhibition test)
Bacteria (psuedomonas putida) 6500 mg/L
Algae (Microcystis aeruginosa) 1450 mg/L
Green Algae (Scenedesmus quadricauda) 500 mg/L
Protozoa (Entosiphon sulcatum) 65 mg/L
Protozoa (Uronema parduczi Chatton-Lwoff) 6120 mg/L
Fingerling Trout: 24 hr LC50 11,200 mg/L
Guppies (Poecilia reticulata) LC50: (7 days): 11,050 ppm
Creek chub (Semotilus atromaculatus); 24 hr. LC50 >7000 mg/L

OTHER ECOLOGICAL INFORMATION
N/D

CHEMICAL FATE INFORMATION
This product hydrolyzes slowly in wet alkaline or acidic conditions to silicon dioxide and ethanol.

OTHER REGULATORY INFORMATION
No other regulatory information is available on this product.

SECTION 13. DISPOSAL CONSIDERATIONS

WASTE DISPOSAL
The characteristic of ignitability per RCRA could apply to the unused product if it becomes a waste material. The EPA hazardous waste number D001 could apply. It is the responsibility of the waste generator to evaluate whether his wastes are hazardous by characteristics or listing.

CONTAINER DISPOSAL
Containers should be cleaned of residual product before disposal. Empty containers should be disposed of in accordance with all applicable laws and regulations.

SECTION 14. TRANSPORT INFORMATION

SHIPPING DESCRIPTION
Flammable liquid, n.o.s. (contains ethyl silicate and ethyl alcohol)
Class 3, UN 1993, PG III

US DOT EMERGENCY 1993 GUIDE NO. 27
NAERG GUIDE NO. 128

Material Safety Data Sheet

DATE PRINTED: 8/3/2004 PAGE 8
SILBOND 40 MSDS NO. 004

SECTION 14. TRANSPORT INFORMATION (continued)

REQUIRED LABEL(S)
Flammable liquid

ENVIRONMENTAL HAZARDOUS SUBSTANCE
This product does not contain an environmentally hazardous substance nor marine pollutant per 49 CFR 172.101 Appendix.

SECTION 15. REGULATORY INFORMATION

EXPOSURE LIMITS/REGULATORY INFORMATION
(IN MG/M3)

SUBSTANCE DESCRIPTION	REG. AGCY	PEL	TLV	TWA	STEL	CEIL
Ethyl Silicate	OSHA	850	N/D	N/D	N/D	N/D
	ACGIH	N/D	85	N/D	N/D	N/D
	NIOSH	N/D	N/D	85	N/D	N/D
	SUPPLIER	N/D	N/D	N/D	N/D	N/D
LISTED ON THE FOLLOWING: DSL	MA LIST NJ R-T-K	PA LIST TSCA MITI 2-2048				
Ethanol	OSHA	1900	N/D	N/D	N/D	N/D
	ACGIH	N/D	1880	N/D	N/D	N/D
	NIOSH	N/D	N/D	1900	N/D	N/D
	SUPPLIER	N/D	N/D	N/D	N/D	N/D
LISTED ON THE FOLLOWING: DSL	MA. LIST NJ R-T-K	PA. LIST TSCA CAA 111 MITI 2-202				
Ethyl Polysilicates	OSHA	N/D	N/D	N/D	N/D	N/D
	ACGIH	N/D	N/D	N/D	N/D	N/D
	NIOSH	N/D	N/D	N/D	N/D	N/D
	SUPPLIER	N/D	N/D	N/D	N/D	N/D
LISTED ON THE FOLLOWING: DSL	PA. LIST TSCA MITI 7-486					

LEGEND:

EXPOSURE LIMIT DESCRIPTIONS

CEIL	Ceiling Exposure Limit
PEL	Permissible Exposure Limit
STEL	Short Term Exposure Limit
TLV	Threshold Limit Value
TWA	Time Weighted Average

REGULATORY LIST DESCRIPTIONS

CAA 111	Clean Air Act Sect. 111
CAA 112	Clean Air Act Sect. 112
CERCLA	CERCLA Hazardous Substances
DSL	Domestic Substance List-Canada
IARC	IARC Carcinogens-Grps. 1,2A,2B
MA LIST	Massachusetts Substance List
NDSL	Non-Domestic Subst. List-Canada
NJ R-T-K	New Jersey R-T-K Hazard. Sub.
PA. LIST	Penn. Hazardous Substance List
PROP 65	California Proposition 65
SARA 302	SARA Title III , Section 302
SARA 313	SARA Title III , Section 313
TSCA	Toxic Subst. Cont. Act - listed
MITI	Japanese MITI list
N/D	Not Determined

Material Safety Data Sheet

DATE PRINTED: 8/3/2004 PAGE 9
SILBOND 40 MSDS NO. 004

SECTION 16. OTHER INFORMATION

GENERAL:

CREATED BY
Product Stewardship Group

REVISION NO. 004

OTHER INFORMATION
No other information is available.

WHMIS HAZARD CLASS B-2, D2B

HAZARD RATING SOURCE HMIS

HEALTH 0 **FLAMMABILITY** 3

REACTIVITY 0 **OTHER**

REVISION CHANGE(S):

1. Change Emergency Contact Name to Carl McClaughlin

YELLOW BAR SAND
Specifications
Provided by: Cava Building Supply
January 2006

Dun - Rite

SAND AND GRAVEL COMPANY

OFFICE AND MAILING ADDRESS
573 East Grant Ave.
Vineland, New Jersey 08360-2520
Phone # (856) 692-2520
Fax # (856) 692-1105

Plant # 3
Jackson Rd.
Monroe Twp., NJ 08094
Phone # (609) 561-2013
Fax # (609) 561-9164

Plant # 4
Mays Landing RD.
Vineland, NJ 0836[illegible]
Dispatch (856) 825-9900
Fax # (856) 825-9050

Test taken on May 13, 2005

Cava Building Supply
Attn : Dominic

Re; ASTM C-144
Project:

Gentlemen :
This letter is our certification that the Bar sand supplied by Dun-Rite Sand & Gravel Co. to your company meets Astm C-144, and Penn Dot's Table A Fine Aggregate Type C specifications;

The following gradation is listed below: (Plant #4)

BAR SAND ([illegible] lds.)

SIEVE	% PASSING
4	100
8	100
16	99.7
30	72.4
50	32.2
100	2.9
200	.1

Material inorganic and non plastic

If there are any further questions, feel free to contact me at (856) 825-9900 .

Respectfully yours

Ronald Pusloski
Sales Manager

YELLOW BAR SAND
Specifications
Provided by: Cava Building Supply
January 2006

DUN - RITE

SAND AND GRAVEL COMPANY

OFFICE AND MAILING ADDRESS
573 East Grant Ave.
Vineland, New Jersey 08360-2520
Phone # (856) 692-2520
Fax # (856) 692-1105

Plant #3
800 Dutch Mill Rd
Monroe Twp. NJ 08094
Phone # (609) 561-2013
Fax # (609) 561-9164

Plant #4
3765 Mays Landing Rd
Vineland, NJ 08361
Dispatch (856) 825-9900
Fax (856) 825-9050

Material Safety Data Sheet
March 18, 2005

Cava Building Supply
Att: Dominic

Re: Bar Sand
Project: (lds) Plant #4

Item: Crystalline Silica Chemical Components: Silica, Crystalline Quartz (resipirable) Compisition: SiO_2: 95 %	/ Physical / Chemical Characteristics / Boiling Point: 4046F / Specific Gravity: 2.65 / Melting Point: 3050F / Vapor Pressure: none / Evaporation Rate: none / Vapor Density: none / Solubility in Water: insoluble / Appearance: White, Tan, Orange or Brown / Odor: No taste or odor
Permissable Exposure Limits: Exposure airborne crystalline shall not exceed an 8 hour time weighted average(TWA) limit as stated in 29CFR1910.1000	/ Flammable Limits: Material Non Flammable to / Reactivity Limits: Material Non Reactive / Material does not react to skin or ingestion, but may be harmful if inhaled. / Use of respirator is recommended for extended usage / Control Measure: Keep dust down –use of fan, water or ventilation system

Steps to be taken in case material is released or spilled: Use dustless methods, water or wet HEPA-type vacuum, if not contaminated. Use water sprays and shovels to clean up spills. Do not dry sweep with broom, do not use compressed air. Dispose in accordance with federal, state and local regulations.

The information contained in this safety data sheet is believed to be correct. Dun – Rite Sand & Gravel makes no warranties and assumes no liability in connection with any use of this information. Users of this product must comply with all applicable federal, state and local regulations and must seek professional opinions regarding their use and hazards.

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GLOSSARY

Absorption – it is the assimilation of fluids into interstitial spaces

Additive –Any material other than basic components of a grout system

Adhesion – it is the bond strength of the unlike materials

Bearing stress – it is the applied load divided by the given area

Bond Strength – it is the resistance to separation of set grout from other materials with which it is in contact; a collective expression for all forces such as adhesion, friction and longitudinal shear

Cohesion – it is the interparticle attraction in a soil mass, relatively independent of soil loads

Compatibility – it is the collective expression used for defining the state of complimentary physical chemical and mechanical properties of two or more different materials.

Composite – it is the expression for engineered materials or structures made from two or more constituent materials with significantly different physical or chemical properties than the complete structure.

Consolidation – the process whereby particles are packed more closely by the application of continued pressure.

Cure time – the interval between combining all grout ingredients or the formation of a gel and a substantial development of its potential properties.

Deformability – it is a measure of the elasticity of the grout to distort in the interstitial spaces as the sediment moves.

Detachment – it is the intra layer separation between the outer cobble layer and the inner puddled earth matrix.

Deformation – it is the change in shape of a material or structure due to an applied force. This can be a result of tensile, compressive, shear or bending forces. It is often described in term of strain.

Differential movement – it is the relative movement of different parts of a structure caused by uneven sinking of the structure.

Ductile – it is the capability to be stretched or deformed without fracturing

Durability – it is the ability of a material, component, assembly, or building to resist weathering action, chemical attack, abrasion, and other conditions of service.

Flexural strength – it is also known as modulus of rupture, bend strength, or fracture strength. Flexural strength is measured in terms of stress, and thus is expressed in pascals (Pa) in the SI system

Grout – a thin mortar containing a considerable amount of water so that it has the consistency of a viscous liquid in order to be poured or pumped into joints, spaces, and cracks within masonry systems.

Homogeneity – it is the state of equilibrium of masonry with voids cracks and pores achieved by the use of a filling material.

Injectability – it is the property of a grout used to define its ability to be injected into the masonry system.

Injection Grouting - the process of injecting fluids that set into cracks or voids used commonly to consolidate or strengthen a structural system.

Mechanical Strength – it is a collective for the overall mechanical behavior of a material (such as stress, deformation, strain and stress-strain relations). Strength is considered in terms of compressive strength, tensile strength, and shear strength, namely the limit states of compressive stress, tensile stress and shear stress respectively.

Modulus of elasticity – the ratio of the unit stress to the corresponding unit of strain in an elastic material that has been subject to strain below its elastic limit.

Micro crack – crack caused by the result of differential ambient conditions to earthen material or simply because of restraint of shrinkage.

Permeability – the property of a porous material that permits the passage of water vapor through it.

Porosity – a ratio, usually expressed as a percent of the volume of voids in a material to the total volume of the material, including the voids. The voids permit gases or liquids to pass through the material.

Reinforcement – it is the material used to induce strength in a masonry system

Rheology – the science dealing with flow of materials, including studies of deformation of hardened concrete, the handling and placing of freshly mixed concrete, and the behavior of slurries, pastes, and the like.

Seismic – of or caused by an earthquake.

Shear – a deformation in which parallel planes slide relative to each other so as to remain parallel.

Shrinkage crack – a crack caused by restraint of shrinkage.

Stress – it is the internal distribution of force per unit area that balances and reacts to external loads applied to a masonry. it is often broken down into its shear and normal components as these have a unique physical significance.

Strain – it is the deformation caused of a material by stress.

Tension – the state or condition of being pulled or stretched.

Tensile strength – the resistance of a material to rupture when subject to tension; the maximum tensile stress, which the material can sustain

Unreinforced masonry – it is the type of masonry where the reinforcement systems occupy less that 25% of the wall surface area.

Viscosity – the internal frictional resistance exhibited by a fluid in resisting a force that tends to cause the liquid to flow.

Wythe – each continual vertical section of wall, one masonry unit in thickness.

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