# PERFORMANCE EVALUATION OF CLAY GROUT FORMULATIONS FOR STRUCTURAL CRACKING IN HISTORIC EARTHEN (MUD BRICK) BUILDINGS

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To my loving family,
without whose support I would
not have made it this far…..

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# CHAPTER 1: HISTORIC EARTHEN CONSTRUCTION

## Mud brick as a building material

Traditional mud bricks are hand molded sun-dried blocks that are made of natural or modified soil containing sand, clay, fibrous material and water to achieve a plastic consistency and hard set.

The addition of fibrous material in the form of dry straw or grass as an additive helps to ensure uniform shrinkage of the mud brick during drying resulting in less warping. Shapes and sizes will vary according to local traditions; however most mud bricks are hand sized rectangular prisms molded by stiff mud in wooden forms, tamped and leveled by hand. The bricks are then demolded, covered with straw and placed on a level surface to further dry. After several days of drying, the adobe bricks are further air dried by turning for a period of four weeks or longer.[1]

## Mud brick construction as a building system

Mud brick construction can be characterized as a technique that is low cost, derived from materials that are locally available, and can be performed with relatively simple technical knowledge. Mud brick construction has two inherent performance characteristics: energy absorption that helps provide good thermal insulation and the ability to form thick load bearing walls. Compared to fired brick, mud brick exhibit low strength-carrying capacity and the inability to resist tensile stresses like most masonry materials.

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[1] Dan Babor and Diana Plian; The preservation of Adobe buildings. Buletinul Institutului Politehnic Din Iasi. Publicat de Universitatea Tehnica, Gheorghe Asachi din Iasi Tomul LVI (LX), Fasc. 1, 2010. Sectia. Constructii Arhitectura

Due to their method of manufacture, mud bricks do not permanently harden, thus remaining vulnerable to moisture. This will affect the strength of the mud brick, i.e. the higher the water content, then lower the strength of the block. Mud bricks are generally laid with mud mortar usually composed of similar material and exhibiting similar properties as the bricks. The mortars are relatively weak and susceptible to hygroscopic swelling and shrinking, thermal expansion and deterioration. In recent times, cement and lime mortars have been used as mortar for stabilized mud bricks but cement mortar and unstabilized mud bricks are incompatible materials in terms of moisture absorption and sensitivity as well as thermal expansion rates which suggest that the use of cement mortar will accelerate the deterioration of mud bricks.[2] When the stresses exceed the tensile capacity of the earthen walls, shear and flexural stresses will cause the earthen walls to crack. Cracking leads to the loss of the monolithic character of the earthen wall. The structural limitations of earthen walls and their failure can occur due to the following reasons:-

- Internal loads from structural members,
- settlement of the foundation, and
- seismic forces

## Importance of preserving earthen buildings

The majority of historic earthen buildings and sites are found in regions such as Latin America, Africa, some parts of Asia, the Middle East and southern Europe, all prone to seismic activity which leaves these building at high risk of damage and collapse. Historic earthen structures like the township of New Gorna in Egypt, the archaeological site at Catal Huyuk in Turkey, the palace at Birket Muz in Oman, the medieval castle in Faraj, Iran and the Alhambra in Spain are

[2] Ibid

a few culturally significant sites that are all at risk from damage and collapse due to seismic activity. It is therefore important to safeguard these buildings through continual repair and maintenance rather than replacement while simultaneously preserving their authenticity.[3]

## Fragility in earthen construction

Earthen structures in general are very durable and long lasting; however, exposure to a few common agents makes the material fragile and prone to failure. These are:-[4]

- Thermal movement
- Water penetration
- Plant growth
- Human agency and animal activity
- Wind

The capacity of mud brick walls and vaults to withstand loads exerted during seismic activity depends on the high mass and density of the masonry although low tensile strength will lead to rupture and cracking frequently observed in the material.[5] However, seismic performance greatly depends on the monolithic behavior of the earthen structure where the good condition of the structural elements and continuity between different connections and junctions present in the building system are essential.[6]

[3] M. Blondey and G.V. Garcia M; Adobe Construction, Catholic University of Peru, Peru
[4] John Warren, Conservation of Earth Structures, Butterworth Heinemann, 1999
[5] H Varum, N. Tarque, D. Silveira, G. Camata et. Al, Structural Behavior and Retrofitting of Adobe Masonry Buildings
[6] R.A.Silva, L. Schueremans, D.V. Oliveira, et.al; On the development of unmodified mud grouts for repairing earth constructions: rheology, strength and adhesion, 2012

# CHAPTER 2: CRACKING AND FAILURE

## Crack formation and types of cracks

Cracking is a phenomenon that occurs constantly throughout the life cycle of a building. It occurs both at the macro and micro level as it responds and tries to accommodate the changes in its surrounding environment due to movement.[7] Almost all the parts of a building are subjected to continuing size changes - expanding or contracting as the material responds to different causes of movement in nature. Depending on the cause of cracking and the extent of intervention needed to be carried out, the crack can be characterized to be reversible or irreversible in character.[8] The following causes are a few of the generic reasons that cause movement and lead to the development of different types of cracks, they are:

- Ground movement
- Foundation failure
- Decay of superstructure
- Moisture movement
- Thermal movement
- Inherent defects
- Inappropriate specification
- Deflection under load

Cracks are generally caused due to dimensional changes. The cracking mechanism generally starts with the development of strain within the unit material or building assembly which leads to distortion and failure. The extent of damage caused in a building will depend on the

[7] Jim Allen, Cracking - Online article; http://www.buildingconservation.com/articles/cracking/cracking.htm

[8] R B Bonshor, L L Bonshor; Cracking in Buildings, Construction Research Communications Ltd. 1996

width of the crack generally characterized as hairline cracks, fine cracks, moderate cracks, and structural cracks.

| Category of damage | Description of typical damage<br>*Ease of repair in italic type* |
|---|---|
| 0 | Hairline cracks of less than about 0.1 mm which are classed as negligible.<br>*No action required.* |
| 1 | Fine cracks which can be *treated easily using normal decoration.* Damage generally restricted to internal wall finishes; cracks rarely visible in external brickwork. Typical crack widths up to 1 mm. |
| 2 | *Cracks easily filled. Recurrent cracks can be masked by suitable linings.* Cracks not necessarily visible externally; *some external repointing may be required to ensure weather-tightness.* Doors and windows may stick slightly and *require easing and adjusting.* Typical crack widths up to 5 mm. |
| 3 | Cracks which *require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced.* Doors and windows sticking. Service pipes may fracture. Weather tightness often impaired. Typical crack widths are 5 to 15 mm, or several of, say, 3 mm. |
| 4 | Extensive damage which requires *breaking-out and replacing sections of walls,* especially over doors and windows. Windows and door frames distorted, floor sloping noticeably*. Walls leaning or bulging noticeably*, some loss of bearing in beams. Service pipes disrupted. Typical crack widths are 15 to 25 mm, but also depends on number of cracks. |
| 5 | Structural damage *which requires a major repair job, involving partial or complete rebuilding.* Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are greater than 25 mm, but depends on number of cracks. |

* *Local deviation of slope, from the horizontal or vertical, of more than 1/100 will normally be clearly visible. Overall deviations in excess of 1/150 are undesirable.*

Table 1: Categorizing typical damages observed in masonry buildings
Source: R B Bonshor, L L Bonshor; Cracking in Buildings

Various aspects like material technology, cause of failure, mechanism of cracking, and performance consequences of cracks lead to the formation of different types of cracking patterns.

Material technology plays an important role in the manner in which the change in crack size can be distinguished; they can be due to thermal movement, moisture movement or chemically induced reactions. Other than the characteristics of the material, building technology, i.e., the placement of building components within different assemblies, has an important role to play in how the building performs under different conditions and how significant forces develop due to dimensional changes. In the case of earthen buildings, the building units i.e., mud brick, are quasi brittle in character and are generally bound together with mortar that is essentially made of the same soil that constitutes the mud brick. So when the mud brick structures fail, this leads to unit masonry cracking and step form cracking.

The heterogeneity of the material causes inherent micro cracks as part of the manufacturing technique which can cause the material to fail due to internal crack growth when overloaded. Similar failure occurs at the joint between the brick and the mortar where the mortar develops micro cracks during the process of construction due to drying shrinkage which remain stable until the load on them increases.[9]

## Failure observed in earthen buildings in seismic areas

In historic earthen buildings formation of cracks is inevitable because of the heterogeneous nature of the material that is used to design the buildings. Although temperature change, moisture and chemically induced size changes do cause cracking in earthen historic buildings,

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[9] R.J Groenenberg, Theses, Adobe structures in earthquake zones: Experimental study on the repair of adobe constructions damaged by earthquake loading and the development of an ATENA-GiD model to simulate shaking table tests for these structures.

the major cracks that develop in this unreinforced masonry are due to the vibrational damage mainly caused by earthquakes.

The walls of the adobe masonry buildings are the main structural elements that bear the entire load. The presence of clay in the soil helps keep all the components of the mixture bound together and also helps bear compressive loads. The thickness of the walls gives the wall the ability to resist gravitation loads which helps keep the adobe walls stable. [10] But during earthquakes, the thickness of the earthen walls generates forces of inertia within the walls that produce tensile stress which, due to the brittle nature of the mud brick, result in material failure and cracking.

Many kinds of cracks form in earthen masonry walls. They could be vertical, horizontal or diagonal; formed due to tension, compression or shear stresses on different sections of wall.

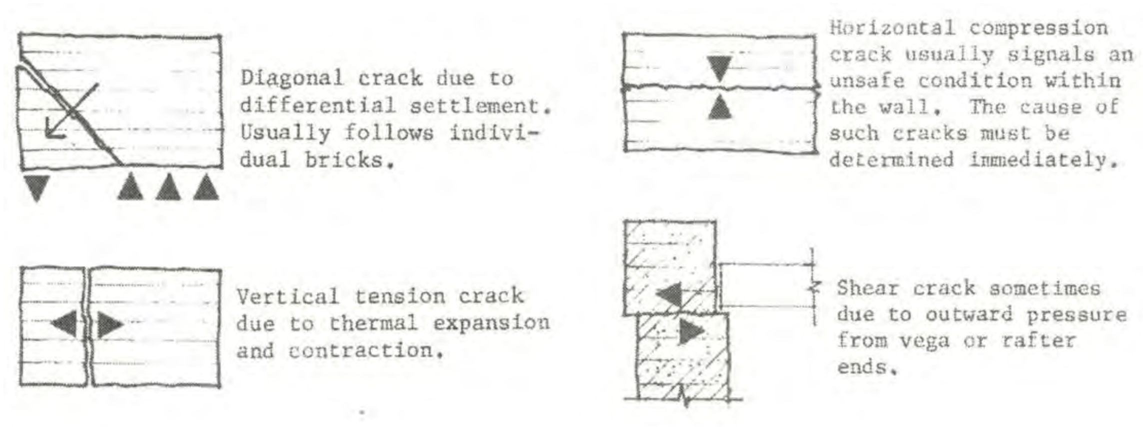


Figure 1: Typical cracks in adobe walls
Source: Practical and technical aspects of adobe construction

[10] Ibid

The extent of damage to a mud brick building depends on the following reasons:-[11]

- Severity of the ground motion during the earthquake
- The integrity of the adobe masonry
- The geometry of the building with respect to its configuration of the openings
- The efficiency and presence of various seismic retrofit measures
- The condition of the building during earthquake

## Collapse mechanism in earthen masonry building

When earthen buildings are subjected to earthquakes, there are three kinds of forces that lead to the different types of failure mechanisms observed: tensile forces, shear forces and flexural forces.[12] Each force affects the mud brick walls in between ways leading to crack patterns that vary depending on the force subjected on the wall .

| Type of stresses exerted on mud brick wall | Crack patterns developed |
| --- | --- |
| **In-plane tensile stresses** | Diagonal cracking, corner cracking, cracks that develop at the openings |
| **Out-plane flexural stresses** | Perpendicular wall junction failure, gable wall collapse, separation damage and wall rocking |
| **Strong ground motion** | Overturning of gable end walls |

Table 2: Different stresses exerted on mud brick walls and crack patterns formed
Source: Earthquake damage to historic and older adobe buildings during the 1994 Northridge

[11] F.A. Webster and E.L Tolles, Earthquake damage to historic and older adobe buildings during the 1994 Northbridge, California Earthquake.
[12] Dandona, Bhavna. "Evaluation of Repair Methods for Structural cracks: Early period Monastic Architecture, Ladakh Case: Mangyu Monastery.."MSc Thesis., University of Pennsylvania, 2006.

Masonry walls that are made up of mud bricks have very low tensile strength, hence when subjected to high tensile stresses they generally crack.[13] Overturning of gable end walls is one such damage mode that is generally observed in historic mud brick buildings that are subjected to out of plane flexural damage and strong ground motion due to severe earthquake. This damage mode generally occurs in walls that have a slenderness ratio less than 5 and are not supported or anchored well to the roof diaphragm.

Following are some other types of damage states that generally can be observed when earthen buildings are subjected to an earthquake:-[14]

- Diagonal cracking
- Perpendicular wall junction failure
- Gable-wall collapse
- Out-of-plane flexural damage
- Tie-rod anchorage failure
- Separation damage
- Horizontal upper-wall damage
- Wall mid-height flexural damage
- Corner crack damage
- Crack damage at openings
- Moisture damage

[13] N. T. Ruiz, G. Camata, E. Spacone, H. Varum and M. Blondet. Elastic and inelastic parameters for representing the seismic in-plane behavior of adobe walls.
[14] Ibid

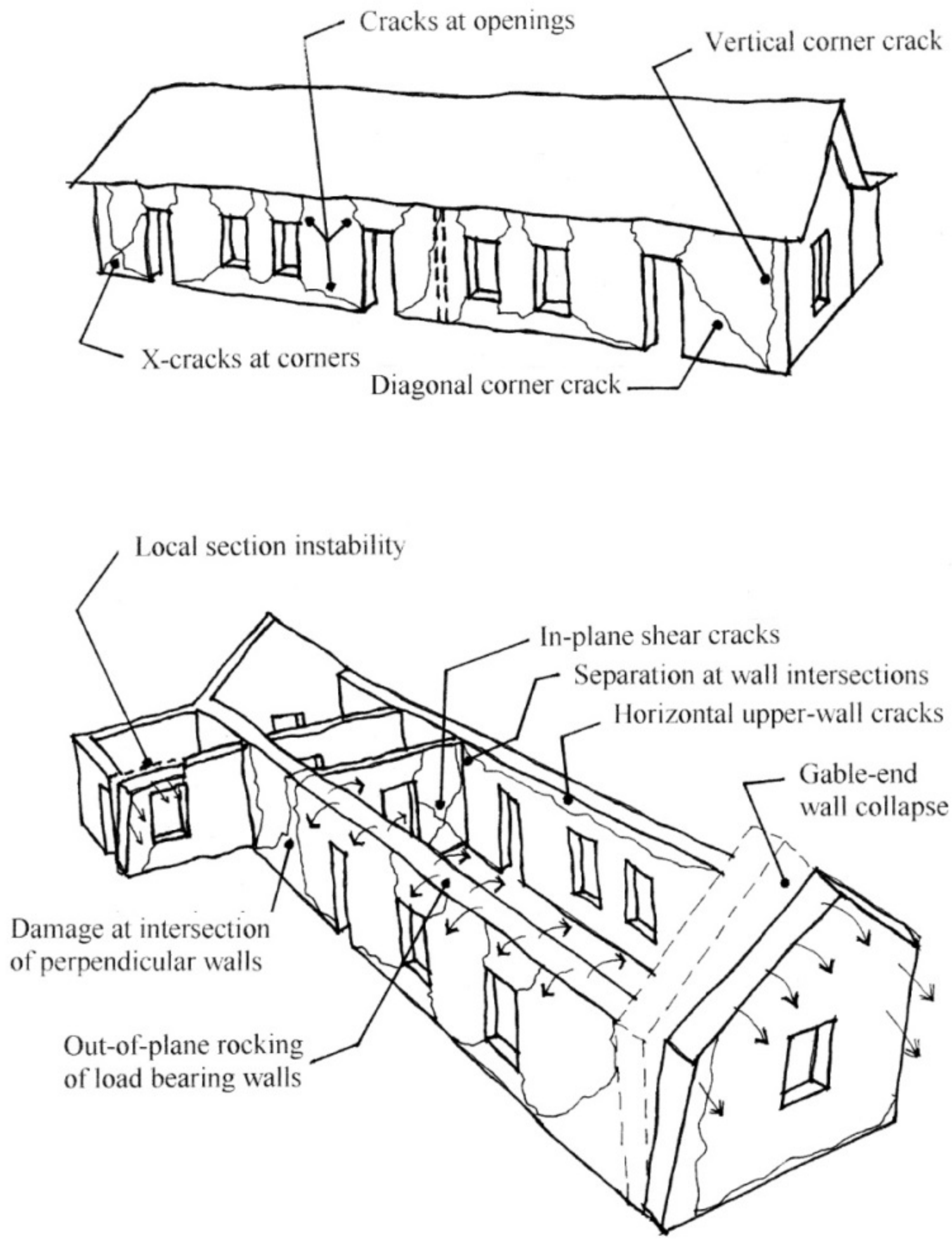


Figure 2: Types of damage states observed in historic earthen buildings
Source: Earthquake Damage to Historic and Older Adobe buildings
during 1994 Northridge, California Earthquake
(Webster and Tolles, 2000)

# CHAPTER 3: LITERATURE REVIEW

## Terminology

*Adobe Soil (Soil)* – A term applied to clay and silt deposits which usually occur in the basin areas and when mixed together in a proper balance of clay, silt and sand insure the production of quality adobe bricks.[15]

*Traditional Adobe bricks (mud bricks)* – Often referred to as untreated, unstabilized or standard sun-dried adobe bricks, the traditional adobe is made with soil composed of a uniform mixture of clay, sand and silt. Usually straw is added to the adobe bricks to prevent the bricks from cracking while being cured.[16]

*Binder* - A binder is defined as the material which impart to the grout properties like cohesion and adhesion which play important role in bonding the small fragments into a coherent mass.

*Grout* - The injection of fluid mortars or adhesives to fill unwanted voids and to re-adhere detached materials.[17]

## Current practices of preserving earthen buildings

As part of the ongoing effort to develop innovative techniques to preserve culturally significant historic earthen buildings in earthquake prone regions, experts have been observing building performance after earthquakes, recording conditions, and proposing recommendations as to how various issues can be tackled.[18] Many organizations like CRATerre

[15] Smith E.W. Adobe brick production in New Mexico, New Mexico Geology Science and Service. Vol 3. No. 2 May 1981.
[16] Ibid
[17] Frank Matero, A program for the conservation of architectural plasters in earthen ruins in the American Southwest. Fort Union National Monument, New Mexico, USA. *Conservation and Management of Archaeological Sites Vol 1*. 1995, P-18
[18] Mary Hardy, Claudia Cancino, and Gail Ostergren, "Proceedings of the Getty Seismic Adobe Project 2006

and the Getty Conservation Institute's Earthen Architecture Initiative are working towards improving ways and means by which preservation of earthen architecture is conducted worldwide. Initiatives by nonprofit organizations like the Getty Seismic Adobe Project (GSAP) have been conducting research to better understand the deterioration of historic earthen buildings due to seismic damage and especially crack development.

Preserving deteriorated adobe buildings is most successful when the techniques and modes of restoration and repairs are as similar as possible to original construction and interventions minimize the risk of developing more new cracks. In order to re-introduce strength and stiffness into the cracked load bearing earthen walls and ensure that these discontinuities do not further propagate damage, various repair techniques can be incorporated.[19] Some of these repair techniques are soft stitching, introduction of tensile reinforcement to repair structural cracks, external buttressing, filling with mortar, partial rebuilding and low pressure grouting techniques. [20]

### Why grouting?

Grouting is one of the many repair techniques that can be introduced in order to reinforce structural stability into the cracked earthen structure with minimal disruption. It has lately been considered as a very reliable and feasible solution to consolidate historic masonry

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Colloquium," Getty Conservation Institute Publications, (Los Angeles: 2009) http://www.getty.edu/conservation/publications_resources/pdf_publications/gsap.html.

[19] Tolles, E.L. Webster F.A., Crosby A. and Kimbro E.E. Survey of Damage to Historic Adobe buildings after the January 1994 Northridge Earthquake. The Getty Conservation Institute Scientific Program Report, Los Angeles.

[20] Warren, J. Conservation of Earth Structures, Butterworth Heinemann, 1999
Dandona, Bhavna. "Evaluation of Repair Methods for Structural cracks: Early period Monastic Architecture, Ladakh Case: Mangyu Monastery.." master\., University of Pennsylvania, 2006.

structures. [21] Grouting can be defined as the injection of fluid mortars or adhesives to fill unwanted voids and to re-adhere detached materials.[22] A grout generally is comprised of three basic elements: binder, aggregate and dispersant (in most cases water).[23] It is formulated in a way that the elements are balanced and exhibit desirable properties that are necessary for an intervention to be successful.

Depending on the architectural practices prevalent in the region, many earthen buildings have earthen or lime based plasters applied on their surface to protect the earthen structure from deterioration. And in some special cases these plaster surfaces can have valuable wall paintings or relief work on them which make them as valuable and culturally significant to the building and its history as any other architectural feature. But when such structures are damaged from earthquake activity, structural wall cracks and plaster detachment can occur requiring non-invasive repair.[24] In such situations access to a crack may not be possible from the other side of the wall and other repair strategies such as pinning and stitching cannot be conducted due to the presence of wall painting or plaster on the wall. [25] The aim of such a grouting intervention is to re-establish the monolithic character of the cracked earthen wall by low-pressure injection of a liquid grout that can be incorporated to structurally strengthen the wall while safeguarding the significant artwork on the plaster of the mud brick structures. This method of grouting the wall with low pressure injection would help introduce controllable amounts of grout into the original fabric where needed while maintaining a high degree of

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[21] R. A. Silva, L. Schueremans and D.V. Oliveira, On the conservation of the Earthen built heritage: Mud grout Injection. 2010

[22] Frank Matero, A program for the conservation of architectural plasters in earthen ruins in the American Southwest. Fort Union National Monument, New Mexico, USA. *Conservation and Management of Archaeological Sites Vol 1*. 1995, P-18

[23] Interdisciplinary Experts Meeting on Grouting Repairs for Large-scale Structural Cracks in Historic Earthen Buildings in Seismic Area. The Getty Conservation Institute. August 13-16, 2007

[24] Cases similar to an ongoing GCI Earthen initiative project of Kuno Tambo Church in the Peruvian Andes.

[25] Interdisciplinary Experts Meeting on Grouting Repairs for Large-scale Structural Cracks in Historic Earthen Buildings in Seismic Area. The Getty Conservation Institute. August 13-16, 2007

flexibility for re-treatment if necessary in the future.[26] The applied grout to reconnect masonry discontinuities would act as an energy absorber during seismic events, inducing generation of a crack in the grout rather than the wall itself, if and when the cracks reopen.[27]

To evaluate whether the formulation of a grout is suitable for the repair of cracked mud brick walls, the following performance criteria (optimal properties) were identified for testing and evaluation:-[28]

- Ease of mixing and injection
- Adequate viscosity in the liquid phase to fill voids by low pressure injection
- Minimal segregation and stability in composition until set
- Reasonable setting time to resist displacement and allow proper cure
- Minimal shrinkage between the liquid and solid state
- Low weight
- Moderate strength within the range of the historic material
- Adequate water vapor permeability to prevent moisture accumulation
- Gap filling potential with good adhesive bonding to the adhered surfaces
- Low toxicity and material compatibility

The aim of grouting seismic cracks in earthen walls is to re-establish material continuity and integrity of the original masonry and thus reduce further and future vulnerability to further

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[26] Claudia N. Cancino and Frank G. Matero, *Assessment of Grouting methods for cracks and Large – Scale Detachment Repairs Casa Grande National Monument*. 9th International Conference on the study and Conservation of Earthen Architecture. Terra 2003

[27] Interdisciplinary Experts Meeting on Grouting Repairs for Large-scale Structural Cracks in Historic Earthen Buildings in Seismic Area. The Getty Conservation Institute. August 13-16, 2007

[28] Bass, Angelyn. "Design and Evaluation of hydraulic lime grouts for in situ reattachment of lime plaster of earthen walls.." master\., University of Pennsylvania, 1998.

damage. Since grouting has a very limited strengthening ability, it is generally considered as a repair technique instead of a seismic retrofit intervention.[29]

## Material Compatibility

This research explores questions related to the formulation of a grout for the repair of cracks in mud brick structures in terms of material availability, minimal strength requirements, and overall durability. Since the structures in question are made of earth, material compatibility of the grout would logically appear to be based on the use of a similar material-in this case local soils, although probably modified. But in order to do so, first the earthen building materials must be analyzed, their soil characterized, so that a grout formulation can be designed. The use of mud grouts to fill cracks in earthen walls ensures good cohesion between the hardened grout and the cracked mud brick structure and a similar response to stresses avoiding differential damage. Also the modulus of elasticity of materials such as cement and lime are sufficiently different mud brick so their introduction can alter the manner in which the earthen wall will move in the event of an earthquake. Evaluation reports of post-treatment damage of walls repaired with cement and other high strength materials confirms the fallacy of the use of cement and polymers for crack repair of masonry and earthen buildings in seismic areas.

## Published Literature on earthen grout

There is a recent and substantial literature on the use of grouts to consolidate historic masonry; however, there is limited published research on grouting earthen buildings.[30]

[29] Interdisciplinary Experts Meeting on Grouting Repairs for Large-scale Structural Cracks in Historic Earthen Buildings in Seismic Area. The Getty Conservation Institute. August 13-16, 2007

Most of these publications agree with the idea of incorporating some amount of soil into the grout but they rely equally on the idea of using additives such as lime and cement to act as the binder component of the grout and to stabilize or eliminate the swelling of clays and thus the instability that is evident in unamended earthen grout mixtures.[31] There are two kinds of earthen grouts that can be prepared and used for repairing cracks with grout – *amended earthen grout* that uses lime or other binders or additives within the grout mixture and *unamended earthen grout* that uses only the clay present within the soil as the binder. In order to assess and evaluate various formulations of the different types of earthen grouts proposed, various tests have been proposed and conducted including a full-scale shaking table and diagonal compressive wallet tests.

## Clay based grouts

A grout binder is defined as the ingredient which imparts cohesive and adhesive strength to the grout bonding the solid particulates together and the whole to the surfaces of the crack or void. In clay based grout, the type and amount of clay plays a major role in how the grout will behave especially in its fluid or working state. High clay content can provide strength to the

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[30] Silva, R A, DV Oliveira, P B Lourenco, L Schueremans, and T Miranda. *Experimental investigation on the repair of rammed earth by means of injection on mud grouts*. *Vernacular Heritage and earthen Architecture: Contributions for Sustainable Development*. Edited by Correia Carlos and Rocha. P-727

[31] Roselund N. Repair of cracked walls by injection of modified mud. In: Proceedings of the 6th International Conference on the Conservation of Earthen Architecture: Adobe 90 Preprints, Las Cruces, New Mexico, 1990, p 336 – 341

Jager, W. and Fuchs C. Reconstruction of the Sistani House at Bam citadel after the collapse due to the earthquake 2003, In: D'Ayala D. and Fodde, E. (Eds.) Preserving Safety and Significance, Proceedings of VI International Conference on Structural Analysis of Historic Constructions 2008, Vol. 2 Bath, p 1181 -87

Vargas J., Blondet M., Cancino C., Ginocchio F., Iwaki C. and Morales K. Experimental results on the use of mud-grouts to repair seismic cracks on adobe walls. In: D'Ayala D. and Fodde E. (Eds.) 2008

On Yee, L. Study of earth grout mixtures for rehabilitation, Msc Thesis, University of Minho, Guimaraes, Portugal 2009

R.A.Silva, L. Schueremans, D.V. Oliveira, et. Al On the development of unmodified mud grouts for repairing earth constructions: rheology, strength and adhesion. 2012 grout but as clay shrinks during its drying phase, shrinkage and the development of cracks will cause loss of strength in the adobe masonry. Research suggests that designing a mud grout is a complex task consideration of the following properties: rheology, fresh state stability, bond strength, chemical stability, microstructure, and moisture response.[32]

Current research on unamended mud grouts aims to understand the primary effect that clay has on earthen grouts. Recent research has studied the effect of the clay fraction on the rheology of the grout and conceptually details the association of drying shrinkage with the presence of clay and water as they interact to form grout.[33] In the research, tests were conducted on artificial soils made from kaolinite and crushed limestone powder that contribute towards understanding the effects of silt and clay on the rheology of the grout with respect to two variables - solid to water ratio and the addition of a deflocculant.

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[32] R.A. Silva, L. Schueremans and D.V. Oliveira; On the conservation of the earthen built heritage: Mud grout injection. 2012

[33] R.A.Silva, L. Schueremans, D.V. Oliveira, et. Al On the development of unmodified mud grouts for repairing earth constructions: rheology, strength and adhesion. 2012

# CHAPTER 4: METHODOLOGY

## Sample procurement: Traditional mud bricks

For the purpose of performing the various tests as part of this thesis, samples of mud brick were procured from a commercial manufacturer, New Mexico Earth Adobes, located outside Albuquerque, New Mexico. New Mexico Earth Adobes is one of the largest adobe (mud brick) manufacturers in the world. The yard produces mud bricks in the traditional way; they mix local soil with water into a mud mixture and carefully hand-pack it into wooden molds and then sun dry them. When the blocks are relatively dry they are turned on edge to complete the drying process of the bricks.[34] According to their website, they use screened local soil, water, straw and for one type of brick emulsified asphalt as an additive.. The company produces three types of mud bricks: *fully stabilized, semi stabilized, and unstabilized* adobes. The mud bricks purchased for thesis were unstabilized adobes manufactured at their yard and then shipped as a single pallet (42"x42"x27" tall with pallet weighing 1800 lbs.) to the Architectural Conservation Lab, School of Design at the University of Pennsylvania, Philadelphia.

## Quantification of mud bricks and sample storage

During the fall 2013 semester, a tentative test matrix was prepared which included many of the possible tests that would be performed to evaluate the performance of an earthen grout for the repair of structural cracks in historic earthen (mud brick) buildings. Since the premise of the thesis is to assess the suitability of local soil for the creation of an optimum mud grout

[34] New Mexico Earth Adobes, website, http://www.newmexicoearth.com/about/about_adobes.html

formulations, additional adobe bricks were also ordered as the main ingredient i.e. *soil* for the grout.

The pallet was delivered on 17th January 2014, and the shipment was immediately disassembled. The bricks where left uncovered, stacked in a Flemish bond pattern one on top of another to form a small stable tower in a store room within the School of Design; only two bricks were found broken.

**Sample preparation for sieve analysis:**

Three mud bricks were randomly chosen from the stack in order to characterize the soil used to prepare the bricks and to formulate the earthen grouts. The three mud bricks were first mechanically crushed by several means:

1) ***Rubber Mallet:*** In order to break the mud bricks into smaller fragments, the bricks were first hammered with the help of a rubber mallet. The use of the rubber mallet generates a sufficient amount of force necessary to break the large fragments into smaller fragments.

Figure 3: Mechanical crushing mud bricks
Source: Iyer 2014

2) ***Mortar and Pestle:*** In an effort to break the fragments down further, a mortar and pestle was used. During this process, a ceramic mortar and a pestle with a rubber tip and wooden body was used. This ensured that the process of grinding did not alter the original particle size of the soil used for the mud brick.

***Limitations and modifications:*** Due to the possibility of a high percentage of clay present in the soil used to make the mud brick, the crushed soil was further prepared with a Labmill 8000 Jar Milling Machine.

Figure 4: Using Mortar and Pestle to crush the sample
Source: Iyer 2014

3) ***Labmill Jar Mill Machine:*** The Labmill 8000 Jar Mill Machine displays a speed ranging from 20- 250 rpm with a maximum recommended load weight of 35 lbs. Labmill 8000 is a superior process of grinding contamination free samples within mill jars that vary from 500 ml to 1 gallon in volume. For the grinding process, a glass jar with an approximate volume

of 900 ml was filled equally with 6mm borosilicate glass beads and the soil fraction retained on the #30 sieve. Once the glass jar is almost half filled with both the soil mixture and borosilicate glass beads, three flat rubber bands are tied around the body of the jar equidistance from each other to ensure that the jar is levelled, in contact with the rolls and there is sufficient friction between the two for ease in the grinding process. This ensures that the glass jar rolls efficiently when placed on the mill machine. Once the machine was switched on, the glass jar was allowed to roll over the mill for a duration of 20 to 30 minutes after which the contents of the jar were emptied onto the #30 sieve to ensure that the clay blebs were successfully broken apart.

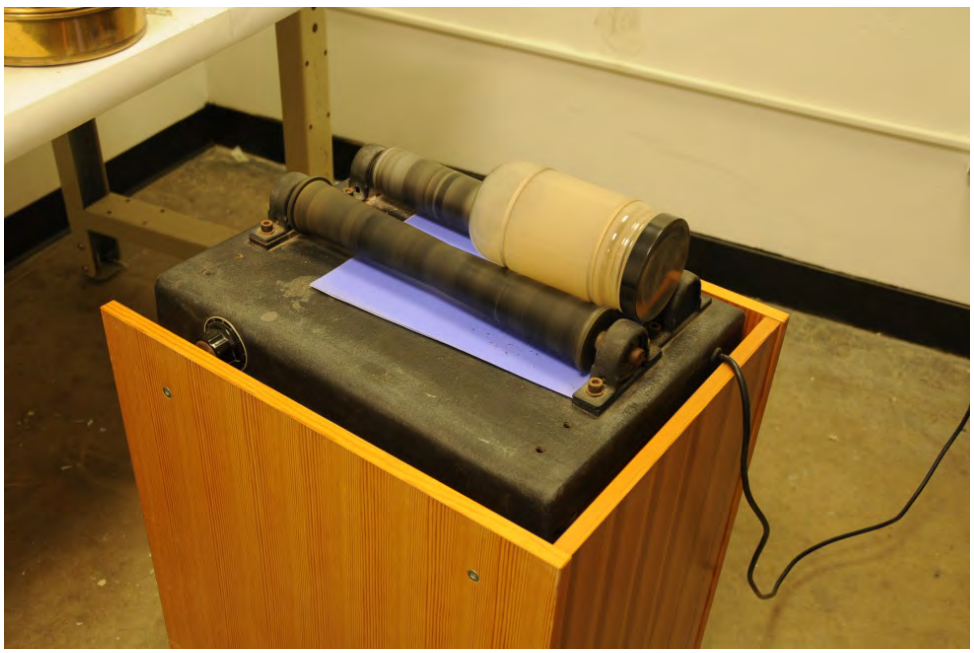

Figure 5: Labmill Jar mill machine to finely crush the sample
Source: Iyer 2014

## Testing Program

This research is based on the assumption that the same or modified soil as that used for a given earthen construction (e.g., mud bricks) should produce a compatible repair method assuming it can be used as a grout to reestablish the monolithic character of the wall. To determine if any given soil can be used as a grout, a test matrix of optimal grout properties was prepared. Obviously any repair method depends on compatibility of all the parts within a system, in this case, the mud brick, mud mortar and grout. Given available time, only the rheology of the grout was tested (Appendices B). This began with characterization of the soil used to make the mud bricks and its suitability as a grout.

***Characterization of mud brick:*** This phase of testing is to understand and quantitatively determine the particle size distribution (i.e., granulometry) of the soil used to make the mud brick. It will help identify the gravel, sand, silt and clay content and the presence of any organic matter. As part of this phase, a preliminary clay identification test was performed using methylene blue to identify the presence of swelling clays such as montmorillinite and smectite.

***Rheology of the grout:*** Rheology describes how a grout will flow before setting point is reached. This is indirectly related to a grout's injectability and its ability to penetrate through and to fill cracks. The test measures efflux time and viscosity of the grout when in liquid phase.

***Dry shrinkage and splitting tensile testing:*** Shrinkage is a critical property of any grout since it affects all other cured properties, especially strength. While strength can be measured in many ways, splitting tensile strength is the preferred test method for brittle masonry materials such as stone, concrete and soil. Although samples were made, they were not tested as part of the scope of this thesis, but will be stored for future testing.

## Mud Grout Design and Formulation

A good mud grout displays fluidity, low shrinkage, and bond strength equal to its own cohesive strength.[35] Four different mud grout formulations were prepared based on different water to solids ratios and the introduction of a de-flocculent, sodium hexametaphosphate.

***Sample testing:*** After determining the particle size distribution of the soil samples, small trials of grout were prepared with varying solids to water ratios to qualitatively observe flow and shrinkage. Three formulations were tested - 2:1, 2.2:1 and 2.4:1 (parts by volume). The following procedure was used to prepare all the samples:

- The samples were measured by volume to achieve the necessary ratio. The samples were added into a container repeatedly in moderate quantity to ensure that the fine soil particles were not lost.
- A stirring apparatus-a spatula was used to rigorously mix the sample for 3 minutes. After the sample was thoroughly mixed, it was immediately poured into an unglazed clay flower pot saucer (within one minute from when the sample was made).
- All the samples were set to air dry at room temperature and relative humidity which was monitored daily for one week. These were monitored for visual shrinkage.

***Grout Components:*** The grout formulations were designed to be aqueous and as low tech as possible given their probable use in rural areas with limited infrastructure. After preparing test samples of different solid to water ratios, it was decided that two different formulations would be tested.

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[35] R.A.Silva, L. Schueremans, D.V.Oliveira; *Grouting as a repair/strengthening solution for earth construction*

***Dispersant/ Deflocculant:*** Very recent research on the effects of a deflocculant on rheology, strength and adhesion was used as a model for the test formulations. The deflocculant sodium hexametaphosphate was added to the mixing water to test its effect on grout flow. A deflocculant helps orient the clay particles along the direction of flow thus reducing friction and viscosity. The deflocculant used in this case was a 2% concentration of sodium hexametaphosphate (HMP) mixed in water by volume.

***Binder and Aggregate:*** The granulometry of the soil used for the adobes displayed a good distribution ratio of sand, silt and clay content. This is important in controlling shrinkage and determining the size of the orifice used for grouting.

***Solid to water ratio:*** The soil that was used as the solid content in the grout formulation was first sieved to remove the coarsest particles retained on the #4 and #8 sieves. The larger aggregate was removed based on the injection orifice and assumed crack width. This sieved soil was then measured out in two proportions by volume, 2:1 and 2.5:1 solids to water content. This variation in solids to water content was chosen so that the effect of the solid content of the grout on its rheology and shrinkage could be observed.

***Formulations:*** Four different grout formulations were prepared and tested for rheology:-

| Sample | Solid content | Water content | Deflocculant (sodium hexametaphosphate) |
|---|---|---|---|
| **Sample A** | 2 | 1 | - |
| **Sample B** | 2 | - | 1 |
| **Sample C** | 2.5 | 1 | - |
| **Sample D** | 2.5 | - | 1 |

Table 3: Different grout formulations with variation in solid to water content and presence of a deflocculant

## Testing Sample Preparation

All the test samples prepared for the flow test were also used to prepare the samples for splitting tensile strength and shrinkage. All sieving to prepare the soil was done according to ASTM D422 and the STP 447 B Manual on Test sieving methods.

***Molds:*** The size and the material necessary to make the molds and their preparation before pouring varied according to the specific standards for each test.

- ***Splitting Tensile Strength test:*** The molds for this test were made using 2″ hollow PVC pipe that were cut to a height of 4″. A slit was introduced along the length of the mold to ensure that the grout samples demolded easily. This slit came in handy as this reduced the loss of samples during demolding. All the splitting tensile samples were mounted onto an acrylic sheet with the help of plumber's putty. An addition 2″ high cylindrical piece of 2″ PVC pipe was attached to the cylindrical mold so that probable sinking of samples could be accounted for. These molds were pre-lubricated with Vaseline gel on the PVC molds and with mineral oil on the base of the acrylic sheet to ensure that the grout did not stick to the molds or the base.

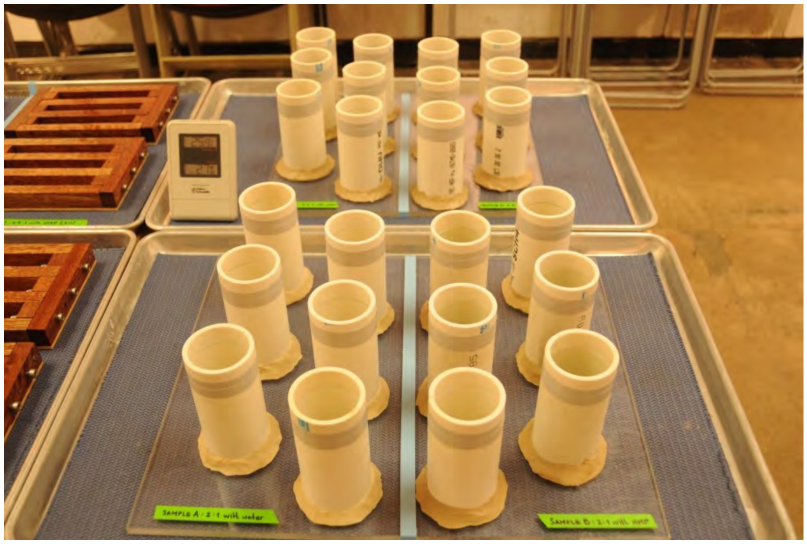

Figure 6: Custom made splitting tensile cylinders
Source: Iyer 2014

- ***Drying shrinkage test:*** The molds for this test were custom made using solid luan of varying shapes and sizes, and a base made from plywood lined with luan veneer on both sides. Each mold was designed to make 3 prism samples of 1″x1″x6-3/4″ dimension. All the different parts of the mold were assembled to screw together with 3/16″ stainless steel #6 flat head Philip screws. Each mold had two stainless steel Humbolt gauge studs set into the 1″x1″ ends of the prism. The gauge studs were set in place with the help of 3/16″ screw heads. These molds were pre-lubricated with mineral oil several times before the pour so that the mold was well soaked with mineral oil and thus would not draw out water excessively from the grout mixture.

Figure 7: Custom made drying shrinkage prisms
Source: Iyer 2014

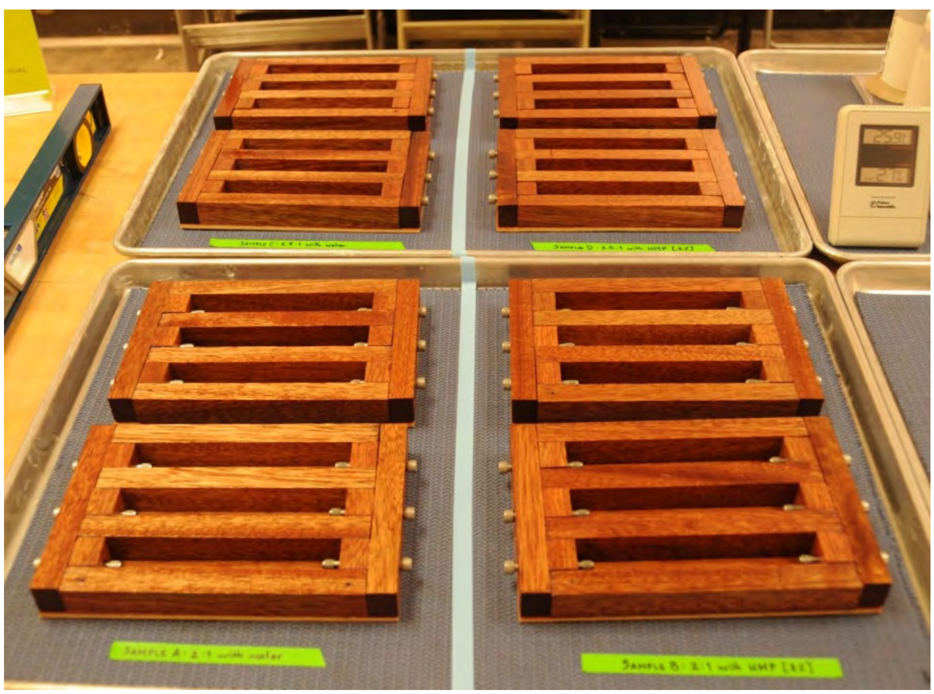

Figure 8: Pre-lubricated drying shrinkage prisms
Source: Iyer 2014

***Mixing:*** The grout was prepared within a work space at the Architectural Conservation Lab at the University of Pennsylvania. The soil obtained from crushing mud bricks was sieved through a No. 8 U.S Standard sieve series as per ASTM Designation E11. This procedure sorted out the large gravel from the soil.

A five gallon stainless steel bucket with tapering sides was used as the mixing bucket to create multiple batches of the different grout formulations. Each grout formulation was mixed in two batches so that manageable portions of the grout could be prepared, mixed and poured. The dry soil mixture and water were poured into the bucket alternately in small quantities so that a thorough grout mixture could be prepared without foaming on the top surface of the grout mixture once it was well mixed. The ingredients were mixed using a hand-held corded Milwaukee 3/8" electric drill of variable speed of 0-850 rpm. A long vertical stainless steel paint mixer paddle was attached to the drill and used to mix the grout for duration of 3-5 mins. Foaming was noticed in the formulations that contained sodium hexametaphosphate.

Figure 9: Mixing grout formulations
Source: Iyer 2014 (Set on tripod)

***Setting up the work space and pouring:*** Different stations with equipment necessary for pouring the different samples were setup in an order that reduced chaos and confusion during the execution. The work space for the flow test was setup closest to the grout mixing station so that the flow test could be performed within one minute from the time the grout was completely mixed to the time it was filled in the flow cone. The grout mixture was constantly agitated until it poured into the flow cone so that the grout did not segregate. Once the flow test was completed, the grout was immediately poured into the pre-lubricated molds. All the molds were sharply rapped on the table for 10 to 15 times so that all the trapped air bubbles were released out from the grout sample. Extra grout was additionally poured into the molds to ensure that the prepared samples were of correct dimension. Between mixing each batch of grout formulation and the different grout formulations all the equipment that was used in the initial grout mixing process was thoroughly cleaned.

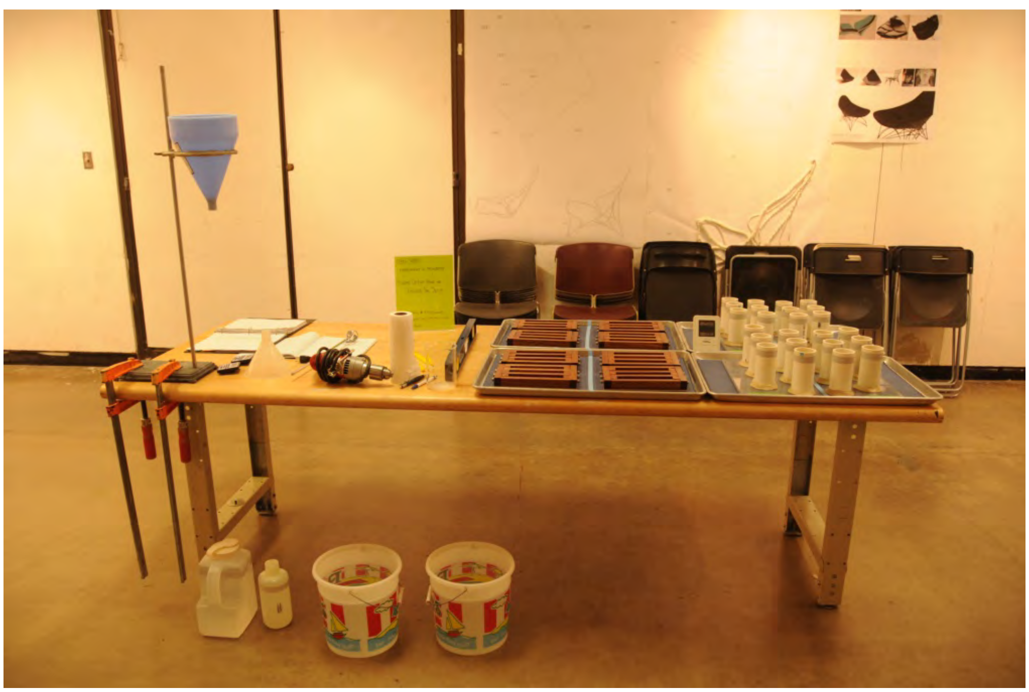

Figure 10: Setting up the workspace for pouring
Source: Iyer 2014 (Set on tripod)

Figure 11: Pouring grout formulations into molds
Source: Iyer 2014 (Set on tripod)

***Molding, Demolding and Curing:*** Once all the samples were poured, the molds were carefully relocated to a designated space within the Architectural Conservation Lab to be cured. The relative humidity and the temperature of the curing station were regularly monitored so that any abnormalities could be analyzed at a later stage with the help of this data. The entire sample was allowed to dry in air for a minimum duration of 28 days.

The drying shrinkage prisms were left to initial cure for a duration of 2 days, after which the excess around and above the mold was scrapped out with the help of a paint scraper tool and a painter's trowel. The cleaned shrinkage prisms were then allowed to further cure within the molds until day 28 before they were entirely demolded so that the samples were completely allowed to cure and did not break during the process of dismantling.


Figure 12: Using wire clay cutter to shape samples while demolding
Source: Naima 2014

The splitting tensile samples were allowed to initially cure for a duration of 7 days before the excess in the capped section and around the mold was cut or levelled with the help of a wire clay cutter and painter's trowel. On day 7, all the samples of different grout formulations (Sample A, C and D) were levelled, demolded and set on a clean acrylic sheet to accelerate the drying of the samples. However during this process of demolding one sample from grout formulation Sample B deformed, so the rest of the samples were allowed to cure within the molds for a longer duration of 28 days. Excess present above and around the mold was cut or levelled out with the help of a wire clay cutter and painter's trowel in a sawing movement.

Figure 13: Detail shot of shaping samples while demolding
Source: Naima 2014

Once all the samples are completely demolded on day 28, they will be allowed to age until they are ready to be tested in the future. The finished samples are labelled to indicate the grout composition and the date when they were poured so that the data is available for future testing.

Figure 14: Drying shrinkage prism samples left to cure
Source: Iyer 2014


Figure 15: Splitting tensile samples left to cure (after demolding)
Source: Iyer 2014

Figure 16: Sample B deformed during demolding
Source: Iyer 2014

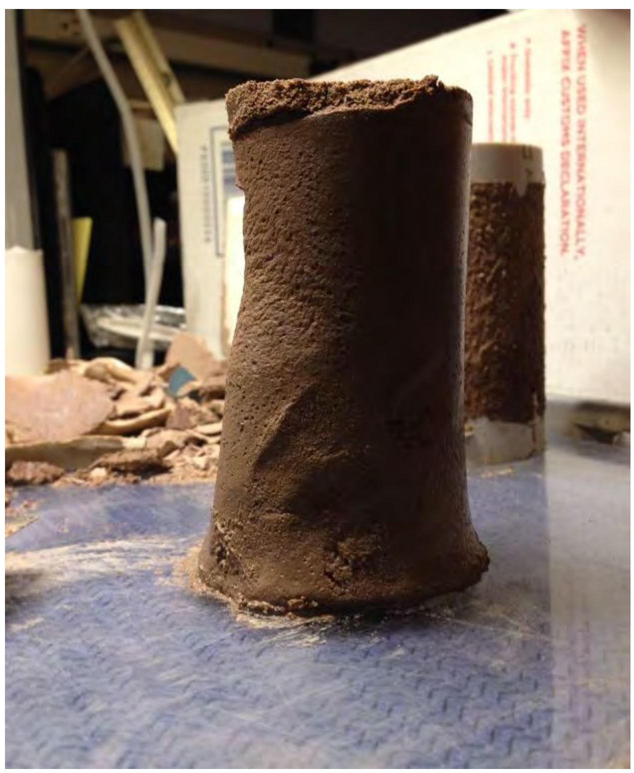


Figure 17: Sample B deformed during demolding
Source: Iyer 2014

# CHAPTER 5: CHARACTERIZATION OF MUD BRICKS

The characterization of mud brick is undertaken to better understand the soil composition including grain size distribution, clay mineralogy, and organic content. of individual mud brick. To ensure the results were representative in characterizing the entire pallet of received commercially produced mud bricks, random sampling of six bricks was performed. Tests were conducted as per ASTM standards with necessary modifications and other test standards developed by CRATerre.

## Visual Analysis of mud brick

Initial visual examination identified the surface of the mud bricks as friable and powdery during handling. The bricks were relatively uniform in size with an average size of 14" X 10" X 4", cuboidal in shape and heavy.

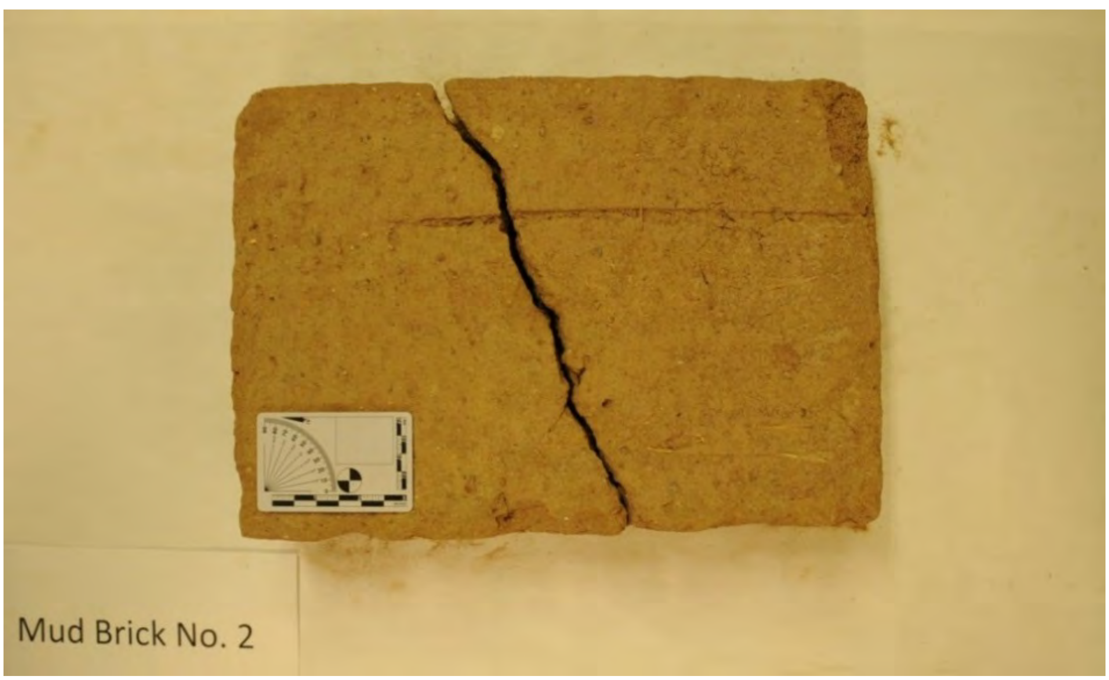


Figure 18: A fractured mud brick from the brick pallet for visual characterization
Source: Iyer 2014

## Dry sieving analysis

***Introduction:*** This test was performed to determine the grain size distribution of the soil used to produce the mud brick.

***Adaptation:*** This test is loosely based on the mechanical sieve shaker method detailed in STP 447 B Manual on Test Sieving Methods and ASTM D421 and ASTM D422. Samples from six mud bricks were prepared using the sample preparation technique already explained in detail in Chapter 5 under sample preparation for sieve analysis.

***Apparatus:***

- Electronic balance, sensitive to 0.1g
- 8-in. round sieve stack with the following U.S Sieve series sieves, they are:-

| Standard Sieve Designation ( mm ) | Alternate Sieve Designation ( inch ) |
|---|---|
| 12.5 | ½ inch |
| 4.75 | No. 4 |
| 2.36 | No. 8 |
| 2.00 | No. 10 |
| 1.18 | No. 16 |
| 0.60 | No. 30 |
| 0.425 | No. 40 |
| 0.30 | No. 50 |
| 0.15 | No. 100 |
| 0.075 | No. 200 |
| 0 | Pan |

Table 4: Sieves used for the sieve stack as per the U.S Sieve series

- Metal scoop
- Mechanical sieve shaker, designed to stimulate a circular motion combined with a tapping action

- Cling wrap roll
- Pre-labelled ceramic evaporating dishes
- 1 brass wire brush to clean the sieves
- 2 natural brittle brush to transfer the materials from the sieves
- Eleven pre-weighed and pre-labelled weighing boats
- Wooden board to level the mechanical sieve shaker

***Materials:*** Six random mud brick samples were selected as part of this test. Table 7 and Table 8 from the STP 447 B Manual on Test sieving methods were referred to determine the total volume of the test sample that was necessary to perform this test (Appendix A).

Since the top most sieve is a ½ in. screen, the suggested bulk volume of the test sample is 800g as per Table 7. Since the sample consists of various particle sizes ranging from large to clay, the weight of the sample was calculated using a density value that ranged from 1.20 g/cm3 (clay) to 1.44 g/cm3 (sand) as per Table 8.

***Procedure:***

1. Setup the mechanical shaker in a relatively open area within the room, on top of a wooden board to ensure that the area where its setup is leveled and does not cause the shaker to topple when in operation.
2. Clean out all the different sieves that form a part of the 8-in sieve stack, to ensure that the results of the particle size distribution are accurate.
3. Measure out the appropriate amount of each of the crushed samples into six different evaporating dishes( Ws).
4. Ensure that the sieves are arranged in ascending order as part of the sieve stack and then tightly wrapped with cling wrap.

5. Pour one sample slowly into the sieve stack so that finer particles present in the sample are not lost.
6. Seal the sieve stack with some more cling wrap after placing a lid over the top sieve to ensure that no sample is lost during the sieving process.
7. Place the sieve stack on the mechanical sieve shaker and tighten the screw to ensure that the sieve stack it securely fastened to the shaker.
8. Turn on the mechanical shaker and keep it running for 10 minutes.
9. Once the mechanical shaker stops, unscrew the sieve stack, remove it and set it on the working table.
10. Unwrap, the cling wrap around the sieves individually making sure to collect any grains that have been caught in the wrap and transfer them into the respective pre-labelled weighing boats.
11. Weigh the mass of each sieved fraction.

***Observations:*** Due to the presence of fine particles in the crushed brick sample, dry sieve analysis showed the presence of fine particles that were agglomerated and adhered to the coarse particles in every sieve which led to false readings.

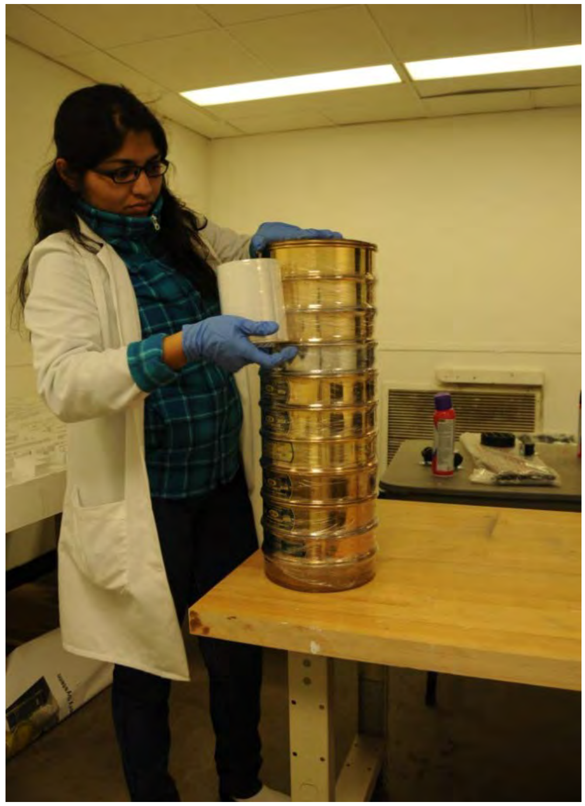

Figure 19: Wrapping the sieve stack with cling wrap
Source: Iyer 2014 (Setup the tripod)

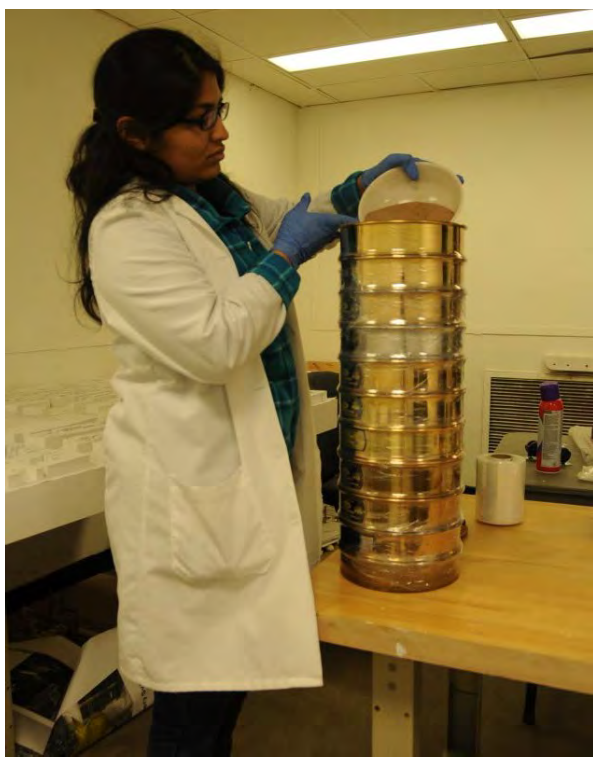

Figure 20: Pouring the sample into the sieve stack with cling wrap
Source: Iyer 2014 (Setup the tripod)

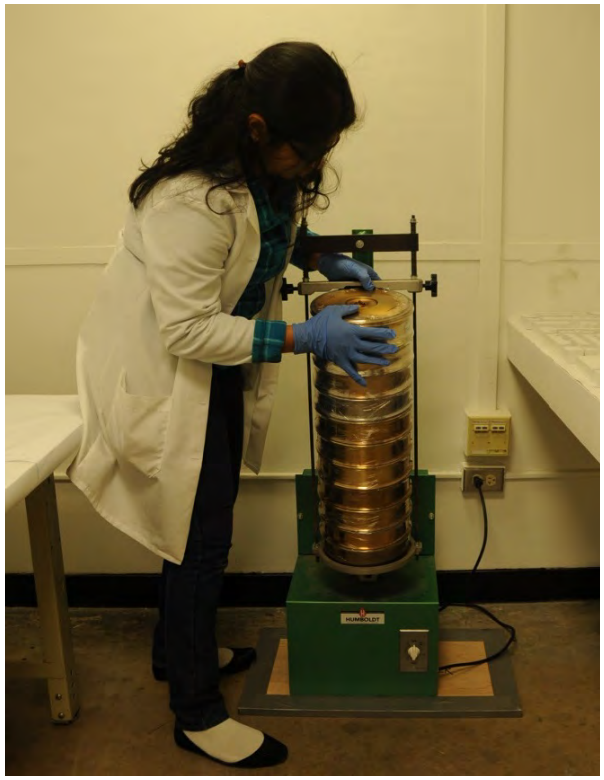

Figure 21: Securely placing the sieve stack on the mechanical shaker
Source: Iyer 2014 (Setup the tripod)

Figure 22: Mechanical shaker used to execute the sieving process
Source: Iyer 2014

## Combined dry and wet sieve analysis

***Introduction:*** This test was performed to determine the particle size distribution of soil used to manufacture the mud brick. The presence of fine particles that agglomerated and adhered to the coarser particles required the use of a combined dry and wet sieving process. This test is based on Stokes law which states that the terminal velocity of a particle is proportional to the square of the particle diameter, which means that particles with a larger diameter will settle faster than the smaller particles.[36]

***Adaptation:*** This test is loosely based on the particle size analysis techniques outlined in ASTM D422, ASTM D1140; testing methods recommended by Houben and Guillaud; and the particle size analysis of soil test. Three crushed mud brick sample were prepared using the sample preparation technique already described in detail in Chapter 5 under sample preparation for sieve analysis.

***Apparatus:***

- Electronic balance, sensitive to 0.1g
- Pre-labelled ceramic evaporating dish
- Stirring apparatus with dispersion cup as mixing apparatus
- Sedimentation cylinder
- 500 ml Pyrex beaker
- Stop watch
- Sieve stack, sieves as mentioned in Table 4
- Hydrometers

[36] Jeanne Marie Teutonico; *A Laboratory Manual for Architectural Conservators*, 1988

- Stainless steel sieve, sieve # 200
- Plastic container for wet sieving
- Rubber stoppers
- 40g/L conc. of sodium hexametaphosphate solution (HMP solution)
- Pyrex glass funnel, transfer fine particles into sedimentation cylinder
- Plastic spatula
- Watch glass
- Oven

***Materials:*** Three samples were used to perform the experiment. Visual examination and the initial dry sieving analysis suggested the presence of a large range of particle sizes in the soil sample indicating the presence of sand, silt and clay particles. Depending on the apparatus available in the lab, and as per ASTM D422, a sample size of approximately 150 g was used to perform the experiment.

***Procedure:***

*Preparation of dispersing agent*

1. The dispersing agent that was prepared for the sedimentation test was made of at a concentration 40g/L. About 40g of HMP compound was measured out into a 600ml Pyrex glass beaker.
2. 500 ml of de-ionized water was then poured into the beaker and stirred with the help of an 8mm glass rod till the entire compound was dissolved in deionized water. The solution was then poured into a plastic container with the help of a funnel.

3. 500 ml of deionized water was further poured into the beaker to ensure that the entire solid compound of HMP was thoroughly dissolved in deionized water and poured into the plastic container.
4. The pH of the freshly prepared HMP was checked to ensure that the solution had a pH of 8 or 9 and was used with a period of a month.

*Soaking the crushed mud brick sample*

1. Approximately 150 g of crushed mud brick sample was measured out into an evaporating dish and allowed to dry for 48 hours in an oven maintained at 60$^{O}$C. After drying to constant weight the sample was allowed to cool in a desiccator to constant weight.
2. The soil sample was weighed and transferred into a 600ml Pyrex glass beaker to which 125 ml of HMP was added and let to sit covered with a watch glass for at least 16 hours to ensure that the soil was completely wet.

Figure 23: Adding 4% solution of sodium hexametaphosphate to soil sample
Source: Iyer 2014

*Stirring the sample*

1. The soil slurry was then transferred into the dispersion cup. Deionized water was used to thoroughly wash the beaker and transfer all the soil particles into the dispersion.
2. More deionized water was added to the dispersion cup to just half full so that the sample did not spill out during the stirring process.
3. Set the stirring apparatus at 10,000 rpm, its lowest setting, and stir the sample for 1 min.

Figure 24: Transferring the sample into mixing apparatus for stirring
Source: Naima 2014

*Wet Sieving*

1. Once the sample is thoroughly stirred, it is transferred onto a stainless steel sieve nested on a plastic container. The test was performed within 1 min of drawing the soil sample from the apparatus.
2. The soil sample is washed thoroughly with the help of a jet of deionized water until all the fine matter is washed thoroughly on the sieve, i.e. until the water is clear. It was made sure that the amount of water used for this purpose was about 500 ml.
3. Extreme care was taken while the soil was being washed so that no material was lost due to splashing during the process of washing or overflowing of water from the container.
4. Once this process was completed the material that was collected in the plastic container was set aside to be used for the sedimentation process.

Figure 25: Separating fine soil particles by wet sieving
Source: Naima 2014

*Backwashing*

1. The soil particles that did not pass through the 75µm sieve were transferred into a pre-labelled and pre-weighed evaporating dish using the process of backwashing.
2. This material was set aside until the top of the suspension became clear which took several days.
3. Once the water cleared, most of it was poured off into a beaker and the remaining soil particles present in the evaporating dish were placed into an untreated oven for drying at 60$^{o}$C.

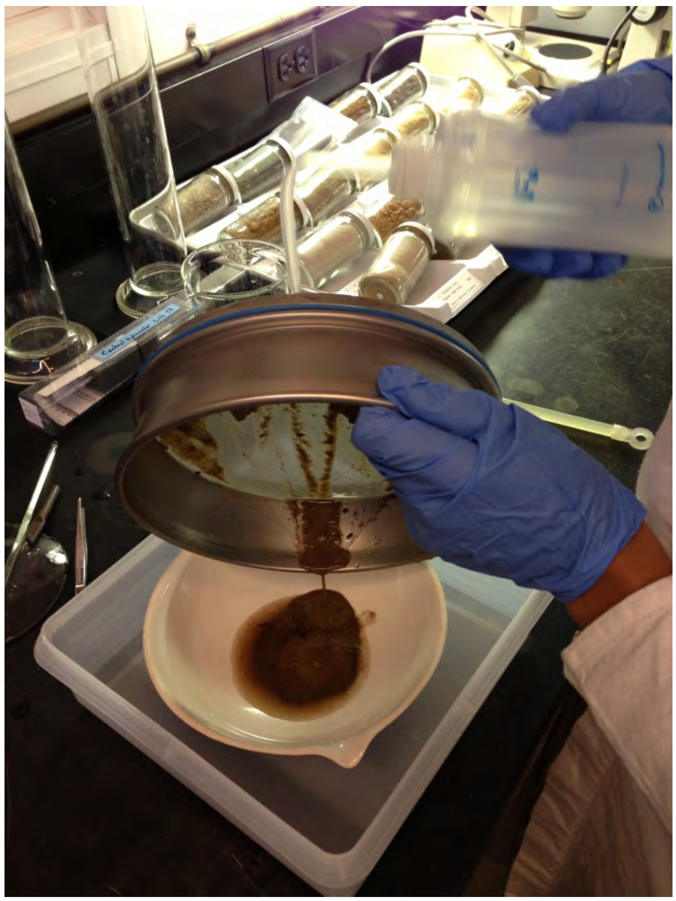

Figure 26: Collecting coarse particles by backwashing
Source: Naima 2014

*Dry Sieving*

1. When the material in the evaporating dish was dry, it was allowed to cool and be weighed. The same process that has been detailed in the dry analysis section was carried out as part of this process.
2. Once the whole process was executed, the weights of the individual samples from the different sieves were recorded to the nearest 0.01g.
3. Since some of the sample was collected in the pan, those fines were added to the other material that was set aside for the analysis using the sedimentation cylinder.

Figure 27: Sample get to dry in evaporating dish before placing in oven
Source: Iyer 2014

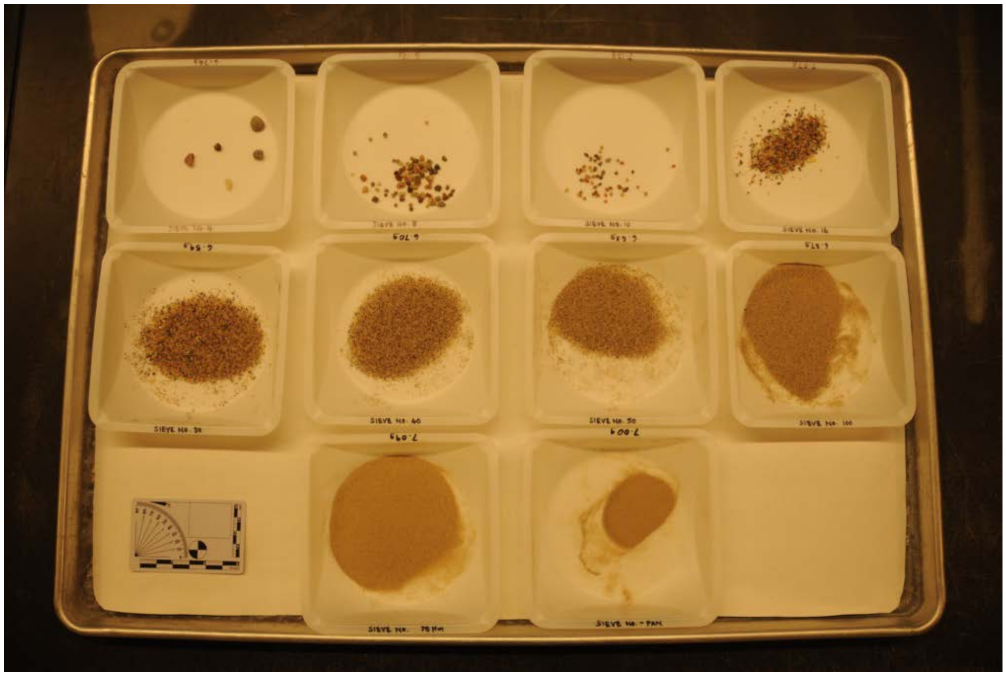

Figure 28: Particle size distribution after dry sieving
Source: Iyer 2014

*Sedimentation*

1. The suspension of the pretreated soil that passed through the 75µm sieve in the wet sieving and the fines that were collected in the pan during dry sieving were transferred to a 1000ml sedimentation cylinder.
2. The wet sieve container was thoroughly rinsed so that the all of the sample was transferred into the sedimentation cylinder. Once the entire sample was transferred, deionized water was added to the cylinder to level it to a volume of 1000 ml.
3. Along with all the other samples that were set up by following the process listed above, a control cylinder was also filled only with deionized water at room temperature and a volume of 1000 ml.
4. Since a bath was not setup to regulate the temperature of both cylinders, the distilled water temperature was adjusted so that all the cylinders, i.e. sedimentation and control cylinders were at the same temperature.

5. Rubber stoppers along with parafilm were used to obtain water tight fit on all the cylinders. Each sedimentation cylinder was made water tight so that the cylinder could be shaken to obtain a uniform suspension. The cylinders were inverted and shaken a few times so that the particles were thoroughly agitated.
6. Once the cylinder was set on the counter, the timers were instantly started.
7. The rubber stoppers on the sedimentation cylinders were then removed and a hydrometer was steadily inserted into the cylinder so that it floats freely in the suspension. It was ensured that the hydrometer did not fiercely bob up and down or rotate when released.
8. All the readings were taken at the top of the meniscus after ½, 1, 2 and 4 mins. Temperature readings corresponding to the sedimentation cylinders were also taken. Separate hydrometers were used to take readings from the sedimentation cylinder and the control cylinder.
9. The rubber stoppers were re-positioned on the sedimentation cylinder, re-agitated and another set of readings after ½, 1, 2 and 4 mins were taken. This process was repeated four times, until two sets of readings agreed within one unit of each other for all four readings.
10. When the readings meet the standard, the sedimentation cylinder was allowed to settle and additional readings were taken at an interval of 8, 15, 30 and 60 minutes and then at 1, 2, 4, 8, 16, 32, 64, 96 hours. The readings were not taken regularly.
11. The temperature readings were taken to the nearest 1$^{O}$C for each hydrometer reading. Each hydrometer reading was subjected to four corrections.

Figure 29: Transferring fine particles into sedimentation cylinder
Source: Naima 2014

Figure 30: Agitating cylinder prior to starting sedimentation experiment
Source: Naima 2014

Figure 31: Soil samples and control in cylinder
Source: Iyer 2014

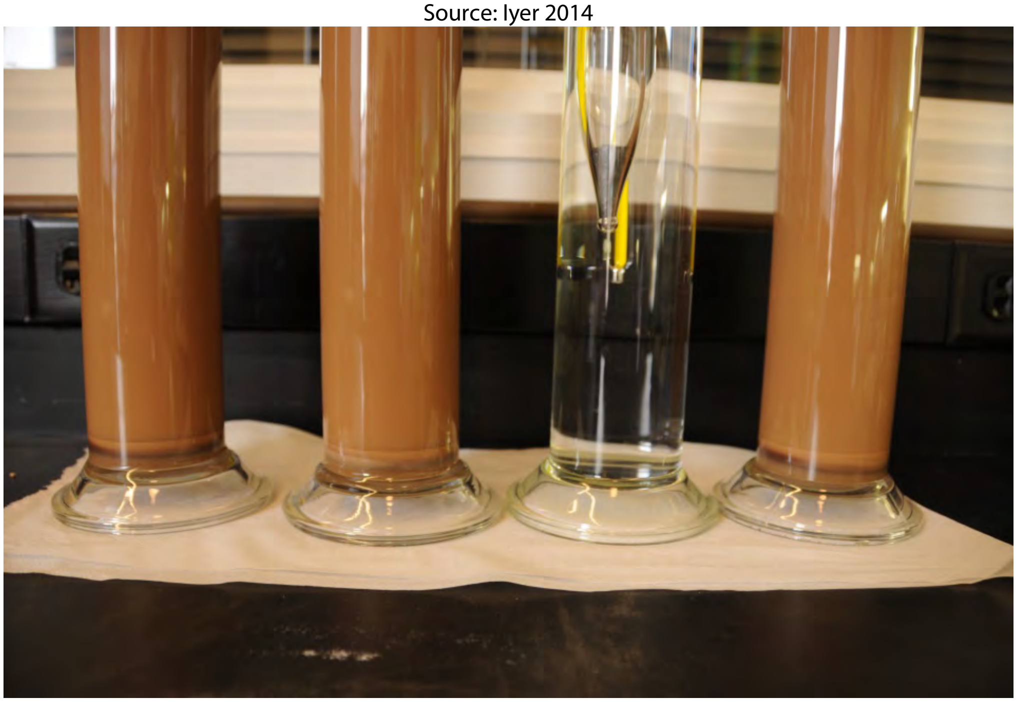

Figure 32: Detail of sedimentation observed in soil samples and control cylinder
Source: Iyer 2014

***Corrections:***

*Unit weight of solids correction (a)*

The value of 'a' is noted in Table 10 of the correction tables in Appendix A. To facilitate calculations, a combined correction factor K which combines temperature and unit weight of the solids is used. K value is a value that is obtained from Table 11, part of Appendix A.

*Meniscus Correction ($C_M$)*

Two readings were taken with the help of a hydrometer after filling three quarters of the cylinder with deionized water. The first reading was taken until the surface of the liquid being measured appears as a straight line instead of an ellipse, this reading is A. A second reading is taken at the upper level of the meniscus, this reading is B. The following readings are now applied to this equation to get the meniscus correction value.

$$C_m = (B-A) * 1000$$

*Temperature Correction ($C_T$)*

The temperature correction reading is determined from Table 9 that is part of Appendix A. This temperature correction is added to the true hydrometer reading (R).

*Dispersing Agent Correction (x)*

In order to apply a dispersing agent correction, 50ml of the dispersing agent (HMP solution) is poured into a pre-labeled and pre-weighed beaker. The weight of the beaker is recorded before the beaker is placed in the oven at 105 – 110$^{O}$C once all the water evaporates; the remaining mass of the dispersing agent is determined by weighing the beaker with the residue matter. This reading is subtracted from the true hydrometer reading (R).

**Zero correction is $x = 2M_d$**

***Calculations:***

The meniscus corrections are applied to the hydrometer reading. Table 12 was used in order to obtain the value of effective depth (L).

The value of specific gravity $G_S$ was considered to between 2.67 – 2.9 as per Table 13 because the soil in question here is a silty clay type of soil.

Other than the Gs and temperature readings as part the test, Table 9 of the attached correction tables was used to obtain the value of constant K. With the values of K, L and the elapsed time in minutes (t), the particle diameter (D) was computed:

$$\boldsymbol{D\ (mm) = k\sqrt{\frac{L}{t}}}$$

Next, the corrected reading (Rc) and the percent finer for the corresponding particle diameter (D) is calculated using the following formulas:

$$\boldsymbol{R_c = R_a - x + C_T}$$

$$\%\boldsymbol{Finer} = \frac{\boldsymbol{R_c(a)}}{\boldsymbol{W_s}}$$

***Observations:*** While the test was being conducted, it was observed that although a significant amount of dispersing agent (sodium hexametaphosphate) was added to the soil sample, the finer particles that form part of the soil sample were initially settling rapidly within the sedimentation cylinder. To constantly agitate the sample before taking readings, a long stir bar was used to stir the samples, while the stir bar was being used, it was observed that a significant amount of iron fillings were stuck to the magnetic end of the rod. This clearly indicated the presence of ferrous particulates in the soil sample.

***Result:*** Following are the results of the particle size analysis of three samples that were randomly chosen from the brick pallet. Percentages of the combined sieve analysis are based on ASTM D422 particle size conversion for clay, silt, sand and gravel. Table 5 summaries the particle size distribution for all the three samples that were tested and a logarithmic graph of the particle size v/s percent finer has been plotted that shows the variation in the particle size distribution of the different mud brick samples. The detailed calculations of the sieve analysis of the sieved sample have been included in Appendix A.

| Mud brick sample | % Gravel | % Sand | % Silt | % Clay |
|---|---|---|---|---|
| Sample #2 | 2.1 | 68.6 | 12.7 | 11.9 |
| Sample #5 | 1.4 | 68.2 | 13.6 | 12.3 |
| Sample #6 | 0.3 | 68.6 | 14.7 | 13.9 |

Table 5: Mud brick grain size distribution

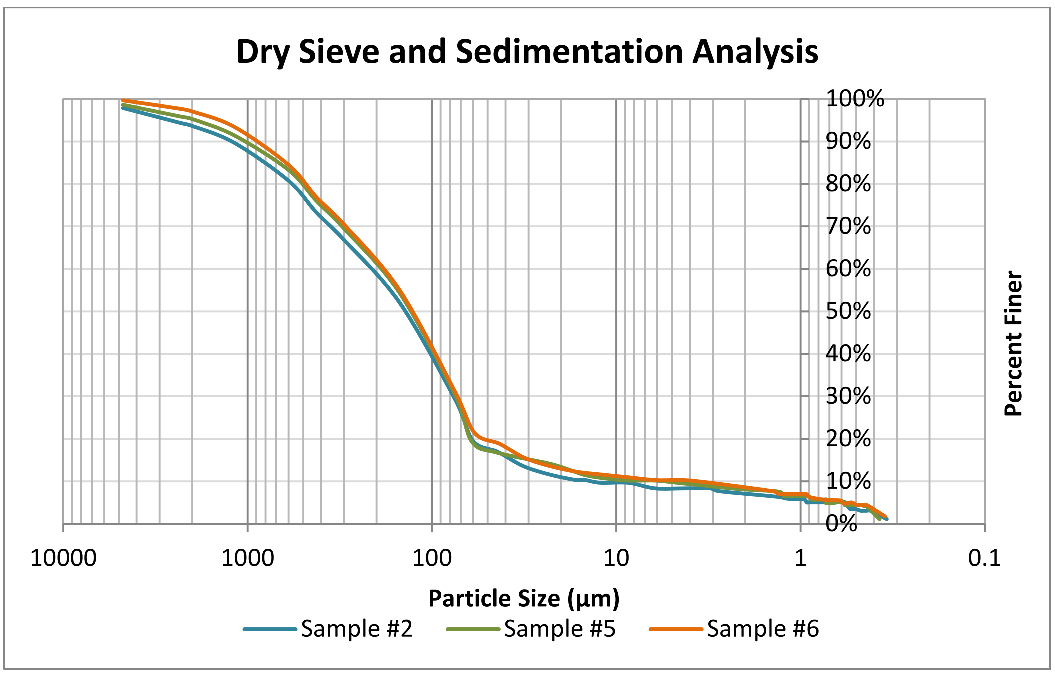


Figure 33: Particle size distribution graph for Mud brick samples

### Quantitative organic content analysis

***Introduction:*** This test was performed to quantitatively determine the presence of organic material such as straw or grass in the mud brick. The organic components are generally added to the brick to delay cracking, accelerate the drying process and to increase the tensile strength of the building component.[37] The test uses the process of decomposing the organic compounds by dry ashing or oxidation to determine the amount of organic compounds present in the sample.[38]

***Adaptation:*** The crushed mud brick sample used as part of this test was prepared using the sample preparation technique as described in Chapter 5 under sample preparation for sieve analysis. The crushed sample was then passed through Sieve no. 10, which was later divided into six smaller specimens to form the sample size for this experiment.

***Apparatus:*** Crushed mud brick sample

- Electronic balance, sensitive to 0.1g
- Pre-labelled ceramic evaporating dish
- 3 pre-labelled petri dishes
- Oven

***Materials:*** Three small sample specimens were prepared and used to perform the experiment. The weight of crushed mud brick samples that were used for the experiment was based on the availabilities of sample.

***Procedure:***

1. Approximately 400g of crush mud brick sample was first passed through US sieve no. #8 to separate out the gravel size particles from the sample and increase the volume of organic matter in the sample.

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[37] H. Houben and H. Guillaud, Earth Construction – A comprehensive guide, CRATerre-EAG, Intermediate Technology Publications, Southampton Row, London, 1994

[38] Chemical Technician's Ready Reference Handbook, P - 321

2. The percent passing through the sieve was divided into three small specimens and oven dried at a temperature of 105$^{O}$C for 6 hours, allowed to cool in a desiccator and then weighed once the samples reached room temperature.
3. The samples were then placed back in the oven at a higher temperature of 300$^{O}$C for 18 hours, allowed to cool in a desiccator and weighed once the samples reached room temperature.
4. The weight difference between dried and combusted sample was calculated to achieve the weight of the combusted organic matter and then the percentage of the organic matter within the total sample.

***Calculations:***

Total weight loss percentage = Original sample weight before placing in the oven ($W_{BO}$) – Sample weight after placing in the oven ($W_{AO}$) / original weight ($W_{BO}$) * 100

$$\textbf{Tot. } W_L = (W_{BO} - W_{AO}) * 100$$

***Observations:*** The sample that was obtained after passing the sample through US sieve no. #8 was visually examined before placing it into the oven. The examination indicated the presence of a significant amount of organic content in the form of dried grass. When the soil sample was taken out of the oven after 6 hours, significant amount of organic matter was still present as a part of the soil sample. When the sample was later taken out of the oven after 18 hours, no organic matter was seen present in the soil sample.

***Results:*** Combustion of the three crushed brick sample led to total weight loss of 2.44 to 2.47 % as compared to their original sample weight. The Initial step of heating the sample in the oven at 110$^{O}$C indicates an initial weight loss of about 1% organic matter still observed during weighing. The reheating of the sample at a temperature of 220$^{O}$C led to the complete combustion of all the organic matter resulting in a weight loss of 1.4 % as per Table 6.

| Adobe Sample | Sample Weight before oven (g) | Sample Weight after $110^{O}C$ (g) | Sample Weight after $220^{O}C$ (g) | Total Weight Loss in percent | % Weight Loss from Water and $CO_2$ | % Weight Loss from Organic Material |
|---|---|---|---|---|---|---|
| Sample A | 62.68 | 62.04 | 61.79 | 2.44 | 1.02 | 1.42 |
| Sample B | 60.00 | 59.37 | 59.15 | 2.47 | 1.05 | 1.42 |
| Sample C | 70.36 | 69.63 | 69.36 | 2.46 | 1.04 | 1.42 |
| | | | | Mean values: | 1.04 | 1.42 |

Table 6: Result of quantitative organic content analysis

## Methyl blue adsorption test

***Introduction:*** The test was performed to quantify the ionic absorption capacity of a material by measuring the amount of methylene blue required to cover both the external and internal surface of the clay particles within the soil sample. Each type of clay mineral has a specific value of absorptive capacity which increases as a function of the specific surface of clay particles and charge. The test helped determine if the clays present in the crushed soil sample are stable or swelling clays and to detect the presence of expanding clays and to semi quantitatively judge their swelling potential.

***Adaptation:*** This test is loosely based on the French standard AFNOR NF P 94-068-1998 that has been modified slightly for use with similar quantities. The crushed mud brick sample used as part of this test was prepared using the sample preparation technique as described in Chapter 5 under sample preparation for sieve analysis.

***Apparatus:*** Crushed brick sample

- Electronic balance, sensitive to 0.1g
- 500 ml Pyrex glass beaker

- Pre labelled filter papers
- 0.01 conc. of methylene blue solution
- Deionized water
- Glass rods
- Chemical spatula

***Materials:*** A fresh batch of methylene blue solution was prepared a few days prior to the test day so that the solution in use reacts in the expected manner. A bulk sample of the crushed brick sample was first oven dried to constant mass at 60ºC. This soil sample was passed through a no. 200 (75 micron) sieve so that all the fines could be collected and the test could be performed on one bulk sample.

***Procedure:***

1. A significant amount of crushed brick sample was first placed in the oven to dry to constant mass at 60ºC.
2. Then the oven dried soil sample was passed through a no. 200 (75 micron) sieve to isolate the fines.
3. A soil sample was prepared where the sample approximately weighed 60g on which this test was conducted.
4. The sample was placed in a beaker with 500ml of deionized water and was dispersed within the water by constantly stirring with a glass rod.
5. Unit doses of 5 ml of 0.01 conc. of methylene blue solution were added to the dispersed sample.

6. After each addition of 5 ml dose of methylene blue, a small quantity of the suspension was collected with a glass rod and a drop was placed onto standard filter paper, producing a dark blue stain.
7. Extra doses of methylene blue were added to the sample and all samples were collected on the filter paper until a light blue halo formed in the wet area around the stain.
8. Once the light blue halo was observed on the filter paper, no further methylene blue was added to the sample and the sample was checked again at one minute intervals to determine the stability of the halo.
9. When the halo persists after five minutes, the test was considered complete.
10. Once the test was completed, the total amount of methylene blue solution used for the experiment was calculated.

*Preparation of Methyl Blue solution*

1. The methylene blue agent that was prepared for this preliminary test to detect swelling clays was made of a concentration 10g/L. About 10g of HMP compound was measured out into a 600ml Pyrex glass beaker.
2. 500 ml of de-ionized water was then poured into the beaker and stirred with the help of an 8mm glass rod till the entire compound was dissolved in deionized water. The solution was then poured into a plastic container with the help of a funnel.
3. 500 ml of deionized water was further poured into the beaker to ensure that the HMP was thoroughly dissolved in the de ionized water and poured into the plastic container.

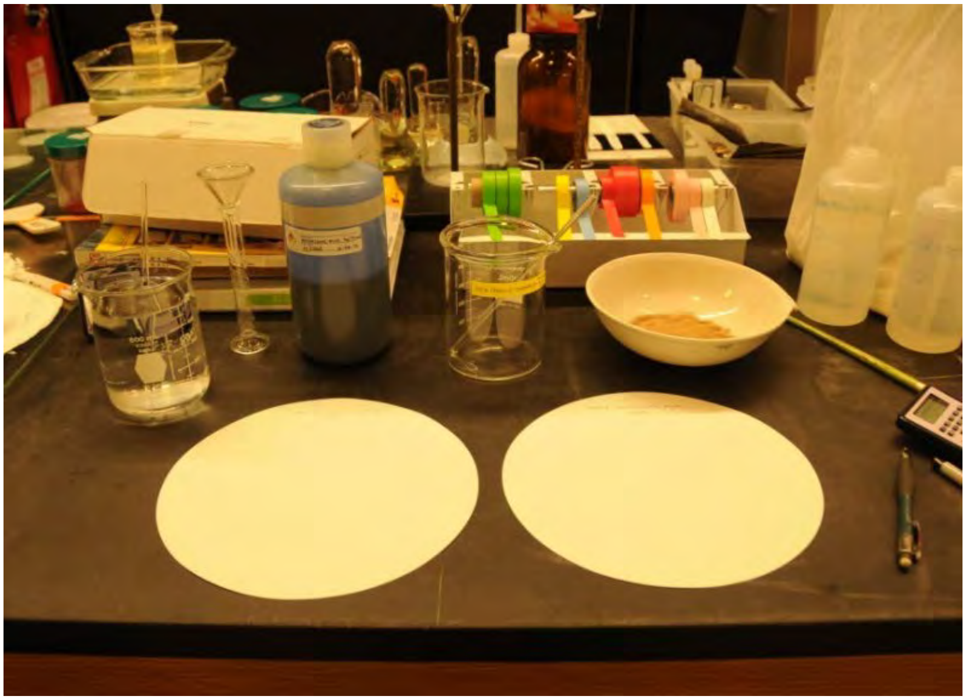

Figure 34: Methylene blue testing set up
Source: Iyer 2014

***Calculations:***

The activity index ($V_B$) of the clay minerals was calculated as follows:

$$V_B = V * 0.01 * 100/W$$

Where, $V_B$ = the activity index of the material in g/100g,

V = volume of methylene blue solution used,

0.01 = the concentration of the methylene blue solution, and

W = the dry weight of the sample used.

The following calculations indicate the amount of methylene blue absorbed by the clay minerals i.e. the total active surface of the particles:

$$S_A = (V_B/100) * (N/W_{MB}) * (130*10^{-20})$$

Where, $S_A$ = total active specific surface ($m^2/g$)

VB = the active index of the material,

N = Avogadro's number ($6.02*10^{23}$), and

$W_{MB}$ = molecular weight of methylene blue (320g)

If the calculated value is found to be within the range from 20 $m^2/g$ to 800 $m^2/g$ it suggests the presence of clay minerals and if the value ranges between 1 $m^2/g$ to 4$m^2/g$ it suggests the presence of inert materials.

Index of activity could be determined if the clay content was determined through dry sieve and sedimentation analysis.

$$\mathbf{A_{CB} = 100\ V_B/CC}$$

Where: ACB = the index of activity (in g of methylene blue in 100g clay fraction)

$V_B$ = the index or blue value of the material (g/100g)

CC = the clay content (%)

A low index of activity suggests that the soil sample is stable; however a high value indicates the presence of swelling clays.

***Observations:*** At the beginning of the experiment when the initial few drops of sample were placed on filter paper, a very faint light blue halo was seen to have appeared around the sample. When 40 ml of methylene blue solution were added to the soil sample, the drops that were collected on the filter paper started to show the presence of a clear light blue halo. Following the presence of the halo with no further methylene blue solution added to the sample at readings taken every minute, it was determined that the light blue halo was stable This concluded that 40ml of methylene blue was sufficient for the test to be completed.

***Results:*** 61.18 g of soil sample was used for the purpose of this experiment. Approximately40 ml of methylene blue solution was added before a blue halo was present for 5 minutes. $V_B$ was calculated to be 0.65g/100g. The total active specific surface (internal and external), $S_A$ was calculated to be 15.89g/$cm^3$. Through sieve analysis and sedimentation, the clay fraction of the sample analyzed was determined to be an average of 13 %. Therefore the activity index was determined to be 0.05 which suggests that the type of clay present in the soil sample is stable.

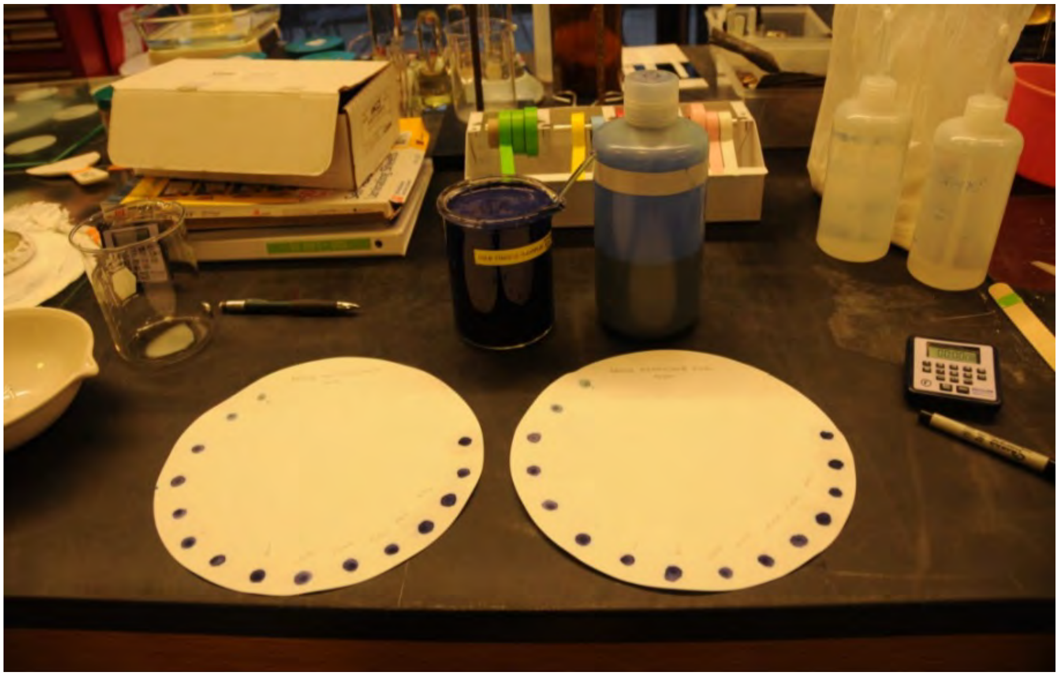

Figure 35: Methylene blue test in progress AMFOR standard
Source: Iyer 2014

Figure 36: Methylene blue test filter paper results. AMFOR standard
Source: Iyer 2014

# CHAPTER 6: RHEOLOGY OF THE GROUT

## Initial Evaluation of grout

The objective of this phase of testing was to identify a group of soil grout mixtures that displayed good working or "wet" properties that together define the rheology of the grout. Assessing the wet and semi-cured states of a grout include the critical properties of shrinkage and viscosity as these properties help determine whether the sample can maintain its dimensional stability. Depending on the results obtained from a preliminary qualitative visual shrinkage test, grout formulations were then shortlisted for further quantitative confirmatory testing of selected rheological properties as well as sample preparation for future physical and mechanical tests of the solid samples

## Qualitative Visual Shrinkage

***Introduction:*** This test was performed as a preliminary but critical test in refining the selection of grout formulations for further testing. The aim of the test was to confirm dimensional stability of grout through shrinkage.

***Adaptation:*** This test is loosely based on the test procedure that has been detailed in Washa (1966, 190). The crushed mud brick sample used as part of this test was prepared using the sample preparation technique explained in Chapter 5 under sample preparation for sieve analysis. This test visually identified shrinkage of possible grout formulations as a function of visible surface cracking and diameter changes in the drying sample.

***Apparatus:***

- Crushed brick sample
- Electronic balance, sensitive to 0.1g

- Equipment necessary for sample preparation
- Pre labelled un-glazed terra cotta saucers
- Stirring apparatus with mixing apparatus
- Deionized water
- Thermo hygrometer
- 500 ml glass beaker
- Plastic mixing spatula

***Materials:*** Most of the mud grout formulations were designed as unamended mud grouts with modifications in the solid to water content ratio in the grout samples. Deionized water was used for the process of preparing these samples, ensuring no addition of salts, impurities or alteration of pH due to the use of regular tap water. The crushed soil samples were passed through sieve no. #8 to ensure that the gravel content was separated out of the soil sample before the soil was used for the grout formulation. This was based on the assumed width of the cracks to be injected and the diameter of the inject cannula for the grout.

***Procedure:***

1. Measure out the amount of soil that constitutes the solid content in the grout formulation. Formulations were:
    a. Sample 1: solid to water content 2:1
    b. Sample 2: solid to water content 2.5:1
    c. Sample 3: solid to water content 3:1
2. Ensure that the soil and deionized water is added to the mixing apparatus in small proportions alternating with deionized water to ensure that bubbles are not formed when the stirring apparatus is used to mix the grout sample.

3. Set the stirring apparatus that runs on an electrical motor at 10,000 rpm at its lowest setting and stir the sample for 3-5 minutes.
4. Once the sample is thoroughly mixed, the sample is poured into four pre-labelled unglazed terracotta saucers per sample. The test was performed within 1 minute of drawing the grout from the apparatus.
5. The samples were sharply rapped on the counter 10 -15 times, so that any air bubbles that formed during pour escaped from the sample.
6. The whole process was repeated the exact same way for each formulation.

Figure 37: Test sample preparation setup
Source: Iyer 2014

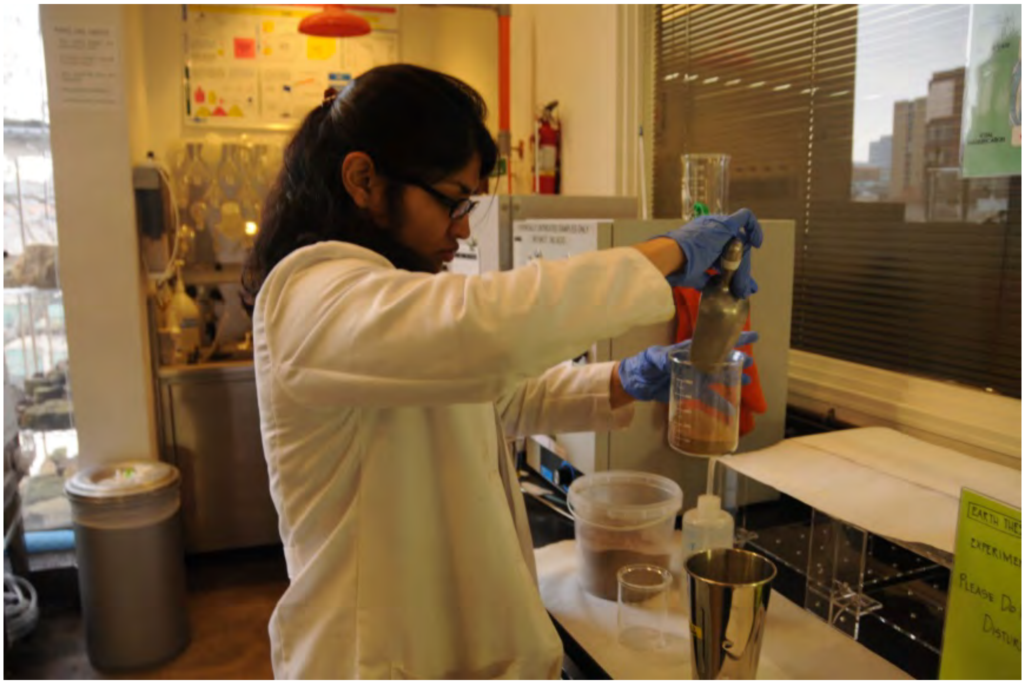

Figure 38: Proportioning the samples for the test;
Source: Lindsay 2014

Figure 39: Mixing the samples with mixing apparatus
Source: Lindsay 2014

Figure 40: Pouring out the samples into unglazed terracotta saucers
Source: Lindsay 2014

Figure 41: All test samples poured into unglazed terracotta saucers (Day 1)
Source: Iyer 2014

Figure 42: All test samples in unglazed terracotta saucers (Day 7)
Source: Iyer 2014

***Observations:*** As the samples were set to air dry within a designated space in the lab, the thermo hydrometer were used to daily monitor the change in temperature and relative humidity close to the curing station for 28 days. The temperature and humidity of the room varied within the range of 21$^{\circ}$C to 25 $^{\circ}$C and 22 % to 33 % in terms of RH.

Of the four cohorts that were prepared for the sample with solids to water ratio of 2.5:1, one cohort showed some cracking. All the cohorts prepared for the test samples with different proportion, showed no signs of cracking. Samples with a solid to water proportion of 3:1 were more difficult to pour and needed the use of a spatula due to higher viscosity.

***Results:***

Since none of the samples showed signs of cracking, technically they could all be tested for viscosity. The cracking of one sample with a solid to water ratio of 2.5:1 was not conclusive enough to eliminate that formulation. Since the samples with a solid to water ratio of 3:1 were difficult to pour, they were eliminated for future testing. The apparent high viscosity of the samples made them unsuitable to be tested as a potential grout formulation. So the samples with a solid to water ratio of 2:1 and 2.5:1 were tested for viscosity.

### Viscosity (Flow test)

***Introduction:*** This test was performed to measure the efflux (time required) for a known quantity of grout to flow through a graduated funnel with a standard diameter outlet. The rate is relative to the rate of the same quantity of water flowing through the funnel. Although the values of the readings that are obtained as part of the experiment do not give a direct measure of viscosity, the reading help to characterize the rate of flow of the different grout formulations.

***Adaptation:*** The test is loosely based on the test procedure that has been described in ASTM C 939-87 Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method) that was modified as proposed by Deere (1982) and Houlsby (1990).[39]

***Apparatus:***

- Pre sieved crushed brick sample
- Electronic balance, sensitive to 0.1g
- Equipment necessary for sample preparation
- Marsh Flow Cone
- Receiving container with exact volume marked

[39] The ASTM standard is designed for a US Army Corps of Engineers flow cone, rather than a Marsh Flow Cone (with an orifice diameter of 4.76mm at 50mm long). The Marsh Flow Cone was chosen over the US Army Corps of Engineers flow cone and others because the Marsh funnel has a greater sensitivity and standardized procedures (Deere 1982, 287). With the Marsh Cone method, only part of the contents is discharged (Houlsby 1990, 98) as opposed to the ASTM method where the entire content of the cone is emptied.

- Ring stand with caulking covered to improve stability
- Carpenter's level
- 3 Stopwatches, 0.2sec tolerance
- Milwaukee drill
- Grout mixing paddle attachment
- Measurement gauge
- Water
- 2 Full immersion thermometers
- Freshly prepared 2% sodium hexametaphosphate solution (HMP solution)
- 5 gallon mixing bucket

***Materials:*** Most of the grout formulations were designed as unamended grouts with varying solid to water content ratio. Each grout formulation was prepared right before the flow test was performed on the sample. Tap water and freshly prepared 2% sodium hexametaphosphate from ACL was used to prepare large quantities of different grout formulations. The crushed mud brick sample was pre-sieved with sieve #8 so that the prepared sample could be used for the purpose of preparing grout formulations.

***Procedure:***

1. 1725 ml of grout sample needed for the test were marked with electrical tape. This container was used as the receiving container.
2. The apparatus was calibrated each time before a grout formulation was tested:-
    a. The flow cone was mounted firmly onto the ring stand with the help of caulking so that the setup was free of vibration.
    b. A carpenter's level was used to level the flow and assure verticality.

c. After closing the bottom of the cone with the help of a finger or a stopper, 1725 ml $\pm$ 5ml of water was poured into the cone to adjust the point gauge and set it as reference. .

d. One minute before using the flow cone for the grout, the cone was moistened to ensure that the grout flowed smoothly through the flow cone.

3. Two flow measurement readings $E_T$ were noted to act as reference point (Time of efflux of water) each time the grout was poured through the flow cone.
4. Note the temperature of dispersant $T_D$ (water or HMP solution) before mixing it to form the grout sample.
5. The solids to dispersant proportion was measured out into a mixing bucket to prepare the different grout formulations and thoroughly mixed for duration of 3 to 5 minutes using a Milwaukee drill and a mixing attachment. The temperature of the grout was recorded, $T_G$ which was recommended to be 23.0 $\pm$ 2.0 $^{O}$C
6. Once the grout samples were thoroughly mixed and clump free, the discharge tube was sealed with a finger and the grout was introduced until the grout surface rose to the point gauge.
7. The finger was then disengaged so that the test could be performed. The stop watch was started immediately when the finger was disengaged from the tube and the duration was recorded until the first break in the continuous flow of grout was observed; two recordings were made when the time difference between effluxes was within 1.8s of their average for each grout formulation.
8. The test for the time of efflux was performed within 1 min of drawing the grout from the mixer. If the grout was held in place over a significant period of time, the grout was constantly agitated so that the grout did not segregate or separate.

9. Once the test was completely executed the grout formulations were poured into the different molds for future testing. Also, the total time for the flow test to be performed in addition to the formulations later being poured was timed with two stopwatches.

Figure 43: Leveling the flow cone before performing the flow test
Source: Iyer 2014 (Setup a tripod)

Figure 44: Pouring the measured grout sample for the flow test
Source: Iyer 2014 (Setup a tripod)

***Observations:***

To keep the solids in suspension and to maintain homogeneity, the samples needed to be constantly agitated. It was easier to mix samples and pour them in smaller batches. So all samples except sample B, were handled in two batches.

Owing to a higher solid to water proportion, samples C and D behaved much better than samples A and B, displaying better homogeneity and a tightly bound nature. Samples A and B were much more fluid in comparison. Sample A could not hold the particles in suspension and they segregated and settled to the bottom of the sample.

The addition of a deflocculant significantly impacted the viscosity even while the solid to water proportion was maintained. Samples B and D flowed much more easily as compared to samples A and C respectively. Sample B thus had low homogeneity coupled with low viscosity. Sample C showed the best behavior overall with optimum homogeneity and viscosity. The addition of a deflocculant reduced the viscosity as observed with sample D.

These visual observations are corroborated by the flow times as illustrated in Appendix B.

***Results:***

An ideal sample displays relatively low viscosity with high homogeneity for it to function well as a grout. Sample A displayed very low viscosity which affected its homogeneity due to the settling of the course fraction in the grout mixture. Based on the calculations, Sample B displayed the best time of efflux which signifies low viscosity, but had low homogeneity although better than sample A. It can be concluded that a solids to water ratio of 2.5:1 exhibits the best combination of viscosity and homogeneity. The addition of a deflocculant displayed a more desirable outcome with sample D as compared to sample B. Overall, sample C achieved the best trade-off between homogeneity and viscosity with sample D close behind.

# CHAPTER 7: CONCLUSIONS

### Granulometry (Combined dry and wet sieve analysis)

Results from the sieve analysis indicate a 5 sand: 1 silt: 1 clay ratio, typical for the composition of most commercial adobes. A major portion of the sand fraction is in the fine particle size range. This helps impart to the mud bricks properties such as compactness without increasing drying shrinkage and the ability to withstand large compressive loads while making it prone to damage from capillary absorption. The moderate presence of the clay in the soil sample suggests that the grout samples should be able to withstand at least moderate levels of flexural and compressive stresses.

### Quantitative organic content analysis

There is a significant loss of weight that is observed in the soil samples when they are heated at high temperatures. The loss of weight during the initial heating of the sample was the possible loss of water and other volatile components with the minute fraction of organic matter present. The reheating of the sample at a higher temperature led to the complete combustion of all the organic matter that was visually and numerically evident. The presence of this organic matter would be beneficial for the grout formulation as it would help prevent the formation of micro cracks within the grout.

### Methyl blue adsorption test

Since the soil samples tested were procured from commercially manufactured mud bricks, it was likely that no swelling clays were employed. The results of the test confirmed this hypothesis; the result suggested that the clays found in the soil sample are stable clays, most likely kaolinite, as it does not swell in the presence of water and has a very low ion fixing capacity. Therefore the presence of stable clays in the grout formulation would help achieve effective compactness without excessive drying shrinkage, and help withstand the compressive loads well in a hardened state while regulating the flow of the grout due to the flocculation of the clay particles in its wet state.

### Visual Shrinkage

The results of the visual shrinkage test reinforced the results that were obtained as part of the methyl blue absorption test. None of the samples showed significant signs of cracking which proved that the samples were dimensionally stable and had a potential to perform well as a grout to reestablish the monolithic character into a cracked wall and as void filler.

### Viscosity (Flow test)

The results calculated for the flow test suggest that even though sample B exhibited the best time of efflux which signifies low viscosity, it was observed that during the test, the heavier particles within the sample B mixture, i.e. the coarse sand particles, settled during the pour resulting in low homogeneity in the mixture. A low solid content in the grout led to the use of a relatively large amount of water which in the future could cause excessive shrinkage in the samples.

An ideal grout formulation should have relatively low viscosity with high homogeneity for it to function efficiently as a grout when in its wet state. In the case of sample C, an increase in the solid fraction of the grout formulation did display an increase in the flow time of the grout formulation but the sample was more homogeneous as compared to sample A and B.

Based on these observations, a solids to water ratio of 2.5:1 performed better than 2:1, hence samples C and D appeared to be more homogeneous as compared to samples A and B. But, in order to ensure that the grout formulation has low viscosity, i.e., flows well, the addition of a deflocculant would be necessary as sample D illustrates. as compared to sample B. Overall, sample C achieved the best compromise between homogeneity and viscosity with sample D a close second.

# CHAPTER 8: FUTURE TESTING AND RECOMMENDATIONS

Initially, a preliminary test matrix was developed identifying the critical properties of a soil grout and the various proposed tests to evaluate the grout and its use in assemblies. In addition to the analysis of any soil content (granulometry and clay mineralogy) and the rheology of a proposed formulation, several other tests have been proposed for future testing. To test the strength of the grout and the bond strength between the grout and the mud brick, various assembly tests were recommended as well as basic mechanical tests of the mud brick itself. This test matrix can be used as a reference for future testing (Table 20 in Appendix C). Some of the tests that are an immediate next step have been listed below. Also, samples for several of these tests were prepared while testing the rheological properties of the earthen grout. These samples were allowed to cure for at least 28 days.

## Test samples for Splitting Tensile and Drying Shrinkage

Once the tests to understand the rheological properties of the earthen grout were performed, the same grout formulations were used to prepare samples for additional mechanical tests. These samples were cured and demolded in the same manner as mentioned in Chapter 5. Following were observations made while pouring samples.

### *Splitting tensile test*

*Observations:* After the samples were poured into the respective molds; they were sharply rapped 10 to 15 times so that all the air bubbles trapped in the sample escaped. . Later, the samples were left to set on the pouring station and were observed for a short duration to make sure that the samples did not sag. During this time, although the samples did not sag significantly, some segregation was observed within the cylindrical molds of sample A and clear water was observed settling close to the bottom of sample A (2:1 solid to water ratio). This probably meant that the excess water present in the sample was bleeding out through the plumber's putty. The other samples performed relatively well.


Figure 45: Splitting tensile samples for Sample A

Source: Iyer 2014

Figure 46: Splitting tensile samples for Sample B
Source: Iyer 2014


Figure 47: Splitting tensile samples for Sample C
Source: Iyer 2014

Figure 48: Separation of water from the grout sample observed (Sample A)
Source: Iyer 2014

Figure 49: Clear water observed close to the plumber's putty (Sample A)
Source: Iyer 2014

***Drying shrinkage***

*Observations:* Similar to the splitting tensile molds, after the samples were poured into the respective molds, they were sharply rapped 10 to 15 times so that all the air bubbles trapped in the sample escaped. Later, the samples were left to set on the pouring station and were observed for a short time to make sure that the samples did not sag. At this time sagging was observed in sample A (more evident) and sample B which can be clearly seen in the samples shaped to form the rectangular shrinkage prisms. Samples C and D, appear to be curing well. Micro cracks were observed close to the corners of the mold in all the different samples in different capacities. Since the sample was still relatively wet and moldable the samples were patted and molded manually by hand so that the cracks did not enlarge further during the process of curing.

Figure 50: Drying shrinkage prisms for Sample A
Source: Iyer 2014

Figure 51: Drying shrinkage prisms for Sample C
Source: Iyer 2014

Figure 52: Drying shrinkage prisms for Sample B
Source: Iyer 2014

### X-Ray Diffraction

Since the preliminary f methylene blue test performed on the mud brick soil samples suggests non-swelling clays, x ray diffraction should be employed to confirm the exact mineralogy of the clays present. .X-Ray diffraction also can determine the presence of the associated parent rock material in the soil mixture.[40]

### Bond strength and Diagonal compression test – adhesion capacity

After an earthen wall cracks, the monolithic character of the wall can be reestablished with the help of an earthen grout intervention. In such cases, an important property that affects the structural behavior of the grouted wall is the shear bond strength between the grout and the cracked wall interface. The interface between the hardened grout and the substrate can be analyzed by the means of performing mechanical tests in direct tension which would help determine the strength of the intervention. Understanding the strength of the intervention is essential because if the bond strength between the grout and the masonry is higher than the cohesive strength of the wall, new failure will result in the wall during an earthquake. The aim of performing this test would be to ensure that the strength of the grouted crack should be moderate; as weak bond strength could lead to disintegration of the repaired section of the wall and strong bond strength would lead to further cracking in the historic structure.[41] Since such a test would require the preparation of a composite specimen, determining the compressive strength, flexural strength and apparent porosity of the mud brick is necessary as

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[40] George W. Brindley, Identification of clay minerals by X-ray Diffraction

[41] Adami C.E, Vintzileou E. and Toumbakari E.E, 2007. Investigation of the bond mechanism between stones or bricks and grouts. In Proceedings of the 5$^{th}$ international conference. Structural analysis of historical constructions: possibilities of numerical and experimental techniques. 6-8 November 2006, New Delhi, India. Vol 2 Eds. P. Lorenco et al., 723-38. New Delhi: MacMillian India; 723

these values would in many cases affect the failure mode and the value of the bond strength of the composite specimen (grout-brick interface).[42]

To further understand the adhesion capacity of any earthen grout, three point bending tests and diagonal compression tests should be performed.[43] The three point bending test helps determine the extent of flexural strength the material would be able to withstand and evaluate how composite or heterogeneous the mud bricks and/or composite specimens can be. These tests help understand the adhesion capacity of the grout in a context where more than two brick substrates are involved. In order to simulate the stresses that an earthen wall would withstand in a real earthquake scenario, diagonal compression tests could be incorporated. This test helps understand how the mud brick and grout would interact when subjected to diagonal tensile (shear) strength and shear modulus. Testing composite specimens in a diagonal compression test would help understand whether the grout would efficiently adhere to cracked sections of the wall and effectively reestablish the monolithic character into the earthen wall. A possible test setup for the diagonal compression test can be performed based on the initial schematic test design as shown in Appendix C.

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[42] Ibid; 724

[43] R.A.Silva, D.V. Oliveira & P.B.Lourenco, 2014. Experimental investigation on the repair of rammed earth by means of injection of mud grouts. Vernacular Heritage and Earthen Architecture: Contributions for Sustainable Development, 727-733. London: Taylor & Francis Group.

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# APPENDIX A: CHARACTERIZATION OF MUD BRICKS

## Dry Sieve Analysis [44]

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TABLE 5—*Suggested bulk volume of test sample for sieve analysis with 8-in. and 200-mm round sieves.*[a]

| Standard Sieve Designation | | Bulk Volume of Material | |
|---|---|---|---|
| Standard | Alternate | Recommended Volume of Material for Test Sample | Maximum Permitted Volume on Sieve on Completion of Sieving |
| 1 | 2 | 3 | 4 |
| 25.0 mm | 1 in. | 1800 $cm^3$ | 900 $cm^3$ |
| 22.4 | 7/8 | 1600 | 800 |
| 19.0 | 3/4 | 1400 | 700 |
| 16.0 | 5/8 | 1000 | 500 |
| 12.5 | 1/2 | 800 | 400 |
| 11.2 | 7/16 | 800 | 400 |
| 9.5 | 3/8 | 600 | 300 |
| 8.0 | 5/16 | 500 | 250 |
| 6.3 | 1/4 | 400 | 200 |
| 5.6 | No. 3 1/2 | 400 | 200 |
| 4.0 | No. 5 | 350 | 150 |
| 2.80 | No. 7 | 240 | 120 |
| 2.0 | No. 10 | 200 | 100 |
| 1.40 | No. 14 | 160 | 80 |
| 1.0 | No. 18 | 140 | 70 |
| 710 μm | No. 25 | 120 | 60 |
| 500 | No. 35 | 100 | 50 |
| 355 | No. 45 | 80 | 40 |
| 250 | No. 60 | 70 | 35 |
| 180 | No. 80 | 60 | 30 |
| 125 | No. 120 | 50 | 25 |
| 90 | No. 170 | 40 | 20 |
| 63 | No. 230 | 35 | 17 |
| 45 | No. 325 | 30 | 15 |
| 38 | No. 400 | 25 | 12 |

[a] The recommended weight of material for a sieve test sample is calculated by multiplying the bulk volume figure in Column 3 by the particular bulk density in grams per cubic centimeter of the material, rounded out within a tolerance of ±25 percent. If the density figure for the material being tested is not readily available, use the factor of the nearest similar material shown in Table 6.

Table 7: Suggested bulk volume of test sample for sieve analysis with 8-in round sieves

[44] STP 447 B Manual on Test sieving methods

TABLE 6—*Typical bulk densities of various particulate materials.* (Weights, per unit of volume, are of divided, crushed, or pulverized materials in freely poured condition.[a])

| Material | Average Weight Lbs/Ft³ | Average Weight G/Cm³ |
|---|---|---|
| Alumina | 44 | 1.23 |
| Aluminum, calcined | 128 | 2.05 |
| Aluminum oxide | 122 | 1.96 |
| Aluminum shot | 96 | 1.54 |
| Ammonium nitrate | 48 | 0.77 |
| Ammonium sulphate | 61 | 0.98 |
| Asbestos ore | 54 | 0.87 |
| Bagasse | 6 | 0.09 |
| Bauxite ore | 75 to 85 | 1.20 to 1.36 |
| Bentonite | 50 to 65 | 0.80 to 1.04 |
| Bicarbonate of soda | 57 | 0.91 |
| Borax | 50 to 61 | 0.80 to 0.98 |
| Boric acid | 58 | 0.93 |
| Calcite | 90 to 105 | 1.44 to 1.68 |
| Calcium carbide | 75 | 1.20 |
| Calcium carbonate | 49 | 0.79 |
| Calcium chloride | 64 | 1.03 |
| Calcium phosphate | 57 | 0.91 |
| Carbon black | 24 | 0.33 |
| Cellulose powder | 16 | 0.26 |
| Cement, portland | 90 to 100 | 1.44 to 1.60 |
| Cement clinker | 75 to 80 | 1.20 to 1.28 |
| Chrome ore | 140 | 2.25 |
| Clay | 30 to 75 | 0.48 to 1.20 |
| Coal, anthracite | 55 | 0.88 |
| Coal, bituminous | 50 | 0.88 |
| Coke breeze | 25 to 35 | 0.40 to 0.56 |
| Coke, petroleum | 25 to 40 | 0.40 to 0.64 |
| Copper ore | 100 to 150 | 1.60 to 2.40 |
| Coquina shell | 80 | 1.28 |
| Corn starch | 40 | 0.64 |
| Diatomaceous earth | 31 | 0.5 |
| Dicalcium phosphate | 64 | 1.03 |
| Dolomite, crushed | 90 to 100 | 1.44 to 1.60 |
| Feldspar, crushed | 65 to 84 | 1.04 to 1.35 |
| Ferrophosphorous | 196 | 3.11 |
| Fire clay | 80 | 1.28 |
| Flour, wheat | 24 | 0.38 |
| Flour, maize | 37 | 0.59 |
| Fluorspar | 90 to 120 | 1.44 to 1.92 |
| Fly ash | 49 | 0.79 |
| Fullers earth | 30 to 40 | 0.48 to 0.64 |
| Garnet | 168 | 2.69 |
| Glass beads | 76 | 1.22 |
| Glass, crushed | 66 | 1.06 |
| Glass cullet | 93 | 1.49 |
| Granite, crushed | 95 to100 | 1.52 to 1.60 |
| Gravel | 90 to 100 | 1.44 to 1.60 |
| Gypsum, calcined | 58 | 0.93 |
| Gypsum, crushed | 90 to 100 | 1.44 to 1.60 |
| Irone ore | 120 to 150 | 1.92 to 2.40 |
| Kaolin | 160 | 2.56 |
| Kyanite | 68 | 1.09 |
| Lime, ground | 60 | 0.96 |
| Lime, hydrated | 25 | 0.40 |
| Limestone, crushed | 85 to 100 | 1.36 to 1.60 |
| Limestone, agricultural | 70 | 1.12 |
| Magnesite | 106 | 1.70 |
| Magnetite | 155 | 2.49 |
| Manganese ore | 120 to 136 | 1.92 to 2.18 |
| Marble, crushed | 90 to 95 | 1.44 to 1.52 |
| Metals, powdered | | |
| Aluminum | 80 | 1.28 |
| Copper | 169 | 2.71 |
| Copper-lead | 364 | 5.84 |
| Iron | 243 | 3.90 |
| Nickel | 263 | 4.22 |
| Stainless steel | 240 | 3.85 |
| Tantalum | 300 | 4.80 |
| Mica | 42 | 0.67 |
| Ore, sintered | 114 | 1.83 |
| Oyster shells, ground | 29 | 0.47 |
| Perlite ore | 65 to 75 | 1.04 to 1.20 |
| Plaster, calcined | 64 | 1.03 |
| Polyethylene pellets | 36 | 0.58 |
| Polyethylene powder | 18 | 0.29 |
| Poly (vinyl chloride) | 30 | 0.48 |
| Potash | 77 | 1.23 |
| Potassium carbonate | 79 | 1.27 |
| Pumice | 40 | 0.64 |
| Rubber, chopped | 36 | 0.58 |
| Rubber, ground | 20 | 0.32 |
| Phosphate rock | 75 to 85 | 1.20 to 1.36 |
| Salt, flake | 61 | 0.98 |
| Salt, rock | 66 | 1.06 |
| Salt, table | 75 | 1.20 |
| Sand | 90 to 100 | 1.44 to 1.60 |

Table 8: Typical bulk densities of various particulate materials

TABLE 6—(Continued)—*Typical bulk densities of various particulate materials.*

| Material | Average Weight Lbs/Ft³ | Average Weight G/Cm³ | Material | Average Weight Lbs/Ft³ | Average Weight G/Cm³ |
|---|---|---|---|---|---|
| Sand, silica | 90 to 100 | 1.44 to 1.60 | Sugar, granulated | 50 | 0.80 |
| Sawdust | 18 | 0.29 | Sugar, powdered | 37 | 0.59 |
| Seacoal | 42 | 0.67 | Sulphur, crushed | 50 to 65 | 0.80 to 1.04 |
| Shale | 100 | 1.60 | Talc, powder | 34 | 0.55 |
| Shot, metal | 230 | 3.69 | Talc, granular | 44 | 0.71 |
| Silica flour | 27 | 0.43 | Traprock, crushed | 105 to 110 | 1.68 to 1.76 |
| Silica gel | 45 | 0.72 | Triple superphosphate, granular | 64 | 1.03 |
| Soapstone, pulverized | 40 | 0.64 | Tungsten carbide | 550 | 8.82 |
| Soda ash, light | 25 to 35 | 0.40 to 0.56 | Urea prills | 43 | 0.69 |
| Soda ash, heavy | 55 to 65 | 0.88 to 1.04 | Vermiculite ore | 80 | 1.28 |
| Soda, bicarbonate | 57 | 0.91 | Wood chips | 13 | 0.21 |
| Sodium nitrate | 78 | 1.25 | Zinc dust | 144 | 2.31 |
| Sodium phosphate | 43 | 0.69 | Zirconium oxide | 200 | 3.22 |
| Sodium sulfate | 96 | 1.54 | Zirconium sand | 162 | 2.60 |
| Steel grit | 228 | 3.66 | | | |
| Stone, crushed | 85 to 95 | 1.36 to 1.52 | | | |

[a] Where a single figure is given, it represents an actual weight of a typical average sample of the material recorded by a research laboratory; therefore, the figure can be expected to vary from sample to sample of the same material.

Cont. Table 8: Typical bulk densities of various particulate materials

## Combined dry and wet sieve analysis

| Temp. (C°) | $C_t$ |
|---|---|
| 15 | -1.10 |
| 16 | -0.90 |
| 17 | -0.70 |
| 18 | -0.50 |
| 19 | -0.30 |
| 20 | 0.00 |
| 21 | 0.20 |
| 22 | 0.40 |
| 23 | 0.70 |
| 24 | 1.00 |
| 25 | 1.30 |
| 26 | 1.65 |
| 27 | 2.00 |
| 28 | 2.50 |
| 29 | 3.05 |
| 30 | 3.80 |

Table 9: Temperature Correction Factors (Ct)

| Unit Weight of Soil Solids ($g/cm^3$) | Correction Factor (a) |
|---|---|
| 2.85 | 0.96 |
| 2.80 | 0.97 |
| 2.75 | 0.98 |
| 2.70 | 0.99 |
| 2.65 | 1.00 |
| 2.60 | 1.01 |
| 2.55 | 1.02 |
| 2.50 | 1.04 |

Table 10: Correction factors (a) for unit weight of solids

| Temp (C°) | UNIT WEIGHT OF SOIL SOLIDS ($g/cm^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2.50 | 2.55 | 2.60 | 2.65 | 2.70 | 2.75 | 2.80 | 2.85 |
| ***16*** | 0.0151 | 0.0148 | 0.0146 | 0.0144 | 0.0141 | 0.0139 | 0.0137 | 0.0136 |
| ***17*** | 0.0149 | 0.0146 | 0.0144 | 0.0142 | 0.0140 | 0.0138 | 0.0136 | 0.0134 |
| ***18*** | 0.0148 | 0.0144 | 0.0142 | 0.0140 | 0.0138 | 0.0136 | 0.0134 | 0.0132 |
| ***19*** | 0.0145 | 0.0143 | 0.0140 | 0.0138 | 0.0136 | 0.0134 | 0.0132 | 0.0131 |
| ***20*** | 0.0143 | 0.0141 | 0.0139 | 0.0137 | 0.0134 | 0.0133 | 0.0131 | 0.0129 |
| ***21*** | 0.0141 | 0.0139 | 0.0137 | 0.0135 | 0.0133 | 0.0131 | 0.0129 | 0.0127 |
| ***22*** | 0.0140 | 0.0137 | 0.0135 | 0.0133 | 0.0131 | 0.0129 | 0.0128 | 0.0126 |
| ***23*** | 0.0138 | 0.0136 | 0.0134 | 0.0132 | 0.0130 | 0.0128 | 0.0126 | 0.0124 |
| ***24*** | 0.0137 | 0.0134 | 0.0132 | 0.0130 | 0.0128 | 0.0126 | 0.0125 | 0.0123 |
| ***25*** | 0.0135 | 0.0133 | 0.0131 | 0.0129 | 0.0127 | 0.0125 | 0.0123 | 0.0122 |
| ***26*** | 0.0133 | 0.0131 | 0.0129 | 0.0127 | 0.0125 | 0.0124 | 0.0122 | 0.0120 |
| ***27*** | 0.0132 | 0.0130 | 0.0128 | 0.0126 | 0.0124 | 0.0122 | 0.0120 | 0.0119 |
| ***28*** | 0.0130 | 0.0128 | 0.0126 | 0.0124 | 0.0123 | 0.0121 | 0.0119 | 0.0117 |
| ***29*** | 0.0129 | 0.0127 | 0.0125 | 0.0123 | 0.0121 | 0.0120 | 0.0118 | 0.0116 |
| ***30*** | 0.0128 | 0.0126 | 0.0140 | 0.0122 | 0.0120 | 0.0118 | 0.0117 | 0.0115 |

Table 11: Values of K for several unit weights of soil solids and temperature combinations

| Original Hydrometer Reading (meniscus corrected only) | Effective Depth L (cm) | Original Hydrometer Reading (meniscus corrected only) | Effective Depth L (cm) | Original Hydrometer Reading (meniscus corrected only) | Effective Depth L (cm) |
|---|---|---|---|---|---|
| 0 | 16.3 | 21 | 12.9 | 42 | 9.4 |
| 1 | 16.1 | 22 | 12.7 | 43 | 9.2 |
| 2 | 16.0 | 23 | 12.5 | 44 | 9.1 |
| 3 | 15.8 | 24 | 12.4 | 45 | 8.9 |
| 4 | 15.6 | 25 | 12.2 | 46 | 8.8 |
| 5 | 15.5 | 26 | 12.0 | 47 | 8.6 |
| 6 | 15.3 | 27 | 11.9 | 48 | 8.4 |
| 7 | 15.2 | 28 | 11.7 | 49 | 8.3 |
| 8 | 15.0 | 29 | 11.5 | 50 | 8.1 |
| 9 | 14.8 | 30 | 11.4 | 51 | 7.9 |
| 10 | 14.7 | 31 | 11.2 | 52 | 7.8 |
| 11 | 14.5 | 32 | 11.1 | 53 | 7.6 |
| 12 | 14.3 | 33 | 10.9 | 54 | 7.4 |
| 13 | 14.2 | 34 | 10.7 | 55 | 7.3 |
| 14 | 14.0 | 35 | 10.5 | 56 | 7.1 |
| 15 | 13.8 | 36 | 10.4 | 57 | 7.0 |
| 16 | 13.7 | 37 | 10.2 | 58 | 6.8 |
| 17 | 13.5 | 38 | 10.1 | 59 | 6.6 |
| 18 | 13.3 | 39 | 9.9 | 60 | 6.5 |
| 19 | 13.2 | 40 | 9.7 | | |
| 20 | 13.0 | 41 | 9.6 | | |

Table 12: Value of Effective Depth

| Soil type | Range of $\mathbf{G_s}$ |
|---|---|
| Sand | 2.63-2.67 |
| Silts | 2.65-2.7 |
| Clay and silty clay | 2.67-2.9 |
| Organic soil | 1+ -2.6 |

Table 13: Range of GS for different soil types

*Dry Sieve Analysis (Combined sieving)*

| Sample #2 | |
|---|---|
| Soaking Period (hr) | 66 |
| Dispersion agent (ml) | 125 |
| Total weight of coarse particles (g) | 457.74 |
| Weight of evaporating dish (g) | 349.34 |
| Weight of coarse soil particles (g) | 108.40 |
| Sum of the percent Msx | 108.31 |
| Weight of the fines in S.cylinder (g) | 43.97 |

| Sieve Number | Screen Size (µm) | $M_{CX}$ (g) | $M_X$ (sample + container) (g) | $M_{SX}$ ($M_X$ - $M_{CX}$) (g) | $\%M_{SX}$ ($M_{SX}$ /$M_{ST}$) *100% | $\%M_{rt}$ Σ $\%M_{SX}$ (on or above) | $\%M_{pt}$ 100% - $M_{rt}\%$ | Total Sample Variables | |
|---|---|---|---|---|---|---|---|---|---|
| ***4*** | *4750* | 7.62 | 10.83 | 3.21 | 2.14% | 2.14% | 97.86% | | |
| ***8*** | *2360* | 7.56 | 12.72 | 5.16 | 3.43% | 5.57% | 94.43% | | |
| ***10*** | *2000* | 7.41 | 8.61 | 1.20 | 0.80% | 6.37% | 93.63% | **$M_{XT}$ (g)** | 150.34 |
| ***16*** | *1180* | 7.67 | 13.66 | 5.99 | 3.98% | 10.35% | 89.65% | | |
| ***30*** | *600* | 7.26 | 20.67 | 13.41 | 8.92% | 19.27% | 80.73% | **$M_{CT}$ (g)** | 349.34 |
| ***40*** | *425* | 7.15 | 18.29 | 11.14 | 7.41% | 26.68% | 73.32% | **$M_T$ (g)** | 457.74 |
| ***50*** | *300* | 6.90 | 16.70 | 9.80 | 6.52% | 33.20% | 66.80% | **$M_{ST}$ (g)** | 108.40 |
| ***100*** | *150* | 7.24 | 29.39 | 22.15 | 14.73% | 47.93% | 52.07% | | |
| ***200*** | *75* | 7.10 | 41.32 | 34.22 | 22.76% | 70.69% | 29.31% | **$M_L\%$** | 0.08% |
| ***pan*** | *1* | 7.04 | 9.07 | 2.03 | 1.35% | 72.04% | 27.96% | | |

Table 14: Dry Sieve Analysis for sample #2

| Sample #5 | |
|---|---|
| Soaking Period (hr.) | 17 |
| Dispersion agent (ml) | 125 |
| Total weight of coarse particles (g) | 464.37 |
| Weight of evaporating dish (g) | 357.76 |
| Weight of coarse soil particles (g) | 106.61 |
| Sum of the percent Msx | 106.58 |
| Weight of the fines in S.cylinder (g) | 43.76 |

| Sieve Number | Screen Size (µm) | $M_{CX}$ (g) | $M_X$ (sample + container) (g) | $M_{SX}$ ($M_X$ - $M_{CX}$) (g) | $\%M_{SX}$ ($M_{SX}$/$M_{ST}$) *100% | $\%M_{rt}$ $\Sigma$ $\%M_{SX}$ (on or above) | $\%M_{pt}$ 100% - $M_{rt}\%$ | Total Sample Variables | |
|---|---|---|---|---|---|---|---|---|---|
| ***4*** | *4750* | 6.76 | 8.84 | 2.08 | 1.38% | 1.38% | 98.62% | | |
| ***8*** | *2360* | 6.18 | 10.23 | 4.05 | 2.69% | 4.08% | 95.92% | | |
| ***10*** | *2000* | 7.12 | 8.12 | 1.00 | 0.67% | 4.74% | 95.26% | $M_{XT}$ (g) | 150.37 |
| ***16*** | *1180* | 7.07 | 12.88 | 5.81 | 3.86% | 8.61% | 91.39% | | |
| ***30*** | *600* | 6.59 | 18.81 | 12.22 | 8.13% | 16.73% | 83.27% | $M_{CT}$ (g) | 357.76 |
| ***40*** | *425* | 6.70 | 17.53 | 10.83 | 7.20% | 23.93% | 76.07% | $M_T$ (g) | 464.37 |
| ***50*** | *300* | 6.63 | 16.53 | 9.90 | 6.58% | 30.52% | 69.48% | $M_{ST}$ (g) | 106.61 |
| ***100*** | *150* | 6.37 | 29.10 | 22.73 | 15.12% | 45.63% | 54.37% | | |
| ***200*** | *75* | 7.09 | 43.17 | 36.08 | 23.99% | 69.63% | 30.37% | $M_L\%$ | 0.03% |
| ***pan*** | *1* | 7.00 | 8.88 | 1.88 | 1.25% | 70.88% | 29.12% | | |

Table 15: Dry Sieve Analysis for sample #5

| Sample #6 | |
|---|---|
| Soaking Period (hr.) | 22 |
| Dispersion agent (ml) | 125 |
| Total weight of coarse particles (g) | 490.58 |
| Weight of evaporating dish (g) | 384.32 |
| Weight of coarse soil particles (g) | 106.26 |
| Sum of the percent Msx | 106.12 |
| Weight of the fines in S.cylinder (g) | 44.78 |

| Sieve Number | Screen Size (µm) | $M_{CX}$ (g) | $M_X$ (sample + container) (g) | $M_{SX}$ ($M_X$ - $M_{CX}$) (g) | $\%M_{SX}$ ($M_{SX}$ /$M_{ST}$) *100% | $\%M_{rt}$ Σ $\%M_{SX}$ (on or above) | $\%M_{pt}$ 100% - $M_{rt}$% | Total Sample Variables | |
|---|---|---|---|---|---|---|---|---|---|
| ***4*** | *4750* | 7.37 | 7.88 | 0.51 | 0.34% | 0.34% | 99.66% | | |
| ***8*** | *2360* | 7.29 | 10.22 | 2.93 | 1.94% | 2.28% | 97.72% | | |
| ***10*** | *2000* | 7.42 | 8.45 | 1.03 | 0.68% | 2.96% | 97.04% | **$M_{XT}$ (g)** | 151.04 |
| ***16*** | *1180* | 7.19 | 12.69 | 5.50 | 3.64% | 6.60% | 93.40% | | |
| ***30*** | *600* | 7.35 | 20.85 | 13.50 | 8.94% | 15.54% | 84.46% | **$M_{CT}$ (g)** | 384.32 |
| ***40*** | *425* | 7.37 | 18.75 | 11.38 | 7.53% | 23.07% | 76.93% | **$M_T$ (g)** | 490.58 |
| ***50*** | *300* | 7.25 | 17.05 | 9.80 | 6.49% | 29.56% | 70.44% | **$M_{ST}$ (g)** | 106.26 |
| ***100*** | *150* | 7.49 | 30.79 | 23.30 | 15.43% | 44.99% | 55.01% | | |
| ***200*** | *75* | 7.47 | 43.64 | 36.17 | 23.95% | 68.94% | 31.06% | **$M_L$%** | 0.13% |
| ***pan*** | *1* | 7.44 | 9.44 | 2.00 | 1.32% | 70.26% | 29.74% | | |

Table 16: Dry Sieve Analysis for sample #6

***Sedimentation Analysis (Combined sieving)***

| **Sample #2** | |
|---|---|
| Weight of beaker (g) | 283.77 |
| Total weight of sample (g) | 434.11 |
| Weight of the soil sample (g) [$M_{XT}$] | 150.34 |

| Date | Time of Reading | Elapsed Time (min) | Temp (Cº) | Hydrometer Reading ($R_a$) | A | B | Meniscus Correction (add it) | Meniscus Corrected Reading ($R_{MC}$) | X (Dispersion agent correction) | $C_T$ | Corrected Reading (Rc) | a | $W_S$ | % Finer of whole sample | L | L/t | K (from table 3) | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2/25/2014** | 5:09 PM | 0.5 | 22 | 34.0 | 0 | 0.001 | 1 | 35.0 | 4.7 | 0.40 | 29.7 | 0.99 | 150.34 | 19.53% | 10.5 | 21.000 | 0.0131 | 0.0600 | 60.03 |
| 2/25/2014 | 5:10 PM | 1 | 22 | 30.0 | 0 | 0.001 | 1 | 31.0 | 4.7 | 0.40 | 25.7 | 0.99 | 150.34 | 16.90% | 11.2 | 11.200 | 0.0131 | 0.0438 | 43.84 |
| 2/25/2014 | 5:11 PM | 2 | 22 | 25.0 | 0 | 0.001 | 1 | 26.0 | 4.7 | 0.40 | 20.7 | 0.99 | 150.34 | 13.60% | 12.0 | 6.000 | 0.0131 | 0.0321 | 32.09 |
| 2/25/2014 | 5:13 PM | 4 | 22 | 22.0 | 0 | 0.001 | 1 | 23.0 | 4.7 | 0.40 | 17.7 | 0.99 | 150.34 | 11.63% | 12.5 | 3.125 | 0.0131 | 0.0232 | 23.16 |
| 2/25/2014 | 5:17 PM | 8 | 22 | 20.0 | 0 | 0.001 | 1 | 21.0 | 4.7 | 0.40 | 15.7 | 0.99 | 150.34 | 10.31% | 12.9 | 1.613 | 0.0131 | 0.0166 | 16.63 |
| 2/25/2014 | 5:19 PM | 10 | 22 | 20.0 | 0 | 0.001 | 1 | 21.0 | 4.7 | 0.40 | 15.7 | 0.99 | 150.34 | 10.31% | 12.9 | 1.290 | 0.0131 | 0.0149 | 14.88 |
| 2/25/2014 | 5:24 PM | 15 | 22 | 19.0 | 0 | 0.001 | 1 | 20.0 | 4.7 | 0.40 | 14.7 | 0.99 | 150.34 | 9.65% | 13.0 | 0.867 | 0.0131 | 0.0122 | 12.20 |
| 2/25/2014 | 5:39 PM | 30 | 22 | 19.0 | 0 | 0.001 | 1 | 20.0 | 4.7 | 0.40 | 14.7 | 0.99 | 150.34 | 9.65% | 13.0 | 0.433 | 0.0131 | 0.0086 | 8.62 |
| 2/25/2014 | 6:09 PM | 60 | 22 | 17.0 | 0 | 0.001 | 1 | 18.0 | 4.7 | 0.40 | 12.7 | 0.99 | 150.34 | 8.34% | 13.3 | 0.222 | 0.0131 | 0.0062 | 6.17 |
| 2/25/2014 | 6:13 PM | 124 | 22 | 17.0 | 0 | 0.001 | 1 | 18.0 | 4.7 | 0.40 | 12.7 | 0.99 | 150.34 | 8.34% | 13.3 | 0.107 | 0.0131 | 0.0043 | 4.29 |
| 2/25/2014 | 8:09 PM | 240 | 22 | 17.0 | 0 | 0.001 | 1 | 18.0 | 4.7 | 0.40 | 12.7 | 0.99 | 150.34 | 8.34% | 13.3 | 0.055 | 0.0131 | 0.0031 | 3.08 |
| 2/25/2014 | 9:09 PM | 300 | 22 | 16.0 | 0 | 0.001 | 1 | 17.0 | 4.7 | 0.40 | 11.7 | 0.99 | 150.34 | 7.68% | 13.5 | 0.045 | 0.0131 | 0.0028 | 2.78 |
| **2/26/2014** | 3:14 PM | 1325 | 22 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.40 | 9.7 | 0.99 | 150.34 | 6.36% | 13.8 | 0.010 | 0.0131 | 0.0013 | 1.34 |
| 2/26/2014 | 9:40 PM | 1711 | 23 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.70 | 9.0 | 0.99 | 150.34 | 5.90% | 14.0 | 0.008 | 0.0130 | 0.0012 | 1.18 |
| **2/27/2014** | 1:09 PM | 2640 | 22 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.40 | 8.7 | 0.99 | 150.34 | 5.70% | 14.0 | 0.005 | 0.0131 | 0.0010 | 0.95 |
| 2/27/2014 | 4:06 PM | 2817 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.005 | 0.0131 | 0.0009 | 0.93 |
| 2/27/2014 | 7:48 PM | 3039 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.005 | 0.0131 | 0.0009 | 0.90 |
| 2/27/2014 | 8:58 PM | 3109 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.005 | 0.0131 | 0.0009 | 0.89 |
| **2/28/2014** | 2:45 PM | 4176 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.003 | 0.0131 | 0.0008 | 0.76 |
| 2/28/2014 | 5:43 PM | 4354 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.003 | 0.0131 | 0.0007 | 0.75 |
| **3/1/2014** | 5:11 PM | 5761 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.002 | 0.0131 | 0.0007 | 0.65 |
| 3/1/2014 | 9:05 PM | 7435 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.34 | 5.04% | 14.2 | 0.002 | 0.0131 | 0.0006 | 0.57 |
| **3/2/2014** | 1:55 AM | 7725 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.34 | 4.39% | 14.3 | 0.002 | 0.0131 | 0.0006 | 0.56 |
| 3/2/2014 | 1:04 PM | 8394 | 22 | 10.0 | 0 | 0.001 | 1 | 11.0 | 4.7 | 0.40 | 5.7 | 0.99 | 150.34 | 3.73% | 14.5 | 0.002 | 0.0131 | 0.0005 | 0.54 |
| **3/3/2014** | 11:11 PM | 9001 | 20 | 10.0 | 0 | 0.001 | 1 | 11.0 | 4.7 | 0.00 | 5.3 | 0.99 | 150.34 | 3.46% | 14.5 | 0.002 | 0.0134 | 0.0005 | 0.54 |
| **3/4/2014** | 1:22 AM | 10212 | 20 | 10.0 | 0 | 0.001 | 1 | 11.0 | 4.7 | 0.00 | 5.3 | 0.99 | 150.34 | 3.46% | 14.5 | 0.001 | 0.0134 | 0.0005 | 0.50 |
| 3/4/2014 | 8:05 PM | 11335 | 22 | 9.0 | 0 | 0.001 | 1 | 10.0 | 4.7 | 0.40 | 4.7 | 0.99 | 150.34 | 3.07% | 14.7 | 0.001 | 0.0131 | 0.0005 | 0.47 |
| **3/5/2014** | 2:30 AM | 11720 | 22 | 9.0 | 0 | 0.001 | 1 | 10.0 | 4.7 | 0.40 | 4.7 | 0.99 | 150.34 | 3.07% | 14.7 | 0.001 | 0.0131 | 0.0005 | 0.46 |
| **3/6/2014** | 1:05 AM | 13075 | 22 | 9.0 | 0 | 0.001 | 1 | 10.0 | 4.7 | 0.40 | 4.7 | 0.99 | 150.34 | 3.07% | 14.7 | 0.001 | 0.0131 | 0.0004 | 0.44 |
| 3/6/2014 | 11:34 PM | 14364 | 22 | 9.0 | 0 | 0.001 | 1 | 10.0 | 4.7 | 0.40 | 4.7 | 0.99 | 150.34 | 3.07% | 14.7 | 0.001 | 0.0131 | 0.0004 | 0.42 |
| **3/12/2014** | 1:55 PM | 21374 | 24 | 6.0 | 0 | 0.001 | 1 | 7.0 | 4.7 | 0.40 | 1.7 | 0.99 | 150.34 | 1.09% | 15.2 | 0.001 | 0.0128 | 0.0003 | 0.34 |

| **Cm = (B - A)* 1000** | |
|---|---|
| **B** | 0.001 |
| **A** | 0.000 |

| **x = 2Md** | |
|---|---|
| **x** | 4.74 |
| **Md** | 2.37 |

| **Md = Wt. of beaker - Wt of beaker (drying)** | |
|---|---|
| Weight of the beaker (g) | 129.91 |
| Weight of the beaker (drying) (g) | 132.28 |

Table 17: Sedimentation Analysis for sample #2

| Sample #5 | |
|---|---|
| Weight of beaker (g) | 185.34 |
| Total weight of sample (g) | 335.71 |
| Weight of the soil sample (g) [$M_{XT}$] | 150.37 |

| Date | Time of Reading | Elapsed Time (min) | Temp (Cº) | Hydrometer Reading ($R_a$) | A | B | Meniscus Correction (add it) | Meniscus Corrected Reading ($R_{MC}$) | X (Dispersion agent correction) | $C_T$ | Corrected Reading (Rc) | a | $W_S$ | % Finer of whole sample | L | L/t | K (from table 3) | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2/22/2014** | 4:19 PM | 0.5 | 21 | 34.0 | 0 | 0.001 | 1 | 35.0 | 4.7 | 0.20 | 29.5 | 0.99 | 150.37 | 19.40% | 10.5 | 21.000 | 0.0133 | 0.0609 | 60.95 |
| 2/22/2014 | 4:20 PM | 1 | 21 | 30.0 | 0 | 0.001 | 1 | 31.0 | 4.7 | 0.20 | 25.5 | 0.99 | 150.37 | 16.76% | 11.2 | 11.200 | 0.0133 | 0.0445 | 44.51 |
| 2/22/2014 | 4:21 PM | 2 | 21 | 26.0 | 0 | 0.001 | 1 | 27.0 | 4.7 | 0.20 | 21.5 | 0.99 | 150.37 | 14.13% | 11.9 | 2.975 | 0.0133 | 0.0229 | 22.94 |
| 2/22/2014 | 4:23 PM | 4 | 21 | 23.0 | 0 | 0.001 | 1 | 24.0 | 4.7 | 0.20 | 18.5 | 0.99 | 150.37 | 12.15% | 12.4 | 1.550 | 0.0133 | 0.0166 | 16.56 |
| 2/22/2014 | 4:27 PM | 8 | 21 | 22.0 | 0 | 0.001 | 1 | 23.0 | 4.7 | 0.20 | 17.5 | 0.99 | 150.37 | 11.50% | 12.5 | 1.250 | 0.0133 | 0.0149 | 14.87 |
| 2/22/2014 | 4:29 PM | 10 | 21 | 21.0 | 0 | 0.001 | 1 | 22.0 | 4.7 | 0.20 | 16.5 | 0.99 | 150.37 | 10.84% | 12.7 | 0.847 | 0.0133 | 0.0122 | 12.24 |
| 2/22/2014 | 4:34 PM | 15 | 21 | 20.0 | 0 | 0.001 | 1 | 21.0 | 4.7 | 0.20 | 15.5 | 0.99 | 150.37 | 10.18% | 12.9 | 0.430 | 0.0133 | 0.0087 | 8.72 |
| 2/22/2014 | 4:49 PM | 30 | 21 | 20.0 | 0 | 0.001 | 1 | 21.0 | 4.7 | 0.20 | 15.5 | 0.99 | 150.37 | 10.18% | 12.9 | 0.215 | 0.0133 | 0.0062 | 6.17 |
| 2/22/2014 | 5:19 PM | 60 | 21 | 19.0 | 0 | 0.001 | 1 | 20.0 | 4.7 | 0.20 | 14.5 | 0.99 | 150.37 | 9.52% | 13.0 | 0.108 | 0.0133 | 0.0044 | 4.38 |
| 2/22/2014 | 6:19 PM | 120 | 21 | 18.0 | 0 | 0.001 | 1 | 19.0 | 4.7 | 0.20 | 13.5 | 0.99 | 150.37 | 8.86% | 13.2 | 0.055 | 0.0133 | 0.0031 | 3.11 |
| 2/22/2014 | 8:20 PM | 241 | 21 | 17.0 | 0 | 0.001 | 1 | 18.0 | 4.7 | 0.20 | 12.5 | 0.99 | 150.37 | 8.20% | 13.3 | 0.027 | 0.0133 | 0.0022 | 2.20 |
| **2/23/2014** | 12:24 AM | 485 | 21 | 16.0 | 0 | 0.001 | 1 | 17.0 | 4.7 | 0.20 | 11.5 | 0.99 | 150.37 | 7.54% | 13.5 | 0.010 | 0.0133 | 0.0013 | 1.30 |
| 2/23/2014 | 3:43 PM | 1404 | 23 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.70 | 10.0 | 0.99 | 150.37 | 6.56% | 13.8 | 0.009 | 0.0130 | 0.0012 | 1.24 |
| 2/23/2014 | 5:37 PM | 1518 | 23 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.70 | 10.0 | 0.99 | 150.37 | 6.56% | 13.8 | 0.009 | 0.0130 | 0.0012 | 1.20 |
| 2/23/2014 | 7:13 PM | 1614 | 23 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.70 | 10.0 | 0.99 | 150.37 | 6.56% | 13.8 | 0.008 | 0.0130 | 0.0011 | 1.15 |
| 2/23/2014 | 9:49 PM | 1770 | 23 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.70 | 10.0 | 0.99 | 150.37 | 6.56% | 13.8 | 0.005 | 0.0130 | 0.0010 | 0.96 |
| **2/24/2014** | 10:50 AM | 2551 | 22 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.40 | 9.7 | 0.99 | 150.37 | 6.36% | 13.8 | 0.005 | 0.0131 | 0.0009 | 0.89 |
| 2/24/2014 | 5:51 PM | 2972 | 22 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.40 | 8.7 | 0.99 | 150.37 | 5.70% | 14.0 | 0.004 | 0.0131 | 0.0009 | 0.88 |
| 2/24/2014 | 8:23 PM | 3124 | 22 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.40 | 8.7 | 0.99 | 150.37 | 5.70% | 14.0 | 0.003 | 0.0131 | 0.0008 | 0.76 |
| **2/25/2014** | 1:54 PM | 4175 | 22 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.40 | 8.7 | 0.99 | 150.37 | 5.70% | 14.0 | 0.003 | 0.0131 | 0.0007 | 0.75 |
| 2/25/2014 | 3:49 PM | 4290 | 22 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.40 | 8.7 | 0.99 | 150.37 | 5.70% | 14.0 | 0.003 | 0.0131 | 0.0007 | 0.72 |
| 2/25/2014 | 8:49 PM | 4590 | 21 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.20 | 7.5 | 0.99 | 150.37 | 4.91% | 14.2 | 0.003 | 0.0133 | 0.0007 | 0.73 |
| 2/25/2014 | 10:35 PM | 4696 | 21 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.20 | 7.5 | 0.99 | 150.37 | 4.91% | 14.2 | 0.003 | 0.0133 | 0.0007 | 0.67 |
| **2/26/2014** | 2:43 PM | 5664 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.37 | 5.04% | 14.2 | 0.002 | 0.0131 | 0.0006 | 0.63 |
| 2/26/2014 | 9:15 PM | 6056 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.37 | 5.04% | 14.2 | 0.002 | 0.0131 | 0.0006 | 0.59 |
| **2/27/2014** | 2:42 AM | 6983 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 150.37 | 5.04% | 14.2 | 0.002 | 0.0131 | 0.0006 | 0.58 |
| 2/27/2014 | 5:40 AM | 7161 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.37 | 4.38% | 14.3 | 0.002 | 0.0131 | 0.0006 | 0.58 |
| 2/27/2014 | 9:23 AM | 7384 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.37 | 4.38% | 14.3 | 0.002 | 0.0131 | 0.0006 | 0.57 |
| 2/27/2014 | 10:30 AM | 7451 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.37 | 4.38% | 14.3 | 0.002 | 0.0131 | 0.0005 | 0.54 |
| **2/28/2014** | 4:16 AM | 8517 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.37 | 4.38% | 14.3 | 0.002 | 0.0131 | 0.0005 | 0.53 |
| 2/28/2014 | 7:14 AM | 8695 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.37 | 4.38% | 14.3 | 0.001 | 0.0131 | 0.0005 | 0.49 |
| **3/1/2014** | 6:35 AM | 10096 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 150.37 | 4.38% | 14.3 | 0.001 | 0.0131 | 0.0005 | 0.46 |
| 3/1/2014 | 10:36 AM | 11777 | 21 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.20 | 6.5 | 0.99 | 150.37 | 4.25% | 14.3 | 0.001 | 0.0133 | 0.0005 | 0.46 |
| 3/1/2014 | 3:26 PM | 12067 | 21 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.20 | 6.5 | 0.99 | 150.37 | 4.25% | 14.3 | 0.001 | 0.0133 | 0.0005 | 0.46 |
| 3/1/2014 | 2:35 AM | 12736 | 20 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.00 | 6.3 | 0.99 | 150.37 | 4.12% | 14.3 | 0.001 | 0.0134 | 0.0004 | 0.45 |
| 3/1/2014 | 12:42 PM | 13343 | 20 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.00 | 6.3 | 0.99 | 150.37 | 4.12% | 14.3 | 0.001 | 0.0134 | 0.0004 | 0.44 |
| **3/5/2014** | 6:04 AM | 18705 | 22 | 6.0 | 0 | 0.001 | 1 | 7.0 | 4.7 | 0.40 | 1.7 | 0.99 | 150.37 | 1.09% | 15.2 | 0.001 | 0.0131 | 0.0004 | 0.37 |

| Cm = (B - A)* 1000 | |
|---|---|
| B | 0.001 |
| A | 0.000 |

| x = 2Md | |
|---|---|
| x | 4.74 |
| Md | 2.37 |

| Md = Wt. of beaker - Wt of beaker (drying) | |
|---|---|
| Weight of the beaker (g) | 129.91 |
| Weight of the beaker (drying) (g) | 132.28 |

Table 18: Sedimentation Analysis for sample #5

| **Sample #6** | |
|---|---|
| Weight of beaker (g) | 201.02 |
| Total weight of sample (g) | 352.06 |
| Weight of the soil sample (g) [$M_{XT}$] | 151.04 |

| Date | Time of Reading | Elapsed Time (min) | Temp (Cº) | Hydrometer Reading ($R_a$) | A | B | Meniscus Correction (add it) | Meniscus Corrected Reading ($R_{MC}$) | X (Dispersion agent correction) | $C_T$ | Corrected Reading (Rc) | a | $W_S$ | % Finer of whole sample | L | L/t | K (from table 3) | D (mm) | D (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2/26/2014** | 6:09 PM | 0.5 | 22 | 37.0 | 0 | 0.001 | 1 | 38.0 | 4.7 | 0.40 | 32.7 | 0.99 | 151.04 | 21.41% | 10.1 | 20.200 | 0.0131 | 0.0589 | 58.88 |
| 2/26/2014 | 6:10 PM | 1 | 22 | 33.0 | 0 | 0.001 | 1 | 34.0 | 4.7 | 0.40 | 28.7 | 0.99 | 151.04 | 18.79% | 10.7 | 10.700 | 0.0131 | 0.0429 | 42.85 |
| 2/26/2014 | 6:11 PM | 2 | 22 | 28.0 | 0 | 0.001 | 1 | 29.0 | 4.7 | 0.40 | 23.7 | 0.99 | 151.04 | 15.51% | 11.5 | 5.750 | 0.0131 | 0.0314 | 31.41 |
| 2/26/2014 | 6:13 PM | 4 | 22 | 25.0 | 0 | 0.001 | 1 | 26.0 | 4.7 | 0.40 | 20.7 | 0.99 | 151.04 | 13.54% | 12.0 | 3.000 | 0.0131 | 0.0227 | 22.69 |
| 2/26/2014 | 6:17 PM | 8 | 22 | 23.0 | 0 | 0.001 | 1 | 24.0 | 4.7 | 0.40 | 18.7 | 0.99 | 151.04 | 12.23% | 12.4 | 1.550 | 0.0131 | 0.0163 | 16.31 |
| 2/26/2014 | 6:24 PM | 15 | 22 | 22.0 | 0 | 0.001 | 1 | 23.0 | 4.7 | 0.40 | 17.7 | 0.99 | 151.04 | 11.58% | 12.5 | 0.833 | 0.0131 | 0.0120 | 11.96 |
| 2/26/2014 | 6:39 PM | 30 | 22 | 21.0 | 0 | 0.001 | 1 | 22.0 | 4.7 | 0.40 | 16.7 | 0.99 | 151.04 | 10.92% | 12.7 | 0.423 | 0.0131 | 0.0085 | 8.52 |
| 2/26/2014 | 7:09 PM | 60 | 22 | 20.0 | 0 | 0.001 | 1 | 21.0 | 4.7 | 0.40 | 15.7 | 0.99 | 151.04 | 10.26% | 12.9 | 0.215 | 0.0131 | 0.0061 | 6.07 |
| 2/26/2014 | 8:10 PM | 121 | 22 | 20.0 | 0 | 0.001 | 1 | 21.0 | 4.7 | 0.40 | 15.7 | 0.99 | 151.04 | 10.26% | 12.9 | 0.107 | 0.0131 | 0.0043 | 4.28 |
| 2/26/2014 | 10:10 PM | 241 | 22 | 19.0 | 0 | 0.001 | 1 | 20.0 | 4.7 | 0.40 | 14.7 | 0.99 | 151.04 | 9.61% | 13.0 | 0.054 | 0.0131 | 0.0030 | 3.04 |
| **2/27/2014** | 1:41 PM | 1172 | 22 | 16.0 | 0 | 0.001 | 1 | 17.0 | 4.7 | 0.40 | 11.7 | 0.99 | 151.04 | 7.64% | 13.5 | 0.012 | 0.0131 | 0.0014 | 1.41 |
| 2/27/2014 | 4:39 PM | 1350 | 22 | 15.0 | 0 | 0.001 | 1 | 16.0 | 4.7 | 0.40 | 10.7 | 0.99 | 151.04 | 6.99% | 13.7 | 0.010 | 0.0131 | 0.0013 | 1.32 |
| 2/27/2014 | 8:20 PM | 1571 | 22 | 15.0 | 0 | 0.001 | 1 | 16.0 | 4.7 | 0.40 | 10.7 | 0.99 | 151.04 | 6.99% | 13.7 | 0.009 | 0.0131 | 0.0012 | 1.22 |
| 2/27/2014 | 9:30 PM | 1641 | 22 | 15.0 | 0 | 0.001 | 1 | 16.0 | 4.7 | 0.40 | 10.7 | 0.99 | 151.04 | 6.99% | 13.7 | 0.008 | 0.0131 | 0.0012 | 1.20 |
| **2/28/2014** | 4:17 PM | 2708 | 22 | 15.0 | 0 | 0.001 | 1 | 16.0 | 4.7 | 0.40 | 10.7 | 0.99 | 151.04 | 6.99% | 13.7 | 0.005 | 0.0131 | 0.0009 | 0.93 |
| 2/28/2014 | 7:14 PM | 2885 | 22 | 14.0 | 0 | 0.001 | 1 | 15.0 | 4.7 | 0.40 | 9.7 | 0.99 | 151.04 | 6.33% | 13.8 | 0.005 | 0.0131 | 0.0009 | 0.91 |
| **3/1/2014** | 6:40 PM | 4291 | 22 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.40 | 8.7 | 0.99 | 151.04 | 5.68% | 14.0 | 0.003 | 0.0131 | 0.0007 | 0.75 |
| **3/2/2014** | 10:37 PM | 5968 | 21 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.20 | 8.5 | 0.99 | 151.04 | 5.55% | 14.0 | 0.002 | 0.0133 | 0.0006 | 0.64 |
| **3/3/2014** | 3:26 AM | 6257 | 21 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.20 | 8.5 | 0.99 | 151.04 | 5.55% | 14.0 | 0.002 | 0.0133 | 0.0006 | 0.63 |
| 3/3/2014 | 2:36 PM | 6927 | 20 | 13.0 | 0 | 0.001 | 1 | 14.0 | 4.7 | 0.00 | 8.3 | 0.99 | 151.04 | 5.41% | 14.0 | 0.002 | 0.0134 | 0.0006 | 0.60 |
| **3/4/2014** | 12:42 AM | 7533 | 20 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.00 | 7.3 | 0.99 | 151.04 | 4.76% | 14.2 | 0.002 | 0.0134 | 0.0006 | 0.58 |
| 3/4/2014 | 8:54 PM | 8745 | 22 | 12.0 | 0 | 0.001 | 1 | 13.0 | 4.7 | 0.40 | 7.7 | 0.99 | 151.04 | 5.02% | 14.2 | 0.002 | 0.0131 | 0.0005 | 0.53 |
| **3/5/2014** | 3:37 PM | 9868 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 151.04 | 4.37% | 14.3 | 0.001 | 0.0131 | 0.0005 | 0.50 |
| 3/5/2014 | 10:01 PM | 10252 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 151.04 | 4.37% | 14.3 | 0.001 | 0.0131 | 0.0005 | 0.49 |
| **3/6/2014** | 8:37 PM | 11608 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 151.04 | 4.37% | 14.3 | 0.001 | 0.0131 | 0.0005 | 0.46 |
| **3/7/2014** | 6:08 PM | 12899 | 22 | 11.0 | 0 | 0.001 | 1 | 12.0 | 4.7 | 0.40 | 6.7 | 0.99 | 151.04 | 4.37% | 14.3 | 0.001 | 0.0131 | 0.0004 | 0.44 |
| **3/13/2014** | 10:30 AM | 21141 | 22 | 7.0 | 0 | 0.001 | 1 | 8.0 | 4.7 | 0.40 | 2.7 | 0.99 | 151.04 | 1.74% | 15.0 | 0.001 | 0.0131 | 0.0003 | 0.35 |

One Hr Change – Daylight Saving else the last time would be 11:30 AM

| **Cm = (B - A)* 1000** | |
|---|---|
| **B** | 0.001 |
| **A** | 0.000 |

| **x = 2Md** | |
|---|---|
| **x** | 4.74 |
| **Md** | 2.37 |

| **Md = Wt. of beaker - Wt of beaker (drying)** | |
|---|---|
| Weight of the beaker (g) | 129.91 |
| Weight of the beaker (drying) (g) | 132.28 |

Table 19: Sedimentation Analysis for sample #6

# APPENDIX B: RHEOLOGY OF THE GROUT

**Test for Viscosity (Flow test)**

**Sample A**

| **Surrounding conditions** | Batch #1 | Batch #2 |
|---|---|---|
| Relative humidity (%) | 26 | 21 |
| Room temperature ($^{O}C$) | 26.4 | 25.7 |

| **Temperature reading** | Batch #1 | Batch #2 |
|---|---|---|
| Mixing water ($^{O}C$) | 18 | 19 |
| Grout ($^{O}C$) | 22 | 22.5 |

| **Duration of mixing** | Time |
|---|---|
| Batch #1 | 4 mins |
| Batch #2 | 4 mins |

| **Time of efflux of water** | Batch #1 | Batch #2 |
|---|---|---|
| Reading # 1 | 4.11 s | 4.23 s |
| Reading # 2 | 3.93 s | 4.11 s |
| Average Reading | 4.02 s | 4.17 s |

| **Time of efflux of grout** | Batch #1 | Batch #2 |
|---|---|---|
| Reading #1 | 6.50 s | 6.51 s |
| Reading #2 | 6.30 s | 6.30 s |
| Average Reading | 6.40 s | 6.40 s |

**Sample B**

| **Surrounding conditions** | Batch #1 |
|---|---|
| Relative humidity (%) | 28 |
| Room temperature ($^{O}C$) | 25.4 |

| **Temperature reading** | Batch #1 |
|---|---|
| Mixing water ($^{O}C$) | 19 |
| Grout ($^{O}C$) | 22 |

| **Duration of mixing** | 7 mins |
|---|---|

| **Time of efflux of water** | Time |
|---|---|
| Reading #1 | 4.08 s |
| Reading #2 | 4.51 s |
| Average Reading | 4.30 s |
| **Time of efflux of grout** | Time |
| Reading #1 | 6.18 s |
| Reading #2 | 5.70 s |
| Average Reading | 5.94 s |

**Sample C**

| **Surrounding conditions** | Batch #1 | Batch #2 |
|---|---|---|
| Relative humidity (%) | **30** | **31** |
| Room temperature ($^{O}C$) | **25** | **24.4** |

| **Duration of mixing** | Time |
|---|---|
| Batch #1 | 4 mins |
| Batch #2 | 4 mins |

| Time of efflux of grout | Batch #1 | Batch #2 |
|---|---|---|
| Reading #1 | 21.01 s | 12.81 s |
| Reading #2 | 19.50 s | 13.65 s |
| Average Reading | 20.25 s | 13.23 s |

| Time of efflux of water | Batch #1 | Batch #2 |
|---|---|---|
| Reading # 1 | 3.93 s | 4.06 s |
| Reading # 2 | 4.11 s | 4.06 s |
| Average Reading | 4.02 s | 4.06 s |

**Sample D**

| **Surrounding conditions** | Batch #1 | Batch #2 |
|---|---|---|
| Relative humidity (%) | 22 | 21 |
| Room temperature ($^{O}C$) | 23.9 | 26.4 |

| **Duration of mixing** | Time |
|---|---|
| Batch #1 | 4 mins |
| Batch #2 | 4 mins |

| **Time of efflux of water** | Batch #1 | Batch #2 |
|---|---|---|
| Reading #1 | 4.11 s | 3.98 s |
| Reading #2 | 4.90 s | 4.00 s |
| Average Reading | 4.50 s | 3.99 s |

| Time of efflux of | Batch #1 | Batch #2 |
|---|---|---|
| Reading #1 | 15.43 s | 9.90 s |
| Reading #2 | 15.93 s | 10.28 s |
| Average Reading | 15.68 s | 10.09 s |

# APPENDIX C: FUTURE TESTING AND RECOMMENDATIONS

| Material | Categories | Test | Standard | Grout | Adobe | Grout - Adobe Assembly | Assembly Crack Width |
|---|---|---|---|---|---|---|---|
| **GROUT** | **Material Characterization** | Compositional analysis | XRD, petrography, ESEM | Yes | No | No | No |
| | | Elemental analysis | XRF, ESEM/EDX | Yes | No | No | No |
| | | Particle size distribution - Seive Analysis | ASTM C136 | Yes | No | No | No |
| | | Atterburg - plastic limit, liquid limit and plasticity index of soil | ASTM 4318, Con Sci Lab 14 | Yes | No | No | No |
| | **Grout Test - Physical Wet** | Setting time - Vicat Needle test | ASTM C 953, ASTM C 191 | Yes | No | No | No |
| | | Expansion and Bleeding | ASTM C 940 | Yes | No | No | No |
| | | Rheological Measurement | UNI 11152 | Yes | No | No | No |
| | | Flow / Viscosity | ASTM C939, ASTM C 937 | Yes | No | No | No |
| | | Injectibility | EN 1771 | Yes | No | No | No |
| | **Grout Test - Physical Dry** | Water Vapor Transmission | NORMAL 21/85,<br>ASTM E96/ E96M - 12<br>RILEM 11.2 | Yes | No | No | No |
| | | Capillary Water absorption | RILEM 11.6<br>NORMAL 11/85<br>EN 1771 | Yes | No | No | No |
| | **Grout Test - Mechanical Strength** | Compressive Strength | ASTM C109<br>NF-EN 1771 and EN 196-1 | Yes | No | No | No |
| | | Drying Shrinkage | ASTM C1148, ASTM C474 | Yes | No | No | No |
| | | Modulus of Elasticity | ASTM C120 | Yes | No | No | No |
| | | Freeze Thaw test | ASTM D 560<br>RILEM V 3 | Yes | No | No | No |
| | | Flexural test<br>[50% higher than direct tensile strength] | ASTM C 348 - 08 | Yes | No | No | No |
| | | Splitting Tensile Strength (Brazilian Test)<br>[10% higher than direct tensile strength] | NF - EN 1771 | Yes | No | No | No |
| **ADOBE** | **Adobe Block Test** | Compressive strength | ASTM C1314-12 | No | Yes | No | No |
| | | Compressive strength<br>(portions of prism broken in flexure) | ASTM C349-08 | No | Yes | No | No |
| | | Water absorption and Drying Behavior | NORMAL 11/85; 7/81 and 29/88<br>ASTM C67-97, ASTM C948-94, ARC Laboratory Handbook, ICCROM 1999 | No | Yes | No | No |
| **GROUT ADOBE ASSEMBLY** | **Grout-Adobe Assembly** | Fragment-test method | (Tassios et al., 1989) | No | No | Yes | 3 mm<br>**10 mm**<br>**20 mm** |
| | | Flexural Test & Bond Strength | ASTM D 1635/ D1635M - 12 | No | No | Yes | 10mm<br>20mm |
| | | Shear Bond Strength | ASTM D 905, BS EN 196-1 | No | No | Yes | 10mm<br>20mm |
| | | Diagonal Compression Test | ASTM E519 (ASTM 2002) | No | No | Yes | 10 mm<br>20 mm |
| | | Shear by Compression Loading | ASTM D 3931-08 | No | No | Yes | 10 mm<br>20 mm |
| | | Three point bending | ASTM E 2769-13 | No | No | Yes | 10 mm<br>20 mm |

Table 20: Preliminary test matrix (For future reference)

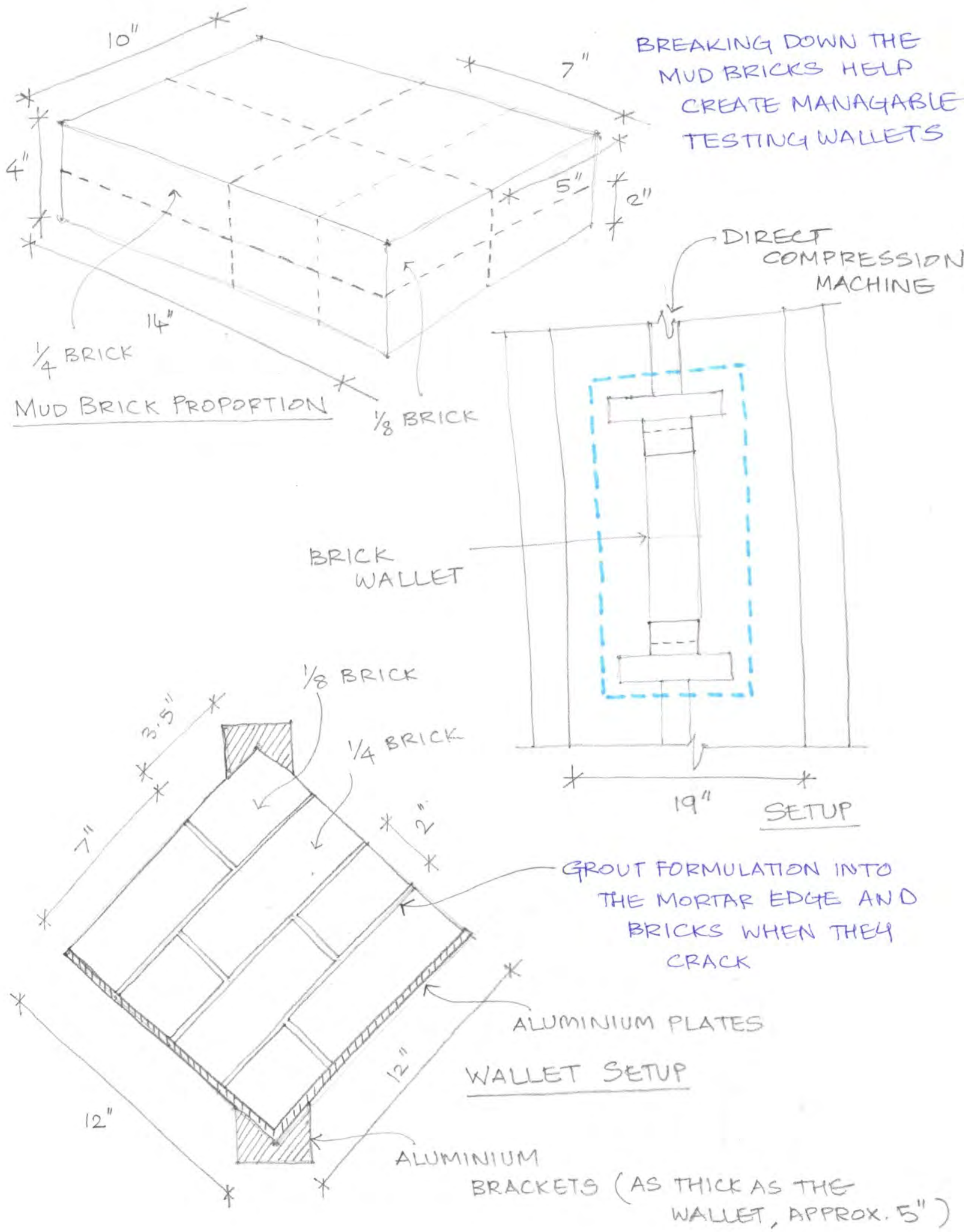


Figure 53: Schematic drawing for to setup the wallet for diagonal compression test

Source: Iyer 2014

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