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UNIVERSITY OF CAPE TOWN



The Suitability of Rammed Earth for Construction in the Cape Town Metropolitan Area

Masters Dissertation

John Thuysbaert
October 2012

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I. Abstract

The use of Rammed Earth dates back to the earliest forms of construction. This is due to its constructional simplicity as well as its use of in-situ material. As technology has developed and people have been able to transport increasingly larger volumes of materials, the use of Rammed Earth in main stream construction has receded. However, given the environmental damage and global warming caused by current conventional methods of construction, society is becoming increasingly aware of negative impacts. 'Sustainable development' is fast becoming a major priority and the uses of non-industrialised materials are being re-considered.

This concept of non-industrialised building or Rammed Earth construction involves materials manufactured using a simple, quick process with low embodied energy, utilising raw materials from the site itself or nearby. However, it needs to be shown that such houses or moderate rise structures meet the needs of the users by fulfilling the standard requirements of structural integrity and durability.

The purpose of this thesis was to explore the suitability for Rammed Earth construction in the Cape Town metropolitan area. This would ultimately lead to drawing up a guideline for building of Rammed Earth housing and structures.

The research involved collecting sixteen soil samples from strategically selected sites in Cape Town. The suitability of a soil was established through a variety of tests, varying between relatively simple field tests and rigorous laboratory analysis. These tests were undertaken to assess soil grading, organic matter content, plasticity and Optimum Moisture Content (OMC). Grading gave an indication of fines present and plasticity indicated the cohesive nature of the fines. More detailed tests were undertaken to determine type and level of soluble salts and mineralogical composition.

The extent of testing Rammed Earth materials depends on the specified application and the novelty of the material in use. A proven material improves the confidence in its qualities and reduces the level of uncertainty and associated risks. Decomposed Granite and Cape Flats soils, both readily available throughout Cape Town, were selected and mixed in various proportions to create soil blends varying in plasticity. Compliance tests were undertaken on unstabilised, cement stabilised and lime stabilised specimen cylinders. Soil classification, moisture-density testing, Unconfined Compressive Strength (UCS), water absorption and drying shrinkage assessments were undertaken.

Results indicated that increasing clay content in soils had a retarding effect on hydration reactions of cement stabilised specimens but promoted pozzolanic reactions for lime stabilised specimens. It was also indicative that a higher clay content present in a specimen led to higher drying shrinkage results due to higher absorption of moisture during mixing to reach OMC. This higher loss of moisture resulted in the clay minerals to contracting and shrinking during drying which led to higher drying shrinkage results.

An optimal soil combination investigation demonstrated that a blend of 50% Cape Flats sand and 50% Decomposed Granite stabilised with 6% cement content and mixed at Optimum Moisture Content (OMC) was the optimum soil combination suitable for Rammed Earth construction in the Cape Town Metropolitan for load bearing applications area according to minimum performance specifications set by Walker *et al.* 2005.

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Definitions

Additive: materials used to improve characteristics of earth for construction, including chemical agents and waterproofing agents.

Adobe: sun-dried earth blocks, formed with wet mud placed into moulds; material may contain a binding agent to limit cracking and improve strength.

Bending Strength: flexural tensile strength of a material which is derived by standard testing.

Binder: material added to improve mechanical properties of earth, such as strength, durability and handling, and reduce cracking due to shrinkage.

Blended or engineered soils: manufactured soils for Rammed Earth construction formed by combining various constituents to provide an ideal grading together with improved physical characteristics. Also sometimes referred to as 'granular stabilisation'. Blending offers the opportunity for greater use of otherwise unsuitable in-situ materials.

Boniness: sections of exposed gravel along the surface of a Rammed Earth wall caused by lack of fines material.

Cations: atoms that have lost an electron to become positively charged.

Characteristic Strength: that value of material strength, as assessed by standard tests, which is exceeded by 95% of the material.

Clay: very fine-grained mineral less than 0.002 mm in size, consisting mainly of hydrated alumino-silicates.

Cob: method of monolithic earth wall construction in which wet lumps (cobs) of earth are progressively stacked in courses without the use of mortar, and shaped by hand without using formwork.

Colloidal: A colloid is a substance microscopically dispersed evenly throughout another substance.

Cohesion of Soil: 'stickiness' characteristic of clay and silt, which is absent from sand and gravel.

Cold Joint: a joint formed between successive layers of Rammed Earth caused by delay in the construction process.

Compaction: process of packing soil particles closer by removing air voids through manual or mechanical means.

Curing: the development of strength, durability and other properties that arise from drying of materials or chemical changes such as cement hydration.

Damp-proof course: horizontal barrier of impervious material built into a wall or pier to prevent moisture movement to any part of the wall or pier.

Drop test: simple method for estimating Optimum Moisture Content of Rammed Earth and stabilised Rammed Earth.

Drying shrinkage: linear volumetric reduction (expressed as a linear shrinkage) caused by loss of moisture from clay fraction on drying.

Durability: resistance to agents of decay, including water-borne deterioration and mechanical abrasion.

Earth: natural subsoil or manufactured mineral material, comprised of varying amounts of clay, silt, sand and gravel, which has sufficient natural cohesion to ensure satisfactory performance for unfired wall construction.

Eaves: the edge of the roof, which projects beyond the external walls.

Efflorescence: soluble salt deposit left on a surface after the evaporation of water.

Embodied Energy of a material: the energy used to extract, process and refine a material before use in product manufacture.

Fly Ash: extremely fine ash by-product from burning pulverised coal, which has pozzolanic properties.

Footing: construction that transfers the load from the building to the foundation.

Formwork: temporary support used in rammed and poured earth construction, and kept in place until material has attained sufficient strength to be self-supporting.

Foundation: ground or subgrade that supports the building.

Gravel: natural or manufactured granular mineral material greater than 2 mm in size.

Hydration: chemical combination with water.

Hydraulic lime: a lime burnt with up to 20 to 22% clay content, which hardens in the presence of water.

Hygroscopic: having the characteristic of absorbing moisture from the atmosphere.

Kaolinite: naturally occurring clay mineral comprised of alternate plate-like sheets; forms the bulk of kaolin (china clay).

Limit state: any limiting condition for which the structure ceases to fulfill its intended function.

Liquid limit: the moisture content (in percent of dry soil mass) at which the soil passes from a plastic to a liquid state.

Load bearing wall: wall supporting any vertical load in addition to its own self-weight.

Maximum dry density: the maximum dry density for densest possible packing of particles of Rammed Earth

Moisture content: water content represented as a percentage of the dry mass of solid materials.

Montmorillonite: a sparsely occurring highly expansive natural clay mineral comprised of three weakly bonded plate-like layers; main component of bentonite.

Movement joint: vertical joints between panels of Rammed Earth to accommodate moisture and thermal movements.

Non-Hydraulic Lime: pure lime that does not set, but hardens slowly by carbonation.

Optimum Moisture Content (OMC): the moisture content of loose Rammed Earth or stabilised Rammed Earth material at which the specified compaction method will achieve the maximum dry density

Permeability: a measure of the ability of a porous material to allow fluids to pass through it.

Pisé de Terre: see Rammed Earth.

Plastic Limit: the moisture content (in percent of dry soil mass) at which the soil passes from a solid to a plastic state.

Plasticity Index: the range of moisture content over which a soil is plastic; the difference between the moisture content at the liquid and plastic limits.

Pozzolan: both natural and artificial material that contains silica, which hardens on drying after mixing with water.

Rammed Earth: monolithic earthen material compacted in situ between temporary formwork; earth often stabilised with binders such as cement and lime.

Rammer: manual or mechanical tool used in compaction of Rammed Earth.

Render: material used to plaster walls for decoration and moisture resistance.

Rising Damp: movement of water up a wall from the ground by capillary action.

Sand: cohesionless granular material comprised mainly of quartz, between 0.06 and 2 mm in size.

Silica Fume: extremely fine pozzolanic material, formed as by-product from the smelting of silicon and Ferro-alloys.

Silt: granular material finer than sand but coarser than clay (0.002–0.06 mm in size).

Smectites: group of clay minerals, including montmorillonite and illite, with expansive properties.

Stabilisation: process to improve properties of earth for construction by densification (compaction), binder addition, or addition of a waterproofing agent.

Subsoil: the layer or bed of earth between the topsoil and bedrock

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1. Introduction

The world we live in has a finite quantity of resources. As the population of the world increases, so does the rate at which these resources are depleted. The construction industry is a major contributor to the consumption of both materials and energy and there is a need for simple, low energy construction methods utilising minimal resources.

The use of Rammed Earth dates back to the earliest forms of construction. This is due to its constructional simplicity as well as its use of in-situ material. As technology has developed and people have been able to transport increasingly larger volumes of materials, the use of Rammed Earth in main stream construction has receded. However, given the environmental damage and global warming caused by current conventional methods of construction, society is becoming increasingly aware of negative impacts. 'Sustainable development' is fast becoming a major priority and the uses of non-industrialised materials is being re-considered.

This concept of non-industrialised building or Rammed Earth construction involves materials manufactured using a simple, quick process with low embodied energy, utilising raw materials from the site itself or nearby. However, it needs to be shown that such houses or moderate rise structures meet the needs of the users by fulfilling the standard requirements of structural integrity and durability.

Additionally, stabilised Rammed Earth is a form of Rammed Earth construction which uses soils combined with either cement or lime to improve the material's physical characteristics. Walker et al. (2005) states that cement stabilisation of Rammed Earth soils has become common practice in Australia. The addition of cement significantly improves wet compressive strength and general durability. However these advantages need to be very carefully weighed against the environmental impact of cement production which accounts for 5% of total carbon dioxide emissions according to Pritchett (2004). Lime improvement and stabilisation of soils is a well-established technique in civil engineering ground works such as road construction where it is added to reduce soil moisture content, reduce plasticity and increase strength. The use of lime in Rammed Earth construction is much less common than the use of cement.

The overall objective of this thesis was to collect and categorise information that will allow the drawing up of a guideline to building stabilised Rammed Earth housing in the Cape Town Metropolitan area.

The aims of the thesis are given below:

- Research and investigate for suitable soils for Rammed Earth construction in the Cape Town Metropolitan area.
- Investigate for other 'non-standard' and 'in-situ' tests to evaluate the earth samples.
- Evaluate the relationships between strength and various stabilisation (lime & cement) fractions.
- Compare Rammed Earth performance from different sites. This will establish whether similar construction methods could be used with soils from different areas.
- Determine methods for testing the structural integrity of Rammed Earth construction.
- Explore the long term effect of shrinkage and volumetric changes associated with clay particles.

1.1. Scope

The scope of the thesis is as follows;

- Tests on the selected soils were carried out in order to classify them.
- Compressive strength, drying shrinkage, rate of drying and water absorption tests were carried out on Rammed Earth specimens.
- Relationships between wet and dry compressive strength and stabiliser fractions of Rammed Earth were explored.

1.2. Limitations

- Testing on full scale walls was unachievable due to the volumes required with the quantity of testing.
- Variables such as compactive effort and density for the compaction of Rammed Earth were difficult to keep constant compared to the compaction of concrete.
- The testing of Montmorillonite in addition to Decomposed Granite was not possible due to time constraints.

1.3. Outline of the Thesis

The thesis is divided into a five chapters. Chapter 2 is a literature review of the subject, providing the reader with a broad overview. Chapter 3 outlines the methodology used in achieving the aims of the thesis, which are stated in Chapter 1. Chapter 4 then discusses the results of the individual tests carried out, highlights the relevant findings, and is also a general

discussion that brings together the individual results and findings discussed. The final chapter in the body of the thesis is chapter 5, “Conclusions and Recommendations”. This chapter concludes the findings of the results and investigates for an optimal soil combination. This chapter also reviews how well the aims of the thesis were met and provides recommendations about further research that could be carried out on this topic.

2. Literature Review

2.1. Introduction

2.1.1. *The Evolution of Rammed Earth*

Earthen materials and Rammed Earth in particular are ancient materials used in construction. They date as far back as the prehistoric era. Today, more than half of the world's human population still lives in shelters built from earth. Unlike the simple earth houses of our prehistoric ancestors, today's earth buildings can be as refined as we care to make them (Easton & Wright, 2007).

Some earthen materials built centuries ago are still performing satisfactorily today. The most famous example is the Great Wall of China which was built approximately 2000 years ago using Rammed Earth, stones, baked bricks and wood (Figure 2.1). To this day, it remains one of the largest construction projects ever undertaken. Rammed Earth is still used today in China for shops, homes and apartment buildings (Easton & Wright, 2007).



Figure 2.1: The Great Wall of China (Easton & Wright, 2007)

Architectural history can trace earth construction in many other parts of the world, especially in the Middle East and Africa. Earth materials were favoured in these regions due to the low annual rainfalls, scarcity of trees, abundance of cheap labour and the high cost of limited building materials. In North Africa, from the time of the pharaohs, the people built their houses of cob, adobe and Rammed Earth. Today, tribesmen in the Atlas Mountains, east of Marrakech,

Morocco, build Rammed Earth dwellings with enormous walls and small windows that protect the residents from the heat (Easton & Wright, 2007).

There is also evidence of ancient Rammed Earth in Europe. Throughout the Rhone valley in France, the tradition of 'stuffed earth' or 'pisé de terre' as it was later called was a leading wall-building method for two thousand years. In South America, the use of 'tapia', the technique of packing moist earth into wooden formwork, was used extensively in many regions of the continent. It is still used in parts of Peru, Chile and Brazil. In Australia, the use of 'pisé de terre' was introduced to the continent during the gold rush period in the 1850s by European gold seekers. Today, Australia is experiencing a renaissance in Rammed Earth construction that is incomparable anywhere else in the world (Easton & Wright, 2007).

In the United States, the current level of interest for Rammed Earth is the third wave in the past two hundred years. The first wave was in the 1840s and the second wave was during the Great Depression of the 1930s. Both previous waves were instigated by the search for a low cost, simple method of construction and ended when low cost transportation and mass production enabled faster methods of construction (Easton & Wright, 2007).

2.1.2. The Renaissance of Rammed Earth

In the 1950s, Rammed Earth construction began to fall out of favour in the developed world (Bui *et al.* 2009) but in the mid-1970s, growing awareness of diminishing natural resources and environmental damage prompted a reconsideration of the advantages of building with earth. From the 1970s to the 1990s, Rammed Earth made progress worldwide. Hugo Houben, Patrice Doat and Hubert Guillard organised a group called CRA-Terre (Centre for the Research and Application of Earth), an academic study programme leading to a Master's of Architecture degree specialising in earth construction methods in Grenoble, France. Graduates of this programme went on to design and implement low-cost projects in developing countries throughout South America, Asia and Africa. The trained students who return to their native countries also introduce improved construction methods. The organisation has been responsible for improving the lives of tens of thousands of people (Easton & Wright, 2007).

In British Columbia, in the early 1990s, Meror Krayenhoff began building with stabilised rammed earth. Stabilisation refers to the addition of cement or lime which leads to an increase in strength and durability. He calls his system SIRE Wall (Stabilised Insulated Rammed Earth) which incorporates rigid insulation in the centre of the wall. His company, Terra Firma Builder, offers a training programme and has recently won numerous prestigious design and

construction awards. In Australia, the stabilised Rammed Earth industry has grown to several dozen companies. The Associated Stabilised Earth Group (asEg) members have built more than two thousand buildings both residential and commercial (Easton & Wright, 2007).



Figure 2.2: Rammed Earth walling at the Alhambra, Granada, Spain (Walker *et al.* 2005)

Village builders in Morocco, Mali, China and other countries have a continuous tradition of building with Rammed Earth over numerous centuries. Today, contractors, designers and engineers are developing new Rammed Earth construction methods. It is hoped that the presence of more qualified builders, a consistency of methods and a uniform standard of practice will ultimately lead to an increase in confidence for architects when specifying its use. The aim is to make an ancient building system better adapted to modern applications (Easton & Wright, 2007).

2.1.3. Sustainability

Given the environmental damage and global warming caused by current conventional methods of construction, society is becoming increasingly aware of its negative impacts. Sustainability is fast becoming a major priority and the uses of non-industrial materials are being re-considered due to the fact that there is an increasing demand for housing as populations increase and the need to reduce the energy consumption, waste and promote the conservation of resources in the construction industry (Morel *et al.* 2001). Non-industrial materials are defined as “Materials used in Civil Engineering manufactured and installed by masons. They are usually local materials i.e. earth, stone, plant fibres mixed with a binder” (Bui *et al.* 2009).

Sustainable development has been defined by the World Commission on Environmental Development (WCED) as follows (WCED, 1987):

“Humanity has the ability to make development sustainable- to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits- not absolute limits but limitations imposed by the present state of technology and social organisation on environmental resources and by the ability of the biosphere to absorb the effects of humanity”.

Construction is an important part of the concept of sustainable development as much energy is used in material manufacturing and transportation. According to the UK Department of the Environment buildings, account for half of all energy used in the world. The primary aims of a construction project are to meet the needs of the current generation. However, the construction process has the ability to compromise the needs of future generations. It is important therefore, if the ideals of sustainable development are adhered to, to ensure that the use of the earth's resources to meet this generation's needs does not compromise future generation's needs (Glavinich, 2008). This leads to the idea of green building and green construction. The term green building has been defined as follows (ASTM, 2006);

“A building that provides the specified building performance requirements while minimising disturbance to and improving the function of local, regional and global ecosystems both during and after its construction and specified service life”

In order for a new building, or more specifically in this case a Rammed Earth house, to be considered 'green', it must employ a simple, low energy construction method utilising minimal resources while meeting all the requirements for a standard house. The construction industry is a major contributor to the consumption of both materials and energy and thus the need for simple, low energy construction method utilising minimal resources.

This concept of non-industrial building or Rammed Earth construction involves materials manufactured using a simple, quick process with low embodied energy, using raw materials from the site itself or nearby (Kouakou & Morel, 2008). Table 2.1 provides a list of embodied energy figures for different materials. Figure 2.3 shows an example of Rammed Earth successfully used for load-bearing applications.

Table 2.1: Embodied Energy Coefficients (University of Wellington, 2012)

Material	MJ/kg
Rammed Earth	0.42
Adobe block	0.47
Concrete block/bricks	0.94
Ceramic brick	2.5
Glazed brick	7.2
Cement	7.8
Glass	15.9
Steel (structural)	35.0

**Figure 2.3: Jasmine Cottage built from Stabilised Rammed Earth, Norfolk (Walker et al. 2005)**

2.1.4. *Benefits and Limitations*

Benefits of Rammed Earth

- **Sustainable Construction**

Walker *et al.* (2005), state that earth is a natural material without processed additives. It produces significantly lower emissions of greenhouse gases and has lower embodied energy than conventional manufactured building materials such as bricks, concrete, steel, and even timber. It is worth noting that reduced toxic chemical content is an attribute of Rammed Earth construction. Appropriate soil is often readily available at the construction site itself which eliminates the energy and cost requirement for lengthy transportation which contributes largely to very low embodied energy of the structure.

In terms of recycling, Rammed Earth without the use of any stabilisers can be disposed of without risk of contaminating the environment.

- **Environmental**

Earth building offers a number of environmental benefits in comparison with other building materials, which include (Standards Australia, 2002):

- Increased potential for recycling and reduction of waste
- Reduction in transportation through use of local materials
- High thermal mass suited to passive solar architecture
- Reduction in use of harmful chemicals
- Reduction in emissions from industrial processes
- Reduction in embodied energy levels

- **Job Creation**

Job creation is a significant benefit as many Rammed Earth building operations can be undertaken by relatively inexperienced labour, though efficient and knowledgeable management is needed. As a labour intensive technology, earth building is well suited to community based low-cost housing schemes in both developed and developing countries (Walker *et al.* 2005). Earth building is suited to a variety of small and large-scale projects including: low rise housing, educational institutions, youth centres, offices, surgeries, petrol stations, hotels, toilets, churches, factories etc (Standards Australia, 2002).

- **Technology**

In comparison with other forms of earthen construction such as cob and adobe, Rammed Earth construction has improved durability, greater density and reduced shrinkage due to compaction, and higher strength and stiffness (Walker *et al.* 2005).

Table 2.2 shows typical characteristics of various construction methods.

Table 2.2: Typical Characteristics of various Construction Methods (Standards Australia, 2002)

Method	Rammed Earth	Mud Brick
Dry Density (kg/m³)	1700 to 2200	1200 to 2000
Dry Compressive Strength (MPa)	1 to 15	1 to 5
Bending Strength (MPa)	0.5 to 2	0 to 0.5

- **Speed of Wall Construction**

Rate of construction is usually between 5 and 10 m²/day for a 300 mm thick Rammed Earth wall for a team of 3 to 4 workers. Once the formwork is removed, walls require little further attention and so the overall speed of construction is favourable compared to other wall construction methods (Walker *et al.* 2005).

- **Health and Performance**

Clays within Rammed Earth walls release or absorb moisture in response to changing local atmospheric conditions. Earth walls are very effective in regulating the internal relative humidity. This property of unstabilised earth walls reduces stress on the building fabric and improves indoor air quality, removing asthma triggers and reducing respiratory diseases. As a dense and bulky material, Rammed Earth also has considerable thermal mass; it can absorb heat during the day and release it at night (Walker *et al.* 2005).



Figure 2.4: Stabilised Rammed Earth house, Western Australia (Walker *et al.* 2005)

Limitations of Rammed Earth

- **Design**

Low strength and durability concerns limit building form. For example, to ensure sufficient lateral resistance, walls are constructed much thicker than other forms of construction. Durability concerns limit construction to sites where there is no risk of

flooding. Sites prone to flooding will require walls to be built on raised footings and with large eaves extensions (Standards Australia, 2002). As far as strength is concerned, it is not suited for the construction of very tall structures, although it can certainly be used for structures 2-3 stories high (Glavinich, 2008).

- **Durability**

Deterioration in the presence of moisture and generally poor durability of earthen materials requires special measures in construction such as: extended eaves, raised footings, protective coatings and regular maintenance work. Some of the materials used to protect earth walls are potentially harmful to the environment. These include: cement and lime used for stabilisation, solvents and heavy metals used in paint (Standards Australia, 2002).

- **Maintenance**

The level of maintenance work is typically high compared to most other forms of construction (Standards Australia, 2002).

- **Soil Suitability**

Not all soils are suitable for the different form of earth building (Standards Australia, 2002). For example, river sand would contain insufficient clay content for a wall to retain its own shape during manufacture. Furthermore, drying shrinkage is detrimental to a wall when using expansive clay soils as a building material.

2.1.5. Economic Cost

The finished cost of Rammed Earth varies greatly depending on the specifications and requirements of the wall finish. Experience has proved that the cost of rammed earth can be comparable to or even cheaper than alternative forms of fully finished masonry wall construction. Though the raw materials are relatively inexpensive, labour costs associated with the handling of materials and formwork comprise the main cost of earth construction. Therefore it is vital that Material preparation be well planned and controlled and formwork systems used efficiently. Handling of formwork typically accounts for 25-50% of construction time and so simplifications in the formwork scheme can provide significant cost savings. Labour costs can be reduced or eliminated through volunteer labour or a self-building

approach. An example of this is a project in the UK such as the Woodley Park Sports Centre shown in Figure 2.5 (Walker *et al.* 2005).



Figure 2.5: Woodley Park Sports Centre, Skelmersdale, Lancashire (Walker *et al.* 2005)

In addition to the initial capital saving on the construction of the house, Rammed Earth offers further savings because of the thermal insulation it provides. According to Hall (2007), it has been shown that during simulated heavy rainfall conditions, the outside temperature dropped by 4°C while the temperature on the inside of the wall only dropped by 1.5°C over a 6 hour period. This suggests that less money needs to be spent on heating in a Rammed Earth house (Hall, 2007). While it has been shown that Rammed Earth construction is economically cheaper in the USA according to Horrigan (1997), very little literature is available regarding the cost of Rammed Earth construction in South Africa.

2.2. Construction of Rammed Earth Walls

2.2.1. Preparation

Rammed Earth can be stabilised with cement or lime. Portland cement is the most common stabiliser used and is typically added in proportions of between 4% and 12% by mass (Standards Australia, 2002). When mixing, materials are either measured by volume or by dry weight. All dried materials are thoroughly mixed together before the addition of water. If soils are blended together to reduce clay or sand content, this is undertaken before adding any additives. Water is then added gradually through a spray nozzle. Wet mixing proceeds for at least 2 to 3 minutes when using a mechanical mixer, longer when mixing by hand. The drop

test (A.1.5) is then used to check that the Optimum Moisture Content (OMC) has been reached. When cement is used, it is important that all fresh material is used within 1 hour from wet mixing. To avoid contamination, mixing is undertaken on heavy-duty polythene sheeting or on a level surface such as a floor slab (Standards Australia, 2002).



Figure 2.6: Construction of a Rammed Earth wall utilising Formwork (Walker *et al.* 2005)

2.2.2. Formwork

The use of formwork (Figure 2.6, 2.7 & 2.8) is an integral part of Rammed Earth construction. As with concrete, Rammed Earth formwork is used as temporary support during compaction and the initial stages of curing until the wall has attained sufficient strength to be self-supporting. The requirements for formwork are (Standards Australia, 2002):

- **Stiffness:** It must be sufficient to maintain form without excessive deflection and distortion during compaction. Forms should not deflect more than 3 mm.
- **Ease of compaction:** Forms should not hinder proper compaction.
- **Strength:** Forms should resist lateral pressures developed during compaction
- **Durability:** Forms must be able to withstand site handling without deterioration
- **Handling ability:** Forms must be able to be lifted by hand to allow easy assembly, alignment and dismantling. Forms are between 600 mm and 900 mm high and 1.5 m to 3 m long.

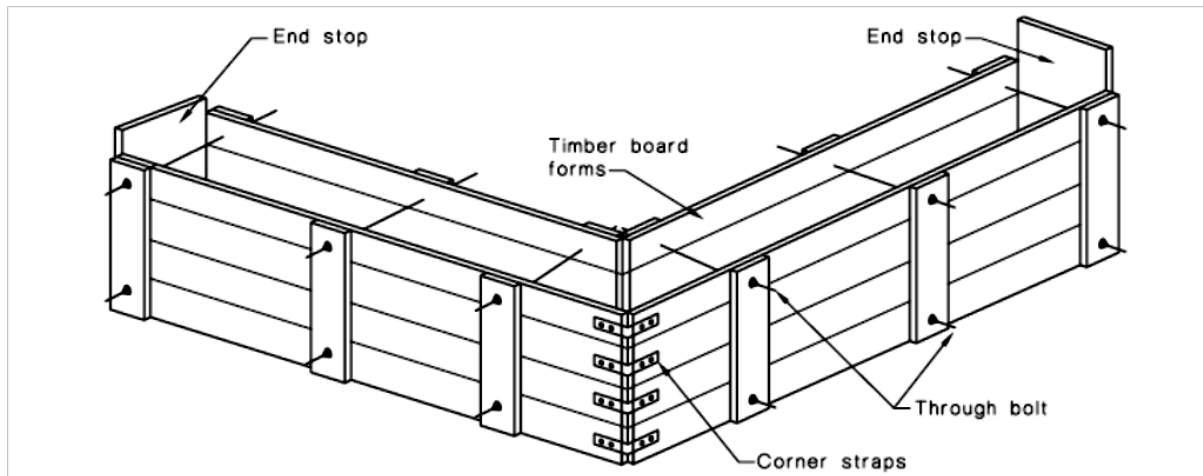


Figure 2.7: Timber formwork (Standards Australia, 2002)

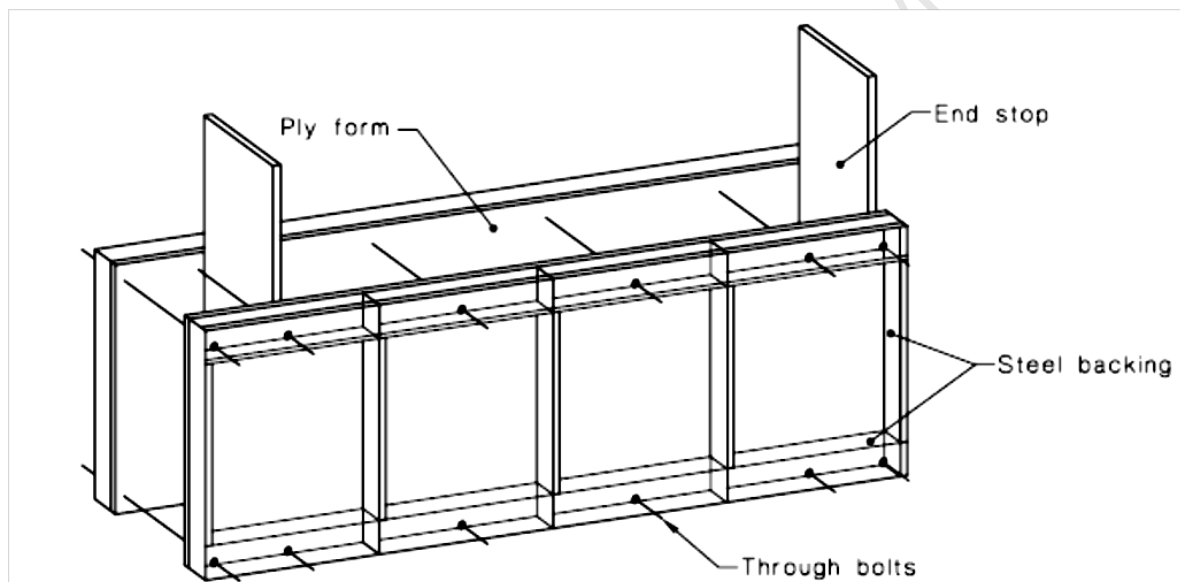


Figure 2.8: Timber forms with steel backing (Standards Australia, 2002)

2.2.3. Construction Process

Once the correct water content for the soil has been established and all the tests (see 2.5.4), mixing and observations have been performed, construction can begin. Formwork is built to act as a mould for the desired shape and dimensions of each wall section. It is usually built out of wood or plywood. The denser the wood, the better the surface finish. The frames must be sturdy and well braced and the two opposing walls clamped together. This is to prevent deformation or bulging from the high compression forces involved (Easton & Wright, 2007). Loose moist soil is then placed in layers 100-150 mm deep and compacted. Manual rammers are used for compaction which is labour intensive as opposed to pneumatically powered

rammers (Walker *et al.* 2005). The soil is typically compacted to 60% of its original height. This is useful in calculating the volume of earth required for the wall. The compaction of the material is done in successive batches to gradually build up the wall until the top of the formwork is reached (Easton & Wright, 2007).

Once the soil has been compacted, the wall will be strong enough that the formwork can immediately be removed. Rammed Earth walls are typically 300-450 mm thick and often exhibit a distinctive layered appearance as a result of the construction process. This attractive appearance is one of the appeals of Rammed Earth construction (Walker *et al.* 2005). The walls are best built in warm weather so that they can harden and dry. Compressive strength increases with curing time and some walls may take up to 2 years to completely cure (Easton & Wright, 2007). This process is illustrated in Figure 2.9. Typical characteristics of Rammed Earth are given in Table 2.3 according to Standards Australia (2002).

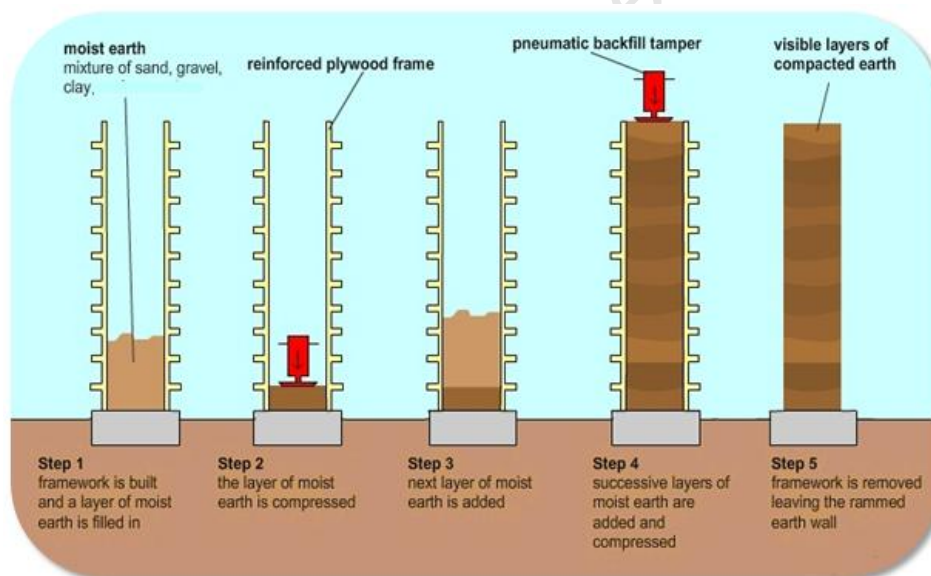


Figure 2.9: Construction process of a Rammed Earth wall (Easton & Wright, 2007)

Table 2.3: Typical Characteristics of a Rammed Earth wall (Standards Australia, 2002)

Dry Density	1700 to 2200 kg/m ³
Dry Compressive Strength	1 to 15 MPa
Bending Strength	0.5 to 2 MPa

2.2.4. Stabilisation

Stabilised Rammed Earth is a form of Rammed Earth construction which uses sub-soils combined with either cement or lime to improve the material's physical characteristics. (Walker *et al.* 2005). Gooding (1993) states that soil can be left unstabilised for construction, but unless it is protected from water the resulting building will not be very durable.

A) Cement Stabilisation

Walker *et al.* (2005) state that cement stabilisation of Rammed Earth soils has become common practice in Australia. The addition of cement significantly improves wet compressive strength and general durability. However these advantages need to be very carefully weighed against the environmental impact of cement production which accounts for 5% of total global carbon dioxide emissions according to Pritchett (2004).

The use of Cement Stabilisation for Rammed Earth

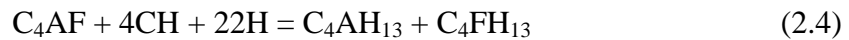
Walker *et al.* (2005) mention that during the past 30 years, considerable experience and expertise in stabilised Rammed Earth has been gained in Australia and parts of the United States of America. Standards Australia, (2002) states that cement is most efficient for soils with less than 15% to 20% clay content. Organic matter should normally not exceed 2%, as it is harmful to cement hydration. Sulphates should also be limited to 2% to 3%. Depending on soil type and type of construction, cement is added in proportions between 2.5% and 15% (by mass) while 4% to 10% are the most common (Standards Australia, 2002).

Cement stabilisation is most suited to soils with clay contents that are relatively low compared with those used for unstabilised Rammed Earth. Clay content must be limited to ensure adequate durability and dimensional stability. As certain clays are more reactive than others, clay type as well as clay content is important (Walker, 2005).

The Mechanism of Cement Stabilisation

According to Umesha *et al.* (2009), when cement is mixed with soil, there will generally be a reduction in liquid limit and plastic limit but there will be an increase in the shrinkage limit and shear strength. The increase in strength is by primary and secondary cementitious reactions in the soil cement matrix. Gooding (1993) states that cementitious stabilisation in combination with densification (compaction) gives soil both wet strength and erosion resistance. Compaction reduces the soil's permeability and enhances the secondary bonding mechanism.

The primary cementation is due to hydration products of Portland cement. Portland cement is a substance containing dicalcium silicate (C_2S) and tricalcium silicate (C_3S). The hydration of Portland cement is described by the following reactions (Owens, 2009):



CH for reactions (2.3) and (2.4) is provided by reactions (2.1) and (2.2). Reaction products have the following characteristics: $C_3S_2H_3$, Calcium silicate hydrate, is in the form of very fine needles and plates and contributes to most of the strength of the hardened cement paste (HCP). CH, calcium hydroxide, is in the form of relatively large crystals which do not contribute to the strength of the HCP. C_4AH_{13} and C_4FH_{13} also do not contribute to the strength of the HCP (Owens, 2009).

As soon as cement is mixed with water, a rapid reaction begins. Cement particles start to dissolve, tricalcium silicate (C_3S) is hydrated to form gel ($C_3S_2H_2$) and release calcium hydroxide (CH). Initially, the paste remains plastic and workable but hardens and gains strength with time. Gooding (1993) states that an insoluble interlocking matrix binding the soil particles is formed and as the matrix is insoluble it gives a strength mechanism which works to restrain the softening and swelling of the soil which significantly reduces the weakening effect of water. The hydration of the calcium silicate also results in the release of free lime (CH) which then reacts further with the clay fraction by reaction with silica from the clay minerals. This forms more calcium silicate gel and is known as a pozzolanic reaction (Gooding, 1993).

B) Lime Stabilisation

Lime improvement and stabilisation of soils is a well-established technique in civil engineering ground works such as road construction where typically 1 to 3% quicklime (Calcium Oxide) is added to reduce soil moisture content, reduce plasticity and increase strength. The use of lime in Rammed Earth construction is much less common than the use of cement.

The use of Lime Stabilisation for Rammed Earth

Lime stabilisation is used with higher clay content soils and often in conjunction with cement. Both hydraulic and non-hydraulic (quicklime) can be used. Non-hydraulic lime is particularly suitable for clayey soils (Standards Australia, 200). The properties of the soil will ultimately determine the degree of reactivity with lime and the ultimate strength of the wall. In general, fine grained soils are considered to be good candidates for lime stabilisation. Unlike cement stabilisation, soils for lime stabilisation may contain organic matter (National Lime Association, 2004).

The likely dosages are between 3% and 12% (by mass) and will increase as clay content increases (Houben & Guillaud, 1994). According to Venkatarama & Lokras (1998), lime stabilisation is ideally suited for stabilisation of expansive soils. However, the National Lime Association (2004) mention that lime achieves its final strength typically 2-3 times longer than the 28 day curing period required for cement.

The mechanism of lime stabilisation

Lime comes in the form of quicklime (Calcium Oxide) which is manufactured by chemically transforming limestone (Calcium Carbonate) into Calcium Oxide. It also comes in the form of hydrated lime (Calcium Hydroxide) which is created when quicklime reacts with water. It is hydrated lime that reacts with clay particles and transforms them into a strong cementitious matrix (National Lime Association, 2004).

When soil is stabilised with lime, the effects are similar to those of cement stabilisation as the clay in the soil is prevented from swelling. But, unlike cement which binds the coarse particles of a soil, lime reacts with the clay minerals in a soil (Walker & Maniatidis, 2003). The chemistry of this process is described in detail below (National Lime Association, 2004):

1. Drying:

Quicklime chemically combines with water (i.e. hydration) and releases heat. A soil is dried because the moisture present participates in this reaction and the heat generated evaporates the additional moisture. The hydrated lime produced by these reactions will now react with the clay particles and will slowly produce additional drying. If hydrated lime is used instead of quicklime, drying occurs only through the reactions with the clay particles, stabilising the soil.

2. Modification:

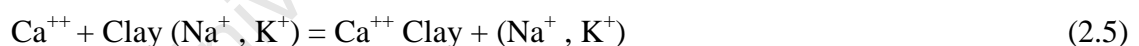
After the initial mixing, the calcium ions from the hydrated lime displace the water at the surface of the clay particles. The soil then becomes granular and friable making it easier to work and compact. The soil's tendency to swell and shrink is decreased and so is its Plasticity Index. This process typically occurs within a few hours and is called "flocculation and agglomeration".

3. Stabilisation:

When sufficient lime and water are added to the soil, the pH increases which enables the clay particles to break down. Silica and Alumina are released and react with Calcium from the lime to form Calcium-Aluminate-Hydrates (CAH) and Calcium-Silicate-Hydrates (CSH). CAH and CSH are cementitious products similar to those formed in cement. These compounds 'crystallise' with time that results in changes in clay plasticity, increase in shear strength and reduction in permeability. They form the matrix that contributes to the strength of lime-stabilised earth walls. The soil is transformed from a sandy, granular material to a hard, relatively impermeable wall with significant load bearing capacity. The process happens within hours and can continue for years.

According to Umesha *et al.* (2009), the chemical interaction plays an important role in lime stabilisation of soils. The following four basic reactions take place when lime is added to soil:

1. Cation exchange



2. Flocculation and Agglomeration

3. Carbonation



4. Pozzolanic reactions



Umesha *et al.* (2009) state that the cation exchange takes place between the metallic ions associated with the surface of the clay particles that are surrounded by a diffuse hydrous double layer (see 2.3.3). The double layer is modified by the ion exchange of calcium because there is an alteration in the density of the electrical charge around the clay particles which leads to the flocculation of particles. This process is mainly responsible for the modification of the engineering properties of clay soils treated with lime. The carbonation reactions results in weak cementing agents. It is the time dependent pozzolanic reaction that is mainly responsible for improvement in soil properties. The pozzolanic reactions are facilitated by the lime creating highly alkaline soil pore chemistry (Umesha *et al.* 2009).

C) *Advantages and limitations of stabilised Rammed Earth*

Advantages:

- **Improved Strength**

Stabilisation improves the mechanical strength of soils, especially when wet. Cement stabilised sub-soils can develop compressive strengths in excess of 10 MPa, dependent on the level of stabilisation and the use of an appropriate soil (see 2.5). Compressive strength improvement follows a linear relationship with increasing cement content. A higher strength allows for thinner walls and resistance to higher loads. Higher strengths provide the opportunity for reinforcing Rammed Earth with materials such as steel (Walker *et al.* 2005).

- **Improved Durability**

Stabilised Rammed Earth may be immersed in water for prolonged periods without the loss of structural integrity. Resistance to rainfall erosion and abrasive damage can be significantly enhanced (Walker *et al.* 2005).

- **Reducing perceived risk**

Engineers, builders, architects and clients are familiar with using materials that have much greater strength and durability. The stabilisation of Rammed Earth lowers the perceived risk of material performance. Stabilised Rammed Earth can be used as a direct replacement of other materials such as fired brick, without a significant variation to building design (Walker *et al.* 2005).

Limitations:

- **Stabilisation is not always necessary**

Stabiliser may be seen as reducing the risk of material failure but with careful selection of soil and attention to design detail, in many situations, high-quality Rammed Earth buildings are achievable without the addition of stabiliser. According to Walker *et al.* (2005), the specifications for soil in stabilised Rammed Earth are more restrictive than for general Rammed Earth.

- **Environmental Impact of Stabilisation**

Cement production is a major contributor to manufactured CO₂ emissions. According to Walker *et al.* (2005), there is approximately 0.8 to 1 tonne of CO₂ released for every tonne of cement produced. Stabilised Rammed Earth typically contains 6% cement and the material in a 300 mm thick wall is likely to contain greater amounts of cement than an equivalent 100 mm thick dense concrete block wall. However, stabilised Rammed Earth walls offer a finished product not requiring plaster or render coats. Stabilised Rammed Earth may also allow for reduced wall thickness and reduce the need for extended eaves protection and maintenance. These benefits should be carefully balanced against the environmental impact of using cement.

CO₂ emissions in lime production are lower than for cement but remain significant. Therefore, hydraulic lime should not be regarded as a more environmentally friendly replacement for cement. Lime stabilised walls may require formwork support for longer periods (2 to 3 days). However, stabilisation with non-hydraulic and hydraulic lime, often in conjunction with cement, is ideally suited to soils with clay content in excess of that desirable for cement stabilisation alone (Walker *et al.* 2005)

2.3. Soil Properties

2.3.1. *Geology of Cape Town*

This thesis is primarily concerned with utilising various soils in the Cape Town Metropolitan area for Rammed Earth construction; therefore it is important to investigate the geology of Cape Town. To understand the geology of Cape Town, the geological features of South Africa must first be investigated. As demonstrated in Figure 2.10, Cape Fold Belt mountain chain extends 700 km from Port Elizabeth running parallel to the South coast to Cape Town. From Cape Town, it runs 150 km north to the Cederberg. This long mountain chain is referred to as the Cape Fold Belt and is made up of sandstone rocks (Compton, 2006).

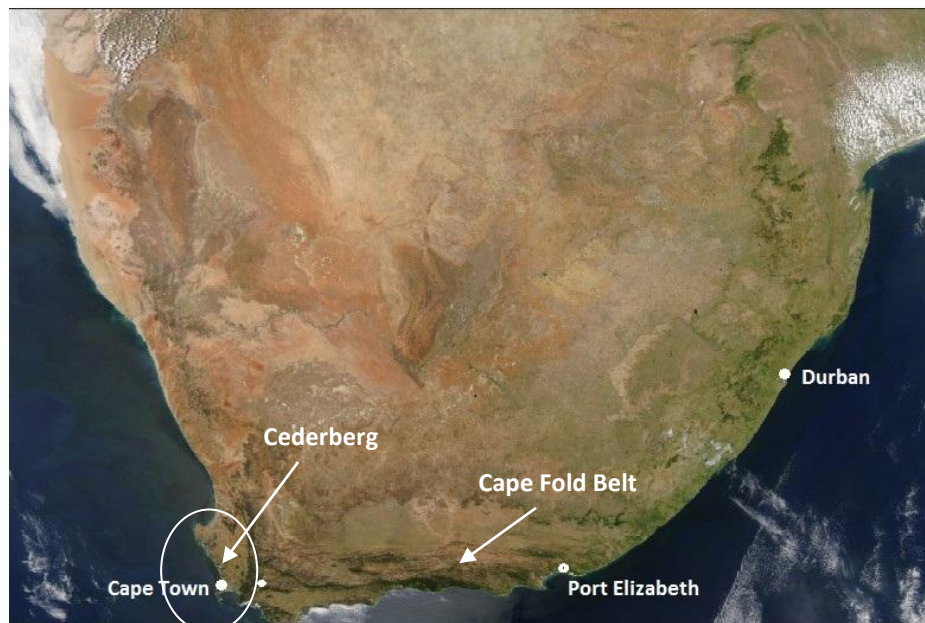


Figure 2.10: A composite image of South Africa from space (Compton, 2006)

The extensive Cape Fold Belt was created by powerful earth movements where enormous tectonic forces pushed large masses of rock upward against the force of gravity. It is these forces which have been on-going for millions of years that have formed and, at present, sustain the landforms of Cape Town. This uplift is countered by the weathering away of the rocks at the surface which ultimately leads to an increased uplift. This additional uplift can be compared to the rise of a boat when a large load is removed. For example, the granite rocks observed today in the Cape Town area are estimated by geologists to have been 10 to 15 km below the surface around 600 million years ago. Table Mountain rises above the Cape Flats because tectonic forces have pushed it up (Compton, 2006).

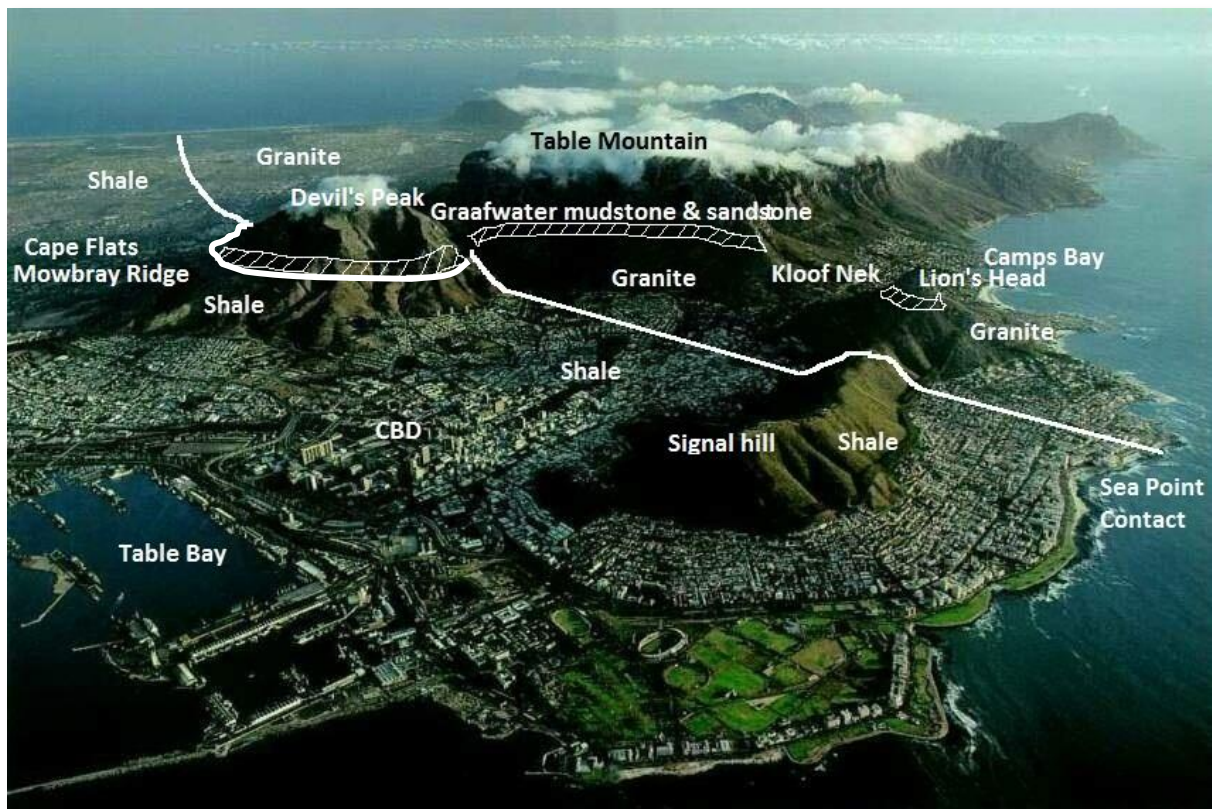


Figure 2.11: The major underlying rocks of Cape Town's landscape. The solid white line represents the contact between shale and granite (Compton, 2006)

From this background, the Cape Town landscape can be understood. The hills and mountains surrounding Cape Town such as Table Mountain, Devil's Peak and Lion's Head are made up mostly of resistant granite and sandstone, whereas the soft and easily worn-away Malmesbury shale form the low-lying areas known as the Cape Flats and CBD (Figure 2.11) including Signal Hill as shown below (Compton, 2006).

An explanation as to why Table Mountain sits apart from the continuous Cape Fold Belt can be given by noticing that the sand that makes up Table Mountain was deposited onto the eroded surface of a 'long-since-cooled' granite. This rules out the possibility that hardening as a result of being baked from below occurred as was the case for the more resistant Malmesbury shale of Tygerberg and Blouberg. The answer is thought to lie during the formation of the Cape Fold Belt where the entire region was initially covered by large-scale folding of sandstone beds. Over time, the crests were worn away before the troughs which resulted in the underlying shale weathering more rapidly than the remaining sandstone trough that is now Table Mountain. The eroded rocks ended up filling offshore basins (Compton, 2006).

2.3.2. *Aggregates*

Aggregates are defined as particles of rock or mineral fragments which, when brought together in a bound or unbound condition, form part or the whole of an engineering structure. Natural sand, gravel and crushed rock aggregates are fundamental to the man-made environment and represent a large proportion of the materials used in the construction industry (Smith & Collis, 2001).

A main contribution of geologists to the study of aggregates is the recognition that rock material owes its properties to its origin, its mineral composition and to the geological processes that have affected it through time. Knowledge of the qualities that determine the suitability of a rock for use as aggregate enables a geologist to make an informed search for new deposits, recognising the relationships that exist between the composition, grain-size, texture, fabric and state of weathering of a rock and its likely performance as an aggregate in an engineering structure or other application (Smith & Collis, 2001).

Rock is a natural material that forms the crust of the earth. Some rocks are relatively weak and easily deformable. Others are hard, strong and durable. Rock so defined includes the 'soil' of engineers which Smith & Collis, 2001 term as: all unconsolidated deposits overlying bedrock. This 'soil' is the aggregate used for Rammed Earth construction. Three broad categories of rock are distinguished here according to their origins (Smith & Collis, 2001).

- *Igneous rocks* derive from molten material that originated below the earth's surface and solidified at or near the ground surface (for example, granite and basalt).
- *Sedimentary rocks* result from the consolidation into layers of loose sediment derived from the breakdown of older rocks, the fragments having been transported and deposited by water, ice or wind (for example, mudrock, sandstone and conglomerate). Some rocks in this category have formed by chemical or organic processes (for example, some limestones).
- *Metamorphic rocks* derive from pre-existing igneous and sedimentary rocks but have been changed from their original state by heat and pressure at depth in the Earth's crust to acquire new characteristics (for example, schist, gneiss, hornfels).

Rammed Earth construction is similar to the creation of sedimentary rocks in the sense that particles of varying size are deposited on top of one another and reconsolidated into a solid mass through pressure. As mentioned previously, each type of rock has different characteristics. Therefore, the best soils for building Rammed Earth walls originate from the

strongest rocks. For example, sedimentary rocks such as limestone result in walls that are less durable while igneous rocks such as granite can be compressed into rock hard walls. Claystones and shales are made up of very fine particles and do not make durable walls. However, most soils can be used to build Rammed Earth with blending, stabilisation and careful construction (Easton & Wright, 2007).

The starting point for any type of earth construction is a good understanding of soil. Soil is a natural material consisting of layers of mineral constituents of variable thicknesses that makes up the top layer of the earth's crust. Soil is created either from the decomposition of dead organisms, or through the breakdown of the earth's various rocks and minerals. This ultimately leads to different soils having greatly varied structural properties when in an engineering structure. Rock types will differ in terms of: colour, hardness, strength, density, durability and chemical composition (Webb, 1998).

2.3.3. Soil Mineralogy

Soils are composed of minerals which are made up from elements present in the crust of the earth. According to Robinson (1977) & Blyth and de Freitas (1984), these elements are primarily (approximately by mass): oxygen (46.6%), silicon (27.7%), iron (5.0%), calcium (3.6%), sodium (2.8%), potassium (2.6%) and magnesium (2.1%). The most common elements occur in rock as oxides, 75% of which are oxides of silicon and aluminium (Powrie, 2007).

Most soils are silicates, which are minerals comprising predominantly silicon and oxygen. As shown in Figure 2.13(a), the basic unit of a silicate is a group comprising one silicon ion surrounded by four oxygen ions at the corners of a regular tetrahedron: $(\text{SiO}_4)^{4-}$. The 4- indicates that the silica tetrahedron has a net negative charge equivalent to four electrons, or valency -4. This is due to the fact that the silicon ion is Si^{4+} while the oxygen ion is O^{2-} . The silica tetrahedron would need to combine with two ions of valency 2+ to become neutrally charged. For example, two metal ions, such as magnesium Mg^{2+} would combine with $(\text{SiO}_4)^{4-}$ to give Mg_2SiO_4 (Olivine). The $(\text{SiO}_4)^{4-}$ groups may link together in different ways with metal ions and with each other to form different crystal structures. Although there are many silicate minerals, their properties depend primarily on their structure (Powrie, 2007).

To the civil engineer, soil is any weakly cemented accumulation of mineral particles formed by the weathering of rocks, the void space between the particles containing water and/or air. Weak cementation can occur due to organic matter or due to carbonates, silicates, or ferrites precipitated between the particles. If the products of weathering are transported either by wind,

gravity, water and glaciers and deposited in a different location, they constitute a transported soil. During transportation, the size and shape of particles can undergo change and the particles can be classified into size ranges. If the products remain at their original location, they constitute a residual soil (Craig, 2005).

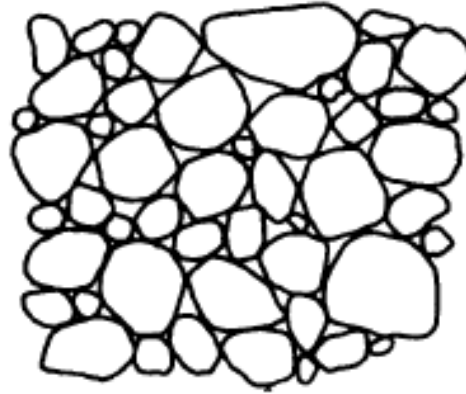


Figure 2.12: Single Grain Structure (Craig, 2005)

The destructive process in the formation of soil from rock may be either physical or chemical. The physical process may be erosion by the action of wind, water or glaciers, or disintegration caused by alternate freezing and thawing in cracks in the rock. The resultant soil particles retain the same composition as that of the parent rock. The shape of particles of this type are termed as angular, flat, elongated and rounded. As shown in Figure 2.12, the structural arrangement of bulky particles is described as single grain. Each particle is in direct contact with adjoining particles without there being any bond between them (Craig, 2005).

1. The Clay Minerals

Chemical processes result in changes in the mineral form of the parent rock due to the action of water, oxygen and carbon dioxide. Chemical weathering results in the formation of groups of crystalline particles of colloidal size known as clay minerals. For example, Kaolinite is formed by the breakdown of feldspar by the action of carbon dioxide and water. Most clay mineral particles are of 'plate-like' form having a high surface area to mass ratio, resulting in surface forces significantly influencing their structure. As shown in Figure 2.13(a), the basic structural units of most clay minerals are a silicon-oxygen tetrahedron and an aluminium-hydroxyl octahedron. There are imbalances in the number of bonds formed in both units which means that the basic units do not exist in isolation, but combine to form sheet structures (Craig, 2005).

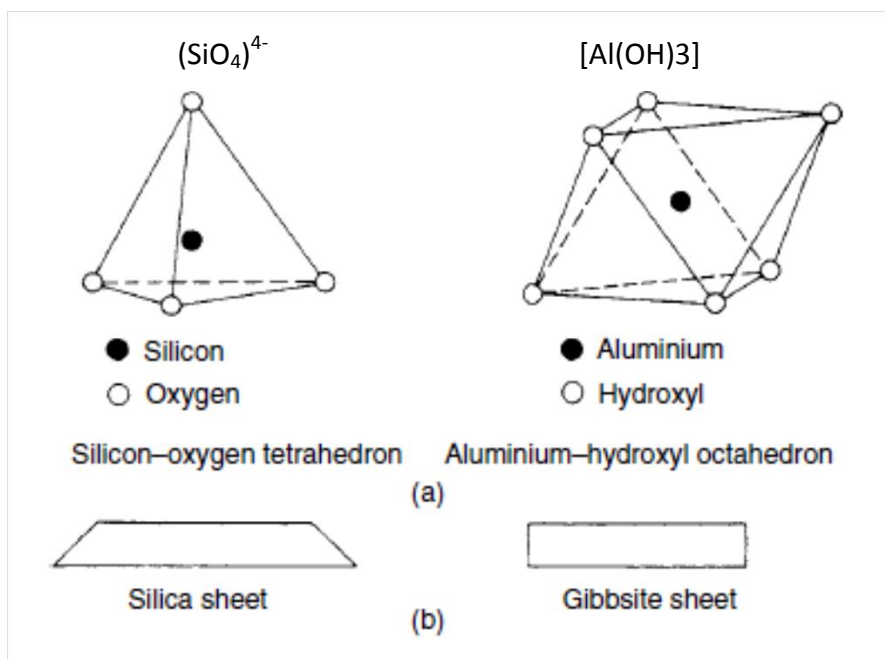


Figure 2.13: Clay Mineral basic units (Craig, 2005)

The tetrahedral units combine by the sharing of oxygen ions to form a silica sheet. The octahedral units combine through shared hydroxyl ions to form a gibbsite sheet. The silica sheet holds a negative charge but the gibbsite sheet is electrically neutral. The sheet structures are represented in Figure 2.13 (b). Silicon and Aluminium may be partially replaced by other elements, resulting in further charge imbalances. This is known as isomorphous substitution. Layered structures then form by the bonding of a silica sheet with either one or two gibbsite sheets. Clay mineral particles consist of stacks of these layers. The structures of the principal clay minerals are represented in Figure 2.14 (Craig, 2005).

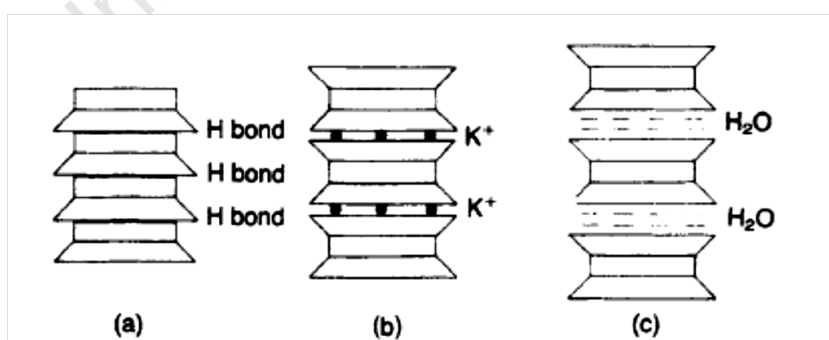


Figure 2.14: (a) Kaolinite, (b) Illite, (c) Montmorillonite (Craig, 2005)

Kaolinite

Kaolinite consists of a structure based on a single sheet of silica combined with a single sheet of gibbsite. The combined silica-gibbsite sheets are held together relatively strongly by

hydrogen bonding and there is very limited isomorphous substitution (Craig, 2005). According to Powrie (2007), it is for these reasons that Kaolinite might be described as the least clay-like of the clay minerals. It tends to form particles which are relatively large for clay. Particles of crystallised Kaolin appear as hexagonal plates with lateral dimensions of 0.1 to 4 μm and thicknesses of 0.05 to 2 μm (Powrie, 2007).

Illite

Illite has a basic three sheet structure consisting of gibbsite combined with two sheets of silica. In the silica sheet there is partial substitution of silicon by aluminium. The combined sheets are linked together by relatively weak bonding due to non-exchangeable potassium ions held between them (Craig, 2005). According to Powrie (2007), illites have the same basic structure as the non-clay mineral muscovite mica. Illite differs from these minerals in that fewer of the silica Si^{4+} positions are taken by aluminium Al^{3+} , so there is less potassium between the layers. Illite particles are smaller than mica particles and the layers are more randomly stacked. Illite may also contain magnesium and iron in the gibbsite sheet. For example, iron-rich Illite which has a characteristic green hue is known as glauconite. Illites occur as small, flaky particles mixed with other clay and non-clay minerals. Illite particles range from 0.1 μm to 0.5 μm in length and may be as small as 3nm in thickness. Unlike Kaolinite and Montmorillonite, their occurrence in high-purity deposits is unknown (Powrie, 2007).

Montmorillonite

Montmorillonite has the same basic structure as illite, a three sheet structure comprising of a sheet of gibbsite between two silica sheets. Montmorillonites have a similar basic structure to the non-clay mineral group known as pyrophyllites (Powrie, 2007). According to Craig (2005), there is a partial substitution of aluminium by magnesium and iron in the gibbsite sheet. In the silica sheet there is partial substitution of silicon by aluminium. The space between the combined sheets is occupied by water molecules and exchangeable cations other than potassium, resulting in very weak bonds which are easily separated by the adsorption of water. For these reasons, Powrie (2007) states that the Montmorillonite particles are very small and can swell significantly by the adsorption of water. Therefore, soils which contain Montmorillonites exhibit a substantial potential for volume change and are sometimes termed expansive soils. Montmorillonite particles are 1 to 2 μm in length and usually occur in multiples of 1nm thickness.

There are two other groups of clay minerals. Palygorskites, which are not common, have a chain structure as opposed to a sheet structure, and Vermiculites which have a similar tendency to swell as montmorillonites (Powrie, 2007).

As discussed previously, the surfaces of clay mineral particles carry negative charges, mainly as a result of the isomorphous substitution but also due to the disassociation of hydroxyl ions. The negative charges result in cations present in the water being attracted to these particles. The cations are not held strongly and if the nature of the water changes, they can be replaced by other cations. This phenomenon is termed as Base Exchange. Cations are attracted to a clay mineral particle but they also tend to repel each other because of their thermal energy. This results in cations forming a dispersed layer adjacent to the clay particle surface, termed the double layer. Forces of repulsion and attraction act between clay mineral particles. Repulsion occurs between the like charges of the double layers and an increase in cation valency or concentration will result in a decrease in repulsive force and vice versa which leads to a decrease in layer thickness and an increase in the net attractive forces between particles. A decrease in water content and an increase in temperature will also result in a decrease in cation layer thickness (Craig, 2005).

Layers of water molecules are held around a clay mineral particle by hydrogen bonding and by attraction to the negatively charged surfaces. The cations also attract water and the clay particle becomes surrounded by a layer of adsorbed water. The water nearest to the particle is strongly held and has a high viscosity which decreases with increasing distance from the particle surface. Adsorbed water molecules can move freely parallel to the particle surface but perpendicular movement is restricted (Craig, 2005).

According to Craig (2005), clay is thus a type of soil possessing cohesion and plasticity. Cohesion is the term used to describe the strength of clay when it is unconfined due to the negative pressure in the water that fills the void space between particles (Craig, 2005). However, Powrie (2007) states that the word 'cohesive' used to describe clays should be avoided, as it implies a strength which is non-frictional in its nature. Surface effects are much more significant in clays than in sands. Clay soils exhibit plasticity which in this context can be defined according to Powrie (2007) as: "The ability to be worked and re-moulded in hand". Surface effects do play a part in this but the main reason clays can be moulded in hand is that they sustain large pore water suctions. These pore water suctions may result in large effective

stresses, hence frictional strength (Powrie, 2007). Craig (2005) concludes that this strength would be lost if the clay were to be immersed in a body of water. It should be noted that all clay-size particles are not necessarily clay mineral particles. If clay minerals are present, they usually exert a significant influence on the properties of a soil (Craig, 2005).

2. *Non-clay Minerals*

The most common non-clay mineral in soils is quartz (SiO_2) which is a framework silicate, in which the silica tetrahedra are grouped to form spirals. Quartz is relatively hard ($H = 7$) and resistant to abrasion. To compare, diamond is the hardest ($H = 10$) and talc, the softest ($H = 1$). Quartz is also chemically and mechanically very stable as it is already an oxide and has a structure without cleavage planes and so the material cannot be split. It is for these reasons that it prevails in sands and gravels which have a larger particle size (Powrie, 2007). According to Passchier & Trouw (2005), Cleavage in structural geology describes a type of planar rock feature that develops as a result of deformation.

Feldspars ($\text{KAlSi}_3\text{O}_8 - \text{NaAlSi}_3\text{O}_8 - \text{CaAl}_2\text{Si}_2\text{O}_8$) also have three-dimensional framework structures but some of the silicon ions have been replaced by aluminium. The resultant excess negative charge is balanced by cations such as sodium, calcium and potassium. This results in a more open structure with lower bond strengths which means that feldspars are not as hard as quartz and therefore they are more easily broken down. This is why they are not as common in soils as they are in igneous rocks. Olivines, amphiboles and pyroxenes are also relatively easily broken down which explains why they are not present in many soils (Powrie, 2007).

3. *Organic (non mineral) Soils*

Some soils, particularly peat, do not result from the breakdown of rock, but from the decay of organic matter. Peat is highly compressible as it usually has a mass density that is only slightly greater than that of water. Like topsoil, these organic soils are not suitable for engineering purposes and should not be relied on. Unlike topsoil, organic soils may be naturally buried below the surface which makes it difficult to detect (Powrie, 2007).

2.3.4. *Particle Size Analysis*

Powrie (2007) mentions that civil engineers describe and classify soils according to their particle size rather than according to their age, origin or mineralogy. The reason is that civil engineers are interested mostly in the mechanical properties of soils, which depends mainly on particle size. Clays are generally more compressible than sands and gravels due to their

impermeability. In sands and gravels, water can flow very easily through the void. The size of the voids is governed by the size of the smallest particles because they can fit into the voids between the larger particles. Powrie (2007) states that the permeability of a soil is related to the maximum size of the smallest 10% of particles by mass. It is for these reasons that in clays, water can move through the voids only slowly. This is why civil engineers find it useful to categorise a soil as a 'clay' or a 'sand' (Powrie, 2007).

In carrying out standard tests, such as soil grading, description and classification, it is important that standard procedures and methods are followed. Without standardisation, the designers would not know whether differences between results were due to differences in the soil, or to differences in the testing procedure. In the UK, standard procedures are followed according to BS1377, 1991; in the US, ASTM D2487-1969, 1970 and in South Africa, SANS 201, 2008. One common system of soil classification according to particle size is the one used in the UK as shown in Table 2.4. There are other systems in the world, particularly in the USA, which differ slightly, but the principle is the same (Powrie, 2007).

Table 2.4: Classification of soils according to particle size in the UK (Powrie, 2007)

Grade	Particle Size		
	<i>Fine</i>	<i>Medium</i>	<i>Coarse</i>
Gravel	2 – 6 mm	6 – 20 mm	20 – 60 mm
Sand	0.06 – 0.2 mm	0.2 – 0.6 mm	0.6 – 2.0 mm
Silt	0.002 – 0.006 mm	0.006 – 0.02 mm	0.02 – 0.06 mm
Clay	< 0.002 mm		

The particle size analysis of a soil sample involves determining the percentage by mass of particles within the different size ranges. The particle size distribution of a soil can be determined by the method of sieving. The soil sample is passed through a series of standard test sieves having successively smaller mesh sizes. The mass of soil retained in each sieve is determined and the cumulative percentage by mass passing each sieve is calculated. Fine particles present in the soil are washed through the sieves (Craig, 2005). According to Powrie (2007), sand is classified as the portion of a soil whose particle size is greater than the 63 μm sieve. Soils containing fine particles must usually be wet-sieved. This involves washing the sample through 63 μm sieve in order to remove the fine particles which could otherwise stick to each other and to the coarser particles, increasing the apparent particle size. The portion of the sample retained on the 63 μm sieve is then oven-dried and dry-sieved. Particles which are

smaller than 63 μm are too small for size determination by sieving. Therefore, a different ‘sedimentation’ technique is used in accordance with BS 1377 (Powrie, 2007).



Figure 2.15: Sieve Analysis Apparatus (Easton & Wright, 2007)

In South Africa, the testing procedures for the ‘pipette method’ are followed in accordance with SANS6244, 2006. The particle size distribution of a soil is then presented as a curve on a logarithmic plot. A soil which has a reasonable spread of particle size is represented by a smooth concave curve (A) in Figure 2.16 is normally described as well-graded. A soil which consists primarily of a single particle size is represented by curve (B) and is described as uniform. A soil which contains small and large particles but few particles of intermediate size is described as gap-graded. The particle size distribution will have a horizontal step. Uniform and gap-graded soils are sometimes referred to as poorly-graded. When a soil is well-graded and compacted, it will pack together well to fill all the voids because it contains a wide range of particle sizes (Powrie, 2007).

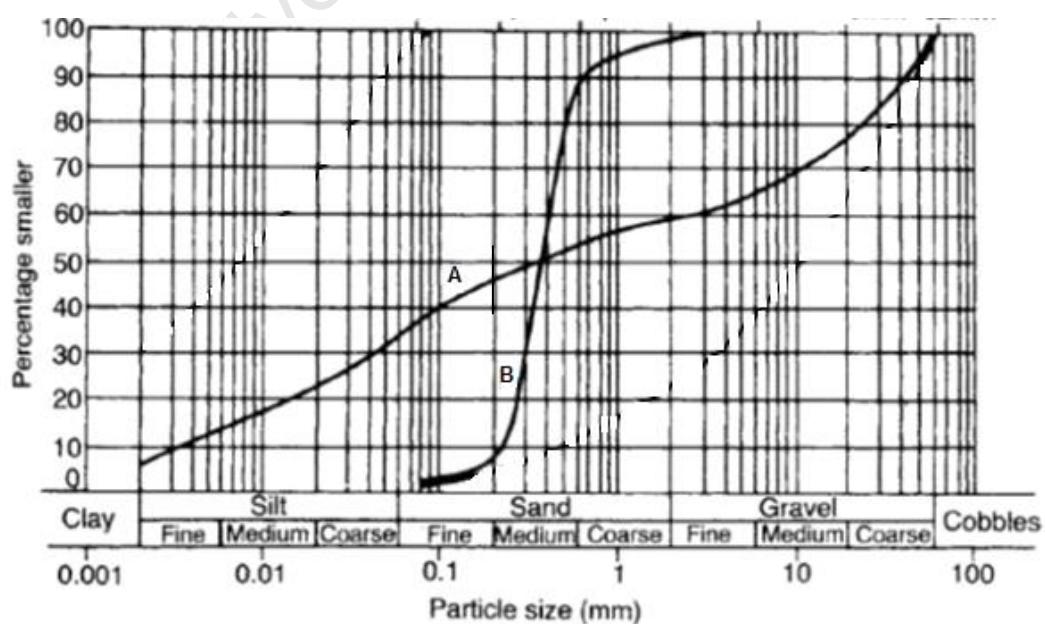


Figure 2.16: Particle size distribution curve (Craig, 2005)

The largest particle size in the smallest 10% of particles is known as the D_{10} particle size. However, the information conveyed by quoting a representative particle size such as D_{10} is limited. The general slope and shape of the distribution curve can be described by means of the coefficient of uniformity (U) and the coefficient of curvature (Z), defined as follows:

$$U = D_{60} / D_{10} \quad (2.9)$$

$$Z = (D_{30})^2 / D_{60}D_{10} \quad (2.10)$$

U is related to the general shape and slope of the particle size distribution curve, the higher the uniformity coefficient, the larger the range of particle size. A soil with a uniformity coefficient U of more than 10 can be regarded as uniformly graded, while soils with a U value less than 10 can be regarded as well-graded. A well-graded soil normally has a coefficient of curvature Z in the range of 1-3 (Powrie, 2007). Note that the way geotechnical engineers describe grading is not the same as the way concrete technologists do.

Particle Size Analysis in terms of Rammed Earth

As described previously, Powrie (2007) mentions that soil is classified by the size of its individual particles and not by its parent rock the reason being that civil engineers are interested mostly in the mechanical properties. He also states that according to BS5930, a soil can be graded into different soil groups (e.g. gravel, sand, silt or clay). In the context of Rammed Earth, each soil group has an important structural attribute. These are described in more detail below.

- *Gravel* is that component with particle sizes larger than sand yet small enough to leave in the mix. Reducing the gravel size will result in a smoother Rammed Earth wall surface (Easton & Wright, 2007).
- *Sands* by themselves are not cohesive, but when bonded with either clay or cement, they become the primary structural aggregate in a Rammed Earth wall (Easton & Wright, 2007).
- *Silt*, unlike clay, is chemically inactive. It does not have a charge to attract water and it will not expand when wet. Its particles do not contribute to the binding process but they will fill voids between the larger grain sizes and increase wall density. If the

percentages of silt in the soil are too high, the wall will decrease in durability and strength. This is because silt particles are small, round and don't have the edges to lock the matrix together. They are also difficult to stabilise as the particles are so small compared to the total surface area that the clay/cement slurry cannot encapsulate all the particles in the soil matrix (Easton & Wright, 2007).

- *Clay* is the binder that holds the other particles together. As discussed in 2.5, the percentage of clay is vital to the quality of a Rammed Earth wall. If there is too little clay, the earth particles will not be cohesive enough. If there is too much clay, the wall will shrink and crack as it dries. Although the shrinkage cracks will initially not result in a weakening of the wall, when it eventually rains the moisture will penetrate the cracks and cause expansion of the soil. After a few years of contraction and expansion, the wall will begin to deteriorate. Clay particles improve wall strength by providing lubrication during compaction and allows the angular sand and gravel particles to pack themselves into the densest configuration possible. Compaction will force the particles into a tighter mass decreasing the air space and increasing their chemical bond. Increasing the density through compaction is a form of stabilisation and the denser the wall, the more the wall will resist water penetration (Easton & Wright, 2007).
- *Organic Soil* - Most construction sites are covered with a layer of organic soil known as topsoil (Figure 2.17), typically 500 mm deep from the surface. This layer contains a high content of organic matter. Organic soil contains plant matter which reacts with cement and has a detrimental effect on the overall strength of a Rammed Earth wall. Organic soil is lighter in weight, smoother to the touch and has a musty smell compared to the deeper sub-soil (Easton & Wright, 2007).

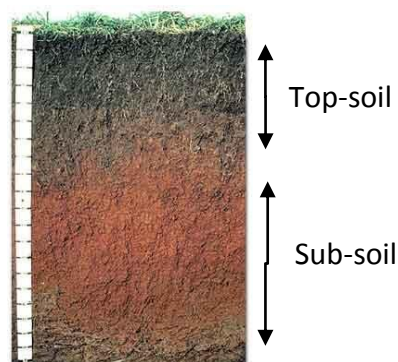


Figure 2.17: Soil Profile distinguishing the difference between Top-Soil and Sub-Soil (Easton & Wright, 2007)

2.3.5. *Plasticity of Fine Soils*

Craig (2005) states that plasticity is an important characteristic in the case of fine soils. He defines plasticity as: “the ability of a soil to undergo unrecoverable deformation without cracking or crumbling”. A soil may exist in one of the liquid, plastic, semi-solid and solid states depending on its water content. Craig (2005) defines water content as: “the ratio of the mass of water in the soil to the mass of solid particles”.

Powrie (2007) states that a clay soil will only exhibit plasticity between certain limits of water content. If the water content is too high, the soil will behave almost like a liquid. If water content is too low, the soil will dry and crumble. The water content below which the soil is brittle is known as the plastic limit (PL). The water content above which the soil will behave as a liquid is known as the liquid limit (LL). The range between the liquid limit and plastic limit is where the soil will behave as a plastic material and is termed as the plasticity index (Powrie, 2007). Craig (2005) states most fine soils exist in the plastic state in the ground. Plasticity is due to the presence of a significant content of clay mineral particles in the soil. The void space between such particles is very small which causes water to be held at negative pressures by capillary tension. This produces a degree of ‘cohesion’ between the particles allowing the soil to be moulded or deformed (Craig, 2005).

The liquid limit, the plastic limit and the plasticity index are related to both mineralogy and the amount of clay present in the soil sample. For example, a sample of soil with a high proportion of kaolinite particles might have a similar plasticity index to a different soil with a smaller proportion of illite or smectite particles. According to Craig (2005), the two effects can be separated by means of a parameter known as the activity A (Equation 2.11). For kaolinite, $A \approx 0.5$. For illite, $0.5 < A < 1$, and for smectite, $1 < A < 7$ (Craig, 2005). The procedures for testing fine soils, known as the Atterberg limits tests (see A.2.9), are followed according to SANS3001-GR10:2008.

$$A = PI / (\text{Percentage of the sample by mass with a particle size of } < 2 \mu\text{m}) \quad (2.11)$$

2.3.6. *Soil Classification Systems*

General classification systems in which soils are placed into groups on the basis of grading and plasticity have been used for many years. The purpose of these systems is that each soil group

is given a letter symbol representing main and qualifying terms. In the UK, the terms and letters used are represented (Table 2.5) in accordance with BS5930. The boundary between coarse and fine soils is generally taken to be 35% fines (Particles smaller than 63 μm) (Craig, 2005). Note that the way geotechnical engineers classify soils is not the same as the way concrete technologists do.

Table 2.5: Terms and Letters used for Soil Classification in accordance with BS5930 (Craig, 2005)

<i>Main Terms</i>	<i>Qualifying terms</i>		
GRAVEL	G	Well graded	W
SAND	S	Poorly graded	P
		Uniform	Pu
		Gap graded	Pg
FINE SOIL, FINES	F	Of low plasticity ($w_L < 35$)	L
SILT (M-SOIL)	M	Of intermediate plasticity ($w_L: 35-50$)	I
CLAY	C	Of high plasticity ($w_L: 35-50$)	H
		Of very high plasticity ($w_L: 70 - 90$)	V
		Of extremely high plasticity ($w_L: > 90$)	E
		Of upper plasticity range ($w_L: > 35$)	U
PEAT	Pt	Organic (may be a suffix to any group)	O

Table 2.6: Composite Types of Soils in accordance with BS5930 (Craig, 2005)

Slightly sandy GRAVEL	Up to 5% sand
Sandy GRAVEL	5 – 20% sand
Very sandy GRAVEL	Over 20% sand
SAND and GRAVEL	About equal proportions
Very gravelly SAND	Over 20% gravel
Gravelly SAND	5 – 20% gravel
Slightly gravelly SAND	Up to 5% gravel
Slightly silty SAND (and/or GRAVEL)	Up to 5% silt
Silty SAND (and/or GRAVEL)	5 – 20% silt
Very silt SAND (and/or GRAVEL)	Over 20% silt
Slightly clayey SAND (and/or GRAVEL)	Up to 5% clay
Clayey SAND (and/or GRAVEL)	5 – 20% clay
Very clayey SAND (and/or GRAVEL)	Over 20% clay

Gravel particles are usually rock fragments, for example, sandstone and schist. As discussed previously, sand particles usually consist of individual mineral grains such as quartz or feldspar. For fine soils, terms such as silty clay should not be used. Fine soils should be described as either silt or clay. The term FINE SOIL or FINES is used when it is not possible

to differentiate between SILT and CLAY. In terms of classification, the principal constituent is written in capital letters. SILT or CLAY is classified as gravelly if more than 50% of the coarse fraction (particles greater than 63 μm) is of gravel size and as sandy if more than 50% of the coarse fraction is of sand size. For example, fine soils containing 35-65% coarse material are described as sandy and/or gravelly SILT (or CLAY). Composite types of soil are described (Table 2.6) in accordance with BS5930 (Craig, 2005). According to Powrie (2007), fine-grained soils may be classified as clays or silts of low, intermediate or high plasticity on the basis of their plasticity index and liquid limit, as shown below in Figure 2.18.

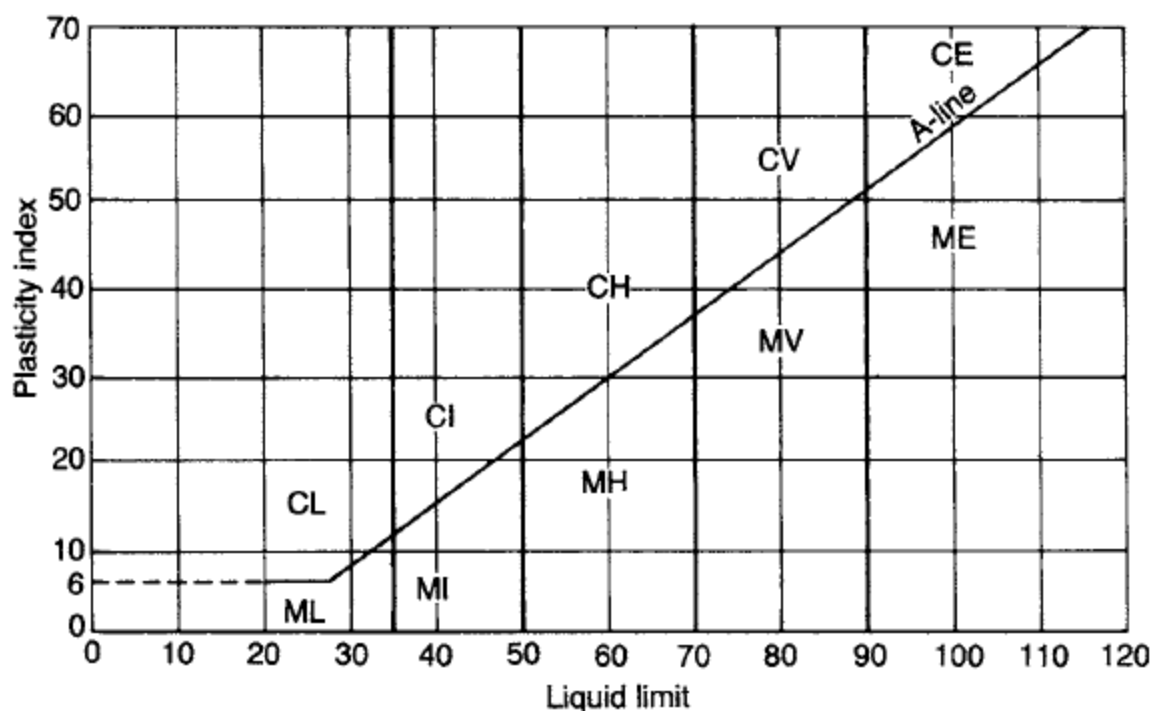


Figure 2.18: Classification System for Fine Soils, based on Plasticity Index and Liquid Limit (BS5930, 1999)

Classification letters are assigned to the soils according to the zone within which the point lies. The letter representing the principal size fraction is placed first in the group symbol. The chart is divided into five ranges of liquid limit. The diagonal line (A-line), should not be regarded as a clear boundary between CLAY and SILT. SILT plots below the A-line and CLAY plots above the A-line. According to Craig (2005), silts exhibit plastic properties over a lower range of water content than clays having the same liquid limit. Fine soils containing significant amounts of organic matter usually have high liquid limits and plot below the A-line as organic silt. Craig (2005) states that a similar classification has been developed in the US, but has less detailed subdivisions.

Examples of soil classification are listed below (Craig, 2005):

- SW – well-graded SAND
- SCL – very clayey SAND (clay of low plasticity)
- CIS – sandy CLAY of intermediate plasticity
- MHSO – organic sandy SILT of high plasticity

2.3.7. *Compaction*

Compaction is the process of increasing the density of a soil by packing the particles closer together with a reduction in the volume of air. There is no significant change in the volume of water in the soil. A higher degree of compaction will give soil higher shear strength. The degree of compaction of a soil is measured in terms of dry density which is defined as the mass of dry solids per unit volume of soil. The bulk density is the soil's mass per unit volume. Dry density can be calculated using equation 1.4 where ρ_d is the bulk density and w , the water content (Craig, 2005).

$$\rho_d = \frac{\rho_s}{1 + w} \quad (2.12)$$

The dry density of a given soil after compaction depends on the water content and the compactive effort which is defined as the energy supplied by the compaction equipment (Craig, 2005). According to BS 1377, the compaction characteristics of a soil can be assessed by performing one of three standard laboratory tests: The proctor test, the modified AASHTO test and the vibrating hammer test. In South Africa, the testing procedures are followed in accordance with SANS 3001-GR30: 2010.

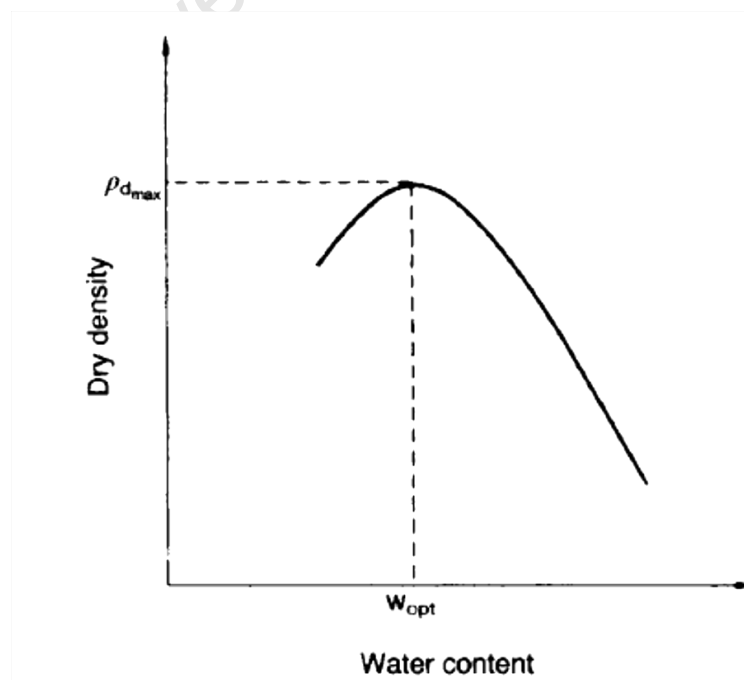


Figure 2.19: Relationship between Dry Density and Moisture Content (Craig, 2005)

After performing one of the three standard methods, dry density is plotted against water content and a curve is obtained, as shown in Figure 2.19. This curve demonstrates that at a certain water content, the compacted soil will have obtained maximum dry density. This is referred to as the optimum water content. Soils are stiff and are difficult to compact at low values for water content. As the water content increases, soils become more compactable which results in higher dry densities. However, once the optimum water content has been reached, the dry density decreases with increasing water content as an increasing proportion of the volume is occupied by water (Craig, 2005).

The maximum possible value of dry density is referred to as ‘zero air voids’. Craig (2005) states that: “if all the air in a soil could be expelled by compaction, the soil would be in a state of full saturation and the dry density would be the maximum value for the given water content”. However, he also mentions that this degree of compaction is unattainable in practice (Craig, 2005).

2.4. Engineering Properties of Rammed Earth

Physical testing of specimens made from Rammed Earth and from stabilised Rammed Earth is recommended in conjunction with the soil classification tests previously described, for the assessment of material suitability. Physical testing of Rammed Earth materials is also necessary to ensure that design requirements and specifications (Table 2.7) are met initially, and they may be checked later during construction (Walker *et al.* 2005).

Table 2.7: Typical Minimum Performance Specifications for Rammed Earth (Walker *et al.*, 2005)

Parameter	Specification
Soil Composition	Meet recommended and agreed specifications for grading, plasticity, shrinkage, chemical composition, mineralogy, colour, texture, organic matter content and soluble salts content
Minimum Dry Density	98% of heavy manual compaction test maximum dry density
Compaction Moisture Content (OMC)	± 1-2% of Optimum Moisture Content
Unconfined Compressive Strength (UCS)	1.0 MPa (General) ; 2.0 MPa (load-bearing)
Erosion Resistance	Erosion rate not greater than 1 mm/min
Surface Abrasion	No general specification
Maximum Drying Shrinkage	Not greater than 0.5% (composite loadbearing) Not greater than 1.0% (other)

2.4.1. *Soil characteristics of Rammed Earth*

- *Cohesion* is due to the strong forces that develop between films of absorbed water bound to clay plates. In unstabilised Rammed Earth, clay is the primary binder and its cohesive strength is necessary to maintain material integrity. In cement and lime stabilised Rammed Earth, clay is only relied upon to maintain form during the early stages of production until the binder has hardened (Standards Australia, 2002).
- *Colour* indicates the soil's constituents and influences its selection for earth building. Black and dark brown soils are often high in organic content. Yellow, yellowish-brown, red and reddish-brown are indicative of the presence of iron. Cement and lime stabilisation will tend to lighten the finished colour (Standards Australia, 2002).
- The *density* of soil depends on moisture content, compactive effort, composition and grading. The densification of soil by expulsion of air voids through compaction is fundamental to Rammed Earth construction. Improving density generally improves strength, durability and thermal conductivity. The dry density of poorly graded soils can also be increased by the addition of particle sizes lacking in the original matrix. For compacted earth building materials to reach their maximum dry density, it is important that they are compacted at their Optimum Moisture Content (Standards Australia, 2002).
- *Plasticity* is the ability of a soil to undergo non-recoverable deformation at a constant volume without crushing or cracking and is due to the presence of clay minerals. Critical soil may be in liquid, plastic or solid state depending on moisture content. Soil moisture contents are known as the liquid limit (LL) and the plastic limit (PL). These define the transition between liquid and plastic, and plastic and solid states. The moisture range over which a soil behaves plastically is defined by its plasticity index (PI), given by: $PI = LL - PL$ (Standards Australia, 2002).

2.4.2. *Dry Density*

In assessment and preparation of materials, moisture-density relationships are determined using the compaction test according to SANS3001-GR30:2010. The test provides optimum moisture and maximum dry density for material passing a 19 mm sieve. In-situ testing of Rammed Earth

to check the achieved density is difficult, so tests are undertaken on cylinders or cubes (see A.2.1) (Standards Australia, 2002).

2.4.3. Compressive Strength

Compressive strength of Rammed Earth is determined by testing cylindrical specimens or earth blocks in uni-axial compression (see A.2.8). Dry Unconfined Compressive Strength (UCS) of Rammed Earth is normally in the range 0.5 – 4 MPa. Stabilised Rammed Earth can achieve strengths in excess of 10 MPa in less than 7 days. Cylinders or earth blocks are prepared in advance in the laboratory or on site. Assumed design values should take account of likely worst-case moisture conditions under the design loading. For example, where significant loading is likely to be applied to newly rammed (damp) walls, lower values of strength and stiffness than the final dry values should be assumed. Compressive strength of moist Rammed Earth materials is likely to be at least 50% lower than the final values. Factors of safety are applied to design capacities based on material strengths to account for variations in materials and quality of work (Walker *et al.* 2005).

2.4.4. Flexural and Shear Strength

The flexural, tensile, and shear strengths of Rammed Earth are generally very low. Although material self-weight and other pre-compression loads will often be sufficient, walls may require a minimum flexural strength to resist lateral loads. Some shear strength may be assumed for cracking resistance, though frictional resistance will often be sufficient. As well as the basic soil characteristics, construction issues such as initial moisture content, extent of ramming and rate of drying influence shrinkage. Over-compaction tends to be disruptive to the flexural and shear strength developed between compaction layers (Walker *et al.* 2005).

2.4.5. Durability

Water-related weathering and mechanical abrasion of surfaces are the primary agents of decay in Rammed Earth buildings. Rainfall causes damage through kinematic impact at the surface, washing out of fines and the cyclic swelling and shrinkage of the clay fraction. The rate of erosion of exposed earthen materials normally decreases with time as surface fines are removed and gravel content is exposed. The collection of moisture at wall bases can be avoided by providing good drainage, damp proofing, surface protection and a suitable eaves overhang. Further protection to external walls may be provided by weather screens or protective coating around the outside of buildings (Walker *et al.* 2005).

Laboratory tests for erosion potential are difficult, at best approximate. This is due to the complexity and long-term nature of weathering that is to be replicated in a few hours or days. The water-spray erosion test (see A.2.7) can provide some relative indication of material performance, but cannot be confidently used to forecast actual performance (Walker *et al.* 2005).

Bui *et al.* (2009) have carried out a series of tests to determine the durability of Rammed Earth. In 1985, a number of stabilised and unstabilised 400 mm thick walls were constructed and exposed to ambient conditions for 20 years. They were then assessed for durability, primarily by checking the erosion of the walls. A Rammed Earth wall can be considered to have finished its life when the erosion of the wall reaches 5% of the original thickness. Stabilised Rammed Earth walls were found to have eroded 2 mm, or about 0.5%. Therefore, at a rate of 0.5% over 20 years, if erosion is linear with respect to time, the stabilised Rammed Earth walls will reach the end of their lives after 200 years. If non-linear erosion occurs, which is expected, the life of the walls will be even longer (Bui *et al.* 2009).

Unstabilised Rammed Earth walls were found to have eroded, on average, about 6 mm (1.6%). Based on the 5% limit, this gives them an expected life of approximately 60 years with linear erosion. The walls constructed for the test had roofs and it was found that the top part of the walls eroded less than the lower parts because of the protection offered by the roofing (Bui *et al.* 2009).

2.4.6. Thermal Properties

Thermal properties of Rammed Earth are related to its density. Both thermal conductivity and capacity increase with material density. As a dense material, Rammed Earth has relatively poor thermal insulating qualities. The capacity of Rammed Earth to store heat is an important characteristic for its use in energy-efficient building design. Thermal heat capacity is the quantity of heat required to raise the temperature of one unit volume of material by one unit of temperature. Table 2.8 shows typical thermal characteristics of walls built from different construction methods.

Table 2.8: Typical Thermal characteristics of walls of different Construction Methods (Standards Australia, 2002)

Method	Rammed Earth	Mud Brick	Concrete
Thickness (mm)	250	300	300
Thermal Resistance ($\text{m}^2 \text{K/W}$)	0.25 to 0.60	0.35 to 0.7	0.15 to 0.33

2.4.7. Deformation

Rammed Earth walls deform owing to elastic displacement under load, thermal expansion, drying shrinkage and creep. To minimise cracking, such movements should be accommodated in design through appropriate detailing and the provision of movement joints.

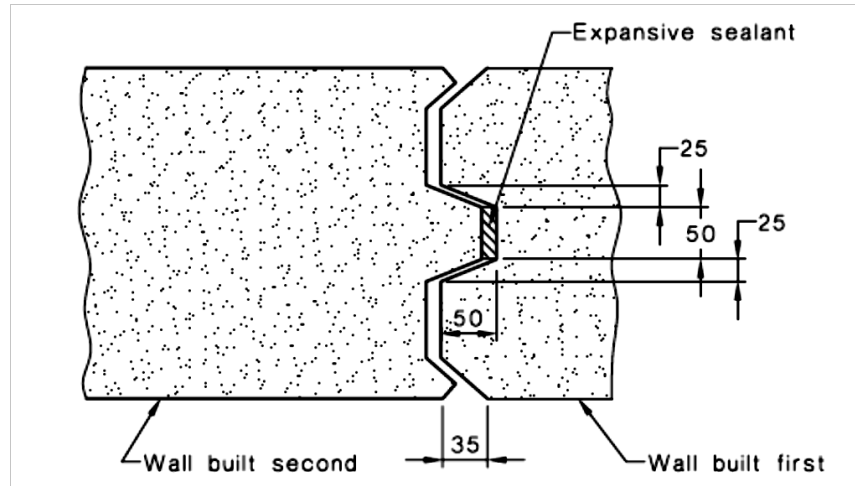


Figure 2.20: Movement Joint in Rammed Earth (horizontal cross-section)

- *Movement Joints* - Vertical movement joints (Figure 2.20) are horizontally spaced to control deformation due to shrinkage and to allow structural deformation to occur without damaging the wall. The horizontal spacing depends partly on the design of the wall and material properties. Joint spacing also depends on the ground conditions and foundations provided (Walker *et al.* 2005).
- *Drying Shrinkage* - After compaction, as the material dries from around 8-14% moisture content (by dry mass) to around 1-5% in ambient conditions, Rammed Earth walls shrink vertically, laterally and longitudinally. The rate at which the material loses moisture and the final moisture content depend on factors such as shelter, environmental conditions and material characteristics. The level of shrinkage depends on the soil grading, clay content, initial and final moisture content and rate of drying. In general, shrinkage will be less than 0.5% but material testing (see A.2.5) should be undertaken (Walker *et al.* 2005).

Horizontal (Figure 2.21) drying shrinkage may be accommodated by the inclusion of movement joints. Vertical shrinkage is principally a concern where load bearing Rammed Earth shares structural support with other elements such as timber or steel. In such cases, quantifying the extent and rate of drying shrinkage is important. For

example, fixings such as wall ties must be able to accommodate the expected level of shrinkage otherwise cracking may occur when restrained. Higher plasticity sub-soils require particular care to minimise potential harmful effects of excessive shrinkage. For example, a localised softening of the material due to a water leak may lead to significant swelling of the material (Walker *et al.* 2005).

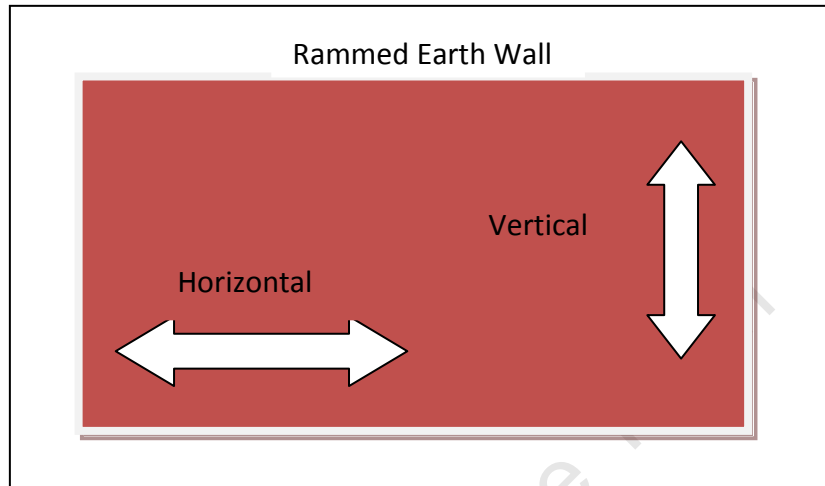


Figure 2.21: Dimensional Reference for a Rammed Earth wall

2.5. Material Selection for Rammed Earth Construction

Selection of an appropriate raw material is critical to the success of Rammed Earth. In-situ materials often prove suitable though they may require modification. Factors influencing the selection of a suitable soil include (Walker *et al.* 2005):

- Colour and texture of compacted material
- Available quality and quantity of in-situ soil
- Storage of materials
- Appropriate engineering properties

Materials not previously used should always be tested for suitability. Sufficient resources (time and money) should be programmed into a project for material testing and selection. Care should be taken to ensure the stability of sub-soils. Laboratory testing (Grading, Atterberg Limits, Clay content & Organic Content) on chemical and physical stability of sub-soils may be required (Walker *et al.* 2005).

If the available in-situ soil is unsuitable, a blended or engineered material may be formed by combining different materials in order to provide the desired mix characteristics. For example,

aggregates with insufficient clay can be improved by the addition of powdered clay. Alternatively, clay and silty soils can be improved by the addition of sand and gravel in suitable proportions. Recent projects where blended soils have been successfully used included the AtEIC building (see 2.6.3) and the Chapel of Reconciliation in Berlin (see 2.6.3) (Walker *et al.* 2005).

2.5.1. Soil Survey

The bulk raw material of Rammed Earth construction is subject to natural variability and not all sub-soils are suitable. Observational survey of trends in local historical and existing earth buildings is a useful starting point to establish the likelihood of finding suitable material in the local area. Soil surveys and geological maps are a useful resource for preliminary appraisal of in-situ material and for finding off-site sources of material. Material from large public works and local quarries are other possible sources (Walker *et al.* 2005).

Site investigation of materials for Rammed Earth should follow recognised procedures for civil engineering. Sufficient samples must be taken from a specific site to ensure that they are representative of the bulk material. Materials may be sampled from bore-holes, stockpiles and ground excavations. Following the sampling of materials, suitability for Rammed Earth construction is assessed on the basis of soil classification tests (grading, plasticity) and physical characteristics of prototype Rammed Earth specimens (Walker *et al.* 2005).

2.5.2. Soil Classification Tests

The level of testing and analysis should reflect and be proportionate to the scale and complexity of the proposed works. Basic soil testing includes tests to determine grading, plasticity and organic matter content. Grading gives an indication of likely compaction and quantity of fines present. Plasticity indicates the cohesive nature of the fines content. Grading and plasticity tests will often provide sufficient indication of clay reactivity and type. However, more detailed tests may be undertaken to determine the level of soluble salts and soil mineralogical composition including clay type. Soil mineralogy may be determined by X-ray diffraction analysis.

There are also various simple field tests that are used as a means of assessing soil suitability. These include: sensory tests (see A.1.1) for soil composition; jar sedimentation test (see A.1.4) for volumetric soil composition; water retention test for indication of fines composition; dry strength test (see A.1.3) and ribbon test (see A.1.2) for clay content; and the shrinkage box test

for plasticity (see A.1.6). These tests may be useful for initial selection but where engineering design is required; such analysis should not be treated as a substitute to laboratory testing.

2.5.3. Soil Criteria for Rammed Earth

In general, soil for Rammed Earth should be well graded, containing gravel, sand, silt and clay fractions. Ideally the soil should have reasonably high sand and gravel content, with some silt and sufficient clay to act as a binder and assist soil compaction. Suitable soils for Rammed Earth in general fall within the upper and lower limit grading curves shown in Figure 2.22 (Walker *et al.*, 2005).

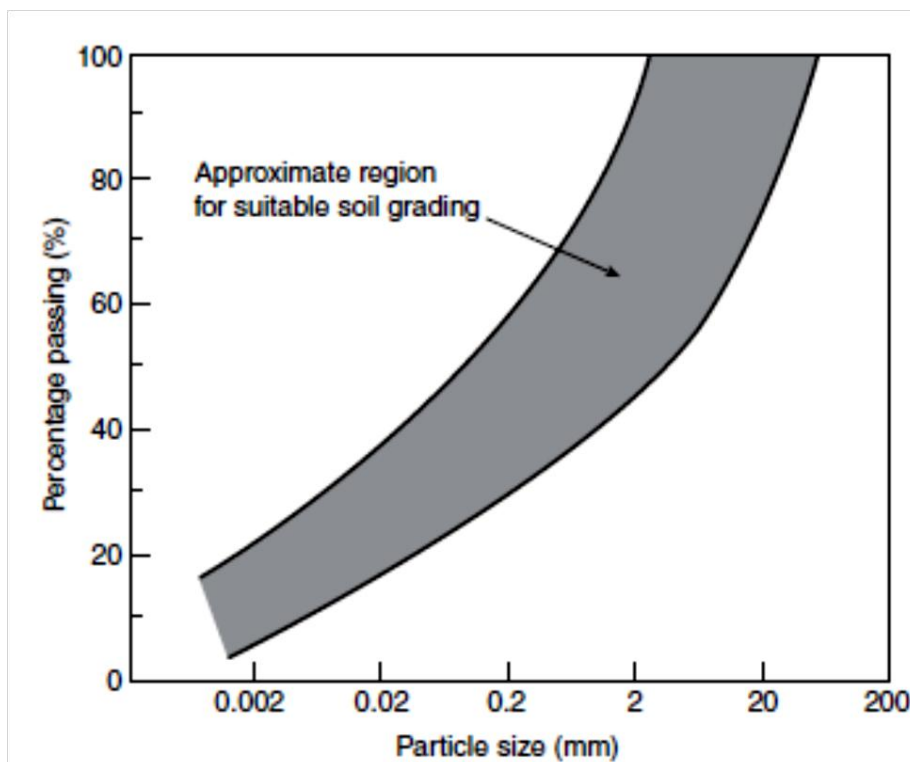


Figure 2.22: Grading limits for Rammed Earth Soils (Walker *et al.* 2005)

2.5.4. Soil Testing

As soil is variable, it is important to assess its suitability for earth construction and to optimize its characteristics to best effect. The suitability of a soil can be established through a variety of tests. Tests vary between relatively simple field tests to rigorous laboratory analysis and are undertaken to assess soil grading, organic matter content, plasticity and Optimum Moisture Content. Grading gives an indication of fines present and plasticity indicates the cohesive nature of the fines. More detailed tests such as the use of an X-ray diffraction machine may be used to determine type and level of soluble salts and mineralogical composition. Characteristics

of a soil will define the need for stabilisation other than compaction. Methods of testing are outlined in Appendix A (Standards Australia, 2002). A summary of testing for the selection of a suitable Rammed Earth material is shown in Table 2.9.

Table 2.9: Summary of Testing for the Selection of a Rammed Earth Material (Walker et al. 2005)

Soil Selection (Testing)	Compliance Testing
<ul style="list-style-type: none"> • Grading Analysis • Clay Content • Atterberg Limits • X-Ray Diffraction • Organic Content 	<ul style="list-style-type: none"> • Wet & Dry Compressive Strength • Drying Shrinkage • Rate of Drying • Water Absorption by Immersion

2.6. Case Studies

2.6.1. Woodley Park Centre for Sports & Arts

Location: Skelmersdale, Lancashire

Built: 1999

Use: Sports hall

The Woodley Park Centre (see Figure 2.5) was built for Sports & Arts by community volunteers following the advice of In-situ Rammed Earth. The exterior non-loadbearing walls were built from cement stabilised and natural Rammed Earth. Material selection was selected by the earth builder using experience and some trial compaction tests. The materials were sourced from a quarry sites up to 40 miles from the project and blended with sand or clay to ensure an ideal mix. The materials were screened down to 20 mm (Maniatidis & Walker, 2003). Reasons for using cement as a stabiliser was primarily due to improved durability, strength combined with reduced risk. The percentage of Portland cement used was between 5%-10%. The fire resistance properties were not considered to be a concern for this project (Maniatidis & Walker, 2003).

Everybody interviewed in the building process acknowledged that the construction process is very much dependent on weather conditions. Dry storage of materials and protection of formwork and fresh walls from rainfall was essential. Storage and movement of large quantities of materials on site needed to be carefully considered in site organisation. These

issues resulted in earth works generally being on the critical path of the project work schedule (Maniatidis & Walker, 2003).

Setting, aligning and stripping down the formwork was the most time consuming task of the building process accounting for up to 80% of the time on site, though it was considered to be around 50-60%. Selection of a suitable formwork system that is light to handle, has sufficient strength and stiffness and easy to erect and align was critical to the rate of working and success of the project. Taking into considerations that the Centre was community built, quoted productivity rates were less than 1 m³ / day for a gang of 3-5 people. Similarly, costs of wall construction were approximately £80 /m² for a 300 mm thick wall. It was noted that Maniatidis & Walker (2003) mentioned that quoted productivity rates and costs for projects built by experienced earth builders were approximately 3 m³ / day and £250 /m² respectively.

2.6.2. Chapel of Reconciliation

Location: Germany, Berlin

Built: 2000

Use: Church

The Chapel of Reconciliation (Figure 2.23) is Germany's first Rammed Earth church. The building was constructed on the already existing site of the former church built in 1894 which was destroyed because it was located in between the dividing walls of East and West Germany. The Rammed Earth wall was built using a mixture of clay and ground remains of the former church. The load bearing interior oval shape wall was 7.2 m high and 600 mm thick. The building technique was initially not authorized and thus the Load Bearing Structures and Building Division of the Technical University of Berlin was commissioned to the project. Their responsibility was to provide a detailed analysis of the Rammed Earth during both manufacturing and installation phases of the project.

Various trial mixtures were tested for their compressive, tensile and shearing strength. The moisture content at time of placing was 8.2% (by mass). Material characteristics included a compressive a compressive strength of 3.2 MPa and drying shrinkage of 0.15%. The 160 m³ of Rammed Earth required for building was mixed homogeneously in a concrete mixer in 2 days.

After installation, the strength development of the Rammed Earth was controlled non-destructively by means of a Building Material Test Hammer (BMTM).

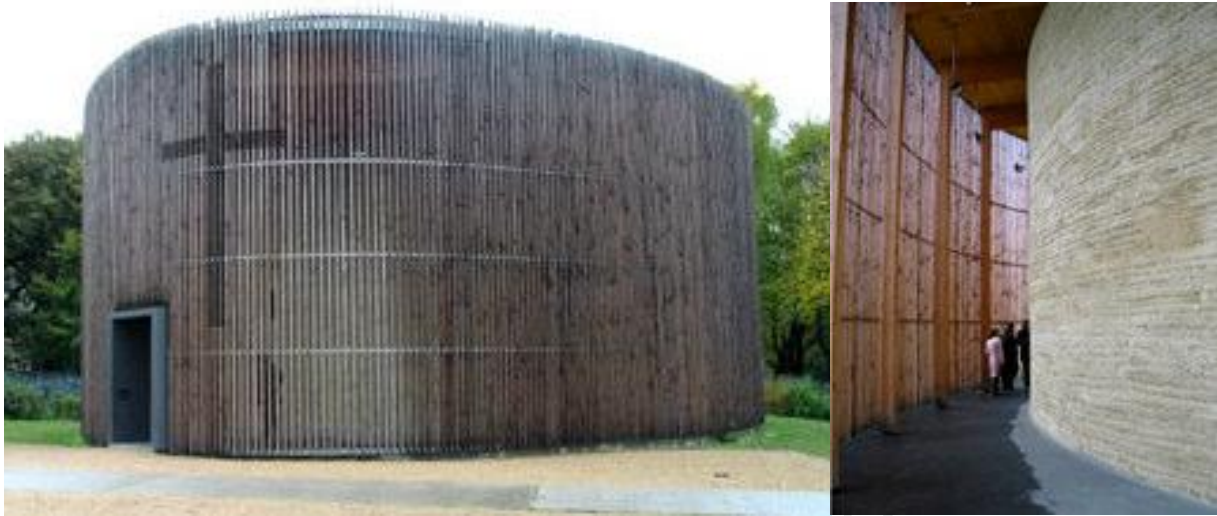


Figure 2.23: Chapel of Reconciliation (Design4deconstruction, 2012)

2.6.3. AtEIC Building/Centre for Alternative Technology

Location: Machynlleth, Powys

Built: 2000

Use: Visitors Centre

The AtEIC building (Figure 2.24) was community-built as a visitor's Centre for Alternative Technology. The internal walls and columns were built from natural Rammed Earth. A comprehensive set of testing was carried out for the AtEIC Building at the University of Plymouth by David Clark which included: grading curves; compressive strength and plastic and liquid limit tests. The benefit of these tests was reflected in the high quality of the walls. However the cost of material testing was seen as a deterrent to some designers and clients. The materials were sourced from quarry sites up to 40 miles from the project and blended with sand or clay to ensure an ideal mix. The materials were screened down to 20 mm (Maniatidis & Walker, 2003).

For structural design, material compressive strength was first established by experimentation and used in structural checks. The size of the wall panels depended on the size of the wall and varied in length from 1800 mm to 3000 mm. Minimising the number of ties in the formwork was an important factor of the compaction process (Maniatidis & Walker, 2003).

The most common problem influencing quality of construction on site was keeping the earth dry prior to, during and following construction. The fresh materials were often protected under temporary covers. For the construction of the AtEIC building, wall construction proceeded after completion of the roof which provided protection for the walls from rainfall. The drop test, used for checking the Optimum Moisture Content at compaction was widely used. It was noted that more experienced builders could judge Optimum Moisture Content by observation and feel alone. Quoted productivity rates were similar to that of the Woodley Park Centre (Maniatidis & Walker, 2003).



Figure 2.24: AtEIC Building/Centre for Alternative Technology (Maniatidis & Walker, 2003)

2.6.4. Conclusion

From the case studies discussed, it was apparent that the benefit of testing (grading curves, compressive strength, and plastic & liquid limit tests) during the material selection process

resulted in a higher quality of Rammed Earth walls. However, the cost of testing was seen as a deterrent to some designers and clients.

All interior walls were built with natural Rammed Earth. Exterior walls of the Woodley Park Centre were built from cement stabilised and natural Rammed Earth. Reasons for using cement as a stabiliser were primarily due to improved durability and strength combined with reduced risk. The construction process for all case studies was very much dependent on weather conditions as dry storage of materials and protection of formwork and fresh walls from rainfall was essential. Furthermore, formwork placement was the most time consuming task of the building process.

In terms of economic costs, labour costs associated with the handling of materials and formwork was observed to be the main costs of earth Rammed Earth construction. This example is demonstrated well with the Woodley Park's (community built) wall construction costing approximately £80 /m² for a 300 mm thick wall while quoted costs for projects built by experienced earth builders were approximately £250 /m².

3. Methodology

3.1. Introduction

This chapter outlines the methodology used to achieve the aims of the thesis. The overall objective of the thesis was to collect and categorise information that will allow for the drawing up of a guideline to building stabilised Rammed Earth housing in the Cape Town Metropolitan area.

The soil properties of Cape Town soil types were researched and 16 soil samples from strategically selected sites were collected. Soil samples were evaluated and classified by performing various tests according to SANS Standards. These tests, in conjunction with Rammed Earth literature, assisted in the selection of a suitable material for Rammed Earth construction. Blends varying in plasticity were manufactured by mixing various fractions of 'non-cohesive' Cape Flats Aeolian sand (CF) with Decomposed Granite soil (DG). Similar tests were undertaken on the different plasticity blends to determine the blend characteristics. The Optimum Moisture Content (OMC) was also evaluated for all blends to determine the moisture content at which the compacted soil achieves the greatest dry density.

Rammed Earth cylindrical specimens were then made and tested in the laboratory for wet & dry compressive strength, drying shrinkage (linear) and water absorption by immersion. During the manufacturing process, cylinders were stabilised with various fractions of cement and lime to determine an optimal stabilising fraction.

3.2. Material Selection

In order to achieve the aims of the thesis, it was important to investigate for a 'suitable' soil. From the literature review, the suitability of a soil for Rammed Earth construction was assessed on the basis of soil classification tests (grading, plasticity) and physical characteristics of prototype Rammed Earth specimens.

3.2.1. Site Investigations

Sixteen soils were investigated from strategically selected sites in the Cape Town Metropolitan area. The sites were selected by inspection of a map with a minimum of 4 sites being selected on the Cape Flats. Sites were selected by identifying construction of swimming pools to reach the required depth of sub-soils located at a depth of at least 500 mm below the surface. Most

construction sites are covered with a layer of organic soil containing plant matter, which according to literature, reacts with cement and has a detrimental effect on the overall strength of a Rammed Earth wall. The swimming pool excavations were used to collect soil samples and a particular effort was made by supervision ensuring that soils were collected from below the topsoil layer.

Table 3.1: Locations of the Evaluated Soils

Soil number	Soil Location	GPS Coordinates
1.	Kommetjie	34°08'25.96"S 18°20'33.56"E
2.	Tokai	34°03'58.36"S 18°25'36.87"E
3.	Bishops court	33°59'26.93"S 18°27'01.10"E
4.	Newlands	33°59'01.28"S 18°26'42.58"E
5.	Vredehoek	33°56'09.79"S 18°25'35.01"E
6.	Constantia, Alphen road	34°00'36.31"S 18°26'59.89"E
7.	Kenilworth	33°59'27.27"S 18°27'56.59"E
8.	Constantia, Le Seuer avenue	34°00'32.72"S 18°26'13.20"E
9.	Hout Bay	34°00'44.55"S 18°22'46.34"E
10.	Pinelands	33°56'04.83"S 18°30'52.37"E
11.	Sea Point	33°54'36.51"S 18°23'28.86"E
12.	Monte Vista	33°53'00.40"S 18°33'17.91"E
13.	Bellville	33°53'43.62"S 18°38'14.50"E
14.	Blouberg	33°50'08.29"S 18°30'54.39"E
15.	Athlone	33°57'58.63"S 18°30'17.99"E
16.	Rondebosch	33°57'25.23"S 18°29'15.84"E

The literature on the geology of Cape Town indicated that there is a contact between shale and granite represented by the solid white line in Figure 3.1. An equal amount of sub-soils from each side of the contact between Malmesbury Shale and Granite were collected to give a good representation of the various sub-soils of Cape Town. The locations of the evaluated soils are displayed in Figure 3.1 and are also documented in more detail in Table 3.1. The white line represents contact between shale and granite.

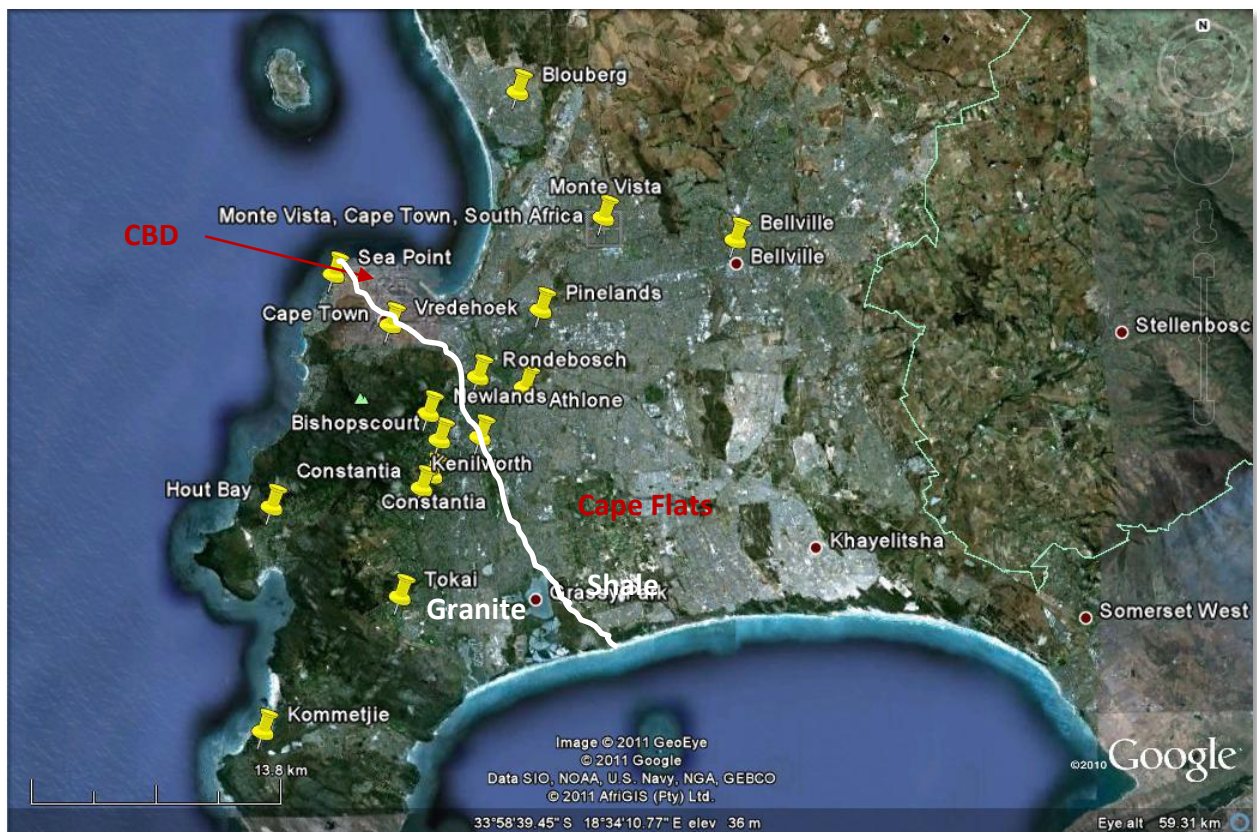


Figure 3.1: Geographical location of Collected Soils (Google Maps, 2011)

3.2.2. Grading Analysis

Soil is classified by the size distribution of its individual particles. In the context of Rammed Earth, each soil group has an important structural attribute (see 2.3.4). The grading analyses were also useful for comparing different soils and confirming plasticity results.

A grading analysis was performed for each soil sample to determine the particle size distribution of the aggregates. This was done by sieving the soil as per SANS 201:2008. Different sieves were used as standardized by the SANS standard. The soil passed through them and collected different sized particles which resulted in a grading curve for each evaluated soil (Figure 3.2).



Figure 3.2: Grading Apparatus

3.2.3. Clay Content

A higher clay content in a soil increases moisture movements and drying shrinkage while lower clay content will decrease its 'cohesive' properties for Rammed Earth construction. It was thus essential to determine the clay content of the soil to give a full understanding of the test results and aid in the soil classification & grading analysis. The SANS standards indicated the 'pipette method' as the method for determining clay content but Kalumba (2011) stated that the 'hydrometer method' was the preferred, internationally recognised method and he recommended using British Standards for this test. Thus, the hydrometer test method was adopted and was followed in accordance with BS 1377 – 2:1990.

3.2.4. Atterberg Limits

In the context of Rammed Earth, Standards Australia (2002) has established a guideline from empirical data based on plasticity limits for the recommendation of stabiliser in the construction of walls. Therefore, plasticity results are important for the classification of soils and for the preparation of Rammed Earth testing cylinders. The sixteen different soils collected were tested for Atterberg Limits according to SANS 3001 – GR10:2008 which is also described in A.2.9. The liquid limit, the plastic limit and the plasticity index are related to both mineralogy and the amount of clay present in the soil sample.



Figure 3.3: Atterberg Limits Apparatus



Figure 3.4: XRD Equipment

3.2.5. X-Ray Diffraction

X-Ray Diffraction analysis is a powerful method by which X-Rays of a known wavelength are passed through a sample to be identified in order to identify a soil's crystal structure and mineralogical composition. In the context of this thesis, it was essential to identify the clay minerals of each soil sample. A sample of soil with a high proportion of Kaolinite particles might have a similar plasticity index to a different soil with a smaller proportion of illite or smectite. The sixteen soil samples were analysed for mineralogical composition and determination of clay type in the Geology department at the University of Cape Town (Figure 3.4).

3.2.6. Presence of Organic Content

Organic soil contains plant matter which reacts with cement and has a detrimental effect on the overall strength of a Rammed Earth wall. Most construction sites are covered with a layer of organic soil known as topsoil. However, Powrie (2007) states that organic soils may also be naturally buried below the surface which makes it difficult to detect. Therefore, it was important to test each soil sample for the presence of organic content. The test which was followed in accordance with SANS 5832:2006 was merely an indicator of organic content and did not give a quantifiable measure.

The test involved preparing a reference solution of tannic acid, ethanol and sodium hydroxide as shown in Figure 3.5. A second beaker of sample soil was then filled with sodium hydroxide solution. The beakers were shaken vigorously and allowed to stand for 24 hours. The depth of colour of the liquid layer was then compared with that of the reference solution. A colour of the liquid layer darker than that of the reference solution indicated a presence of organic matter.



Figure 3.5: Organic content test

3.2.7. Soil Classification

The purpose of soil classification is to give a soil a letter symbol representing main and qualifying terms using the available data from the material selection testing and is important towards fully understanding the behaviour of materials in Rammed Earth construction. Soil classification was followed in accordance with BS5930. The terms and letters used are represented in Table 2.5.

3.2.8. Material Selection

All sixteen sub-soils were evaluated and classified by performing the various aggregate tests mentioned in this section to ultimately determine a 'suitable' material for the manufacture of Rammed Earth cylinders. The results of these tests, which led to the selection of Decomposed Granite (DG) and Cape Flats Sand (CF) as Rammed Earth materials, are laid out and discussed in 4.2. Decomposed Granite was selected as it was the only soil containing clay that was easily identifiable due to its distinct 'red' colour (Figure 3.6) and is readily available throughout the Cape Town area. Readily available Cape Flats Sand was selected as a 'non-cohesive' sand to mix with Decomposed Granite to make blends varying in plasticity.

Figure 3.6: Decomposed Granite (Bishopscourt)



3.3. Rammed Earth Testing

It was decided to manufacture unstabilised, lime stabilised and cement stabilised Rammed Earth test specimens, blended using different proportions of Decomposed Granite (DG) and Cape Flats Aeolian sand (CF). The selection of these 2 soils is discussed in more detail in the next chapter (see 4.2). Before manufacture, the Optimum Moisture Content (OMC) for each soil mixture was established because of the variation in plasticity. Compliance tests were undertaken and compared with minimum performance specifications in Table 2.7. The process is explained in more detail later in this chapter and also illustrated below (Figure 3.7).

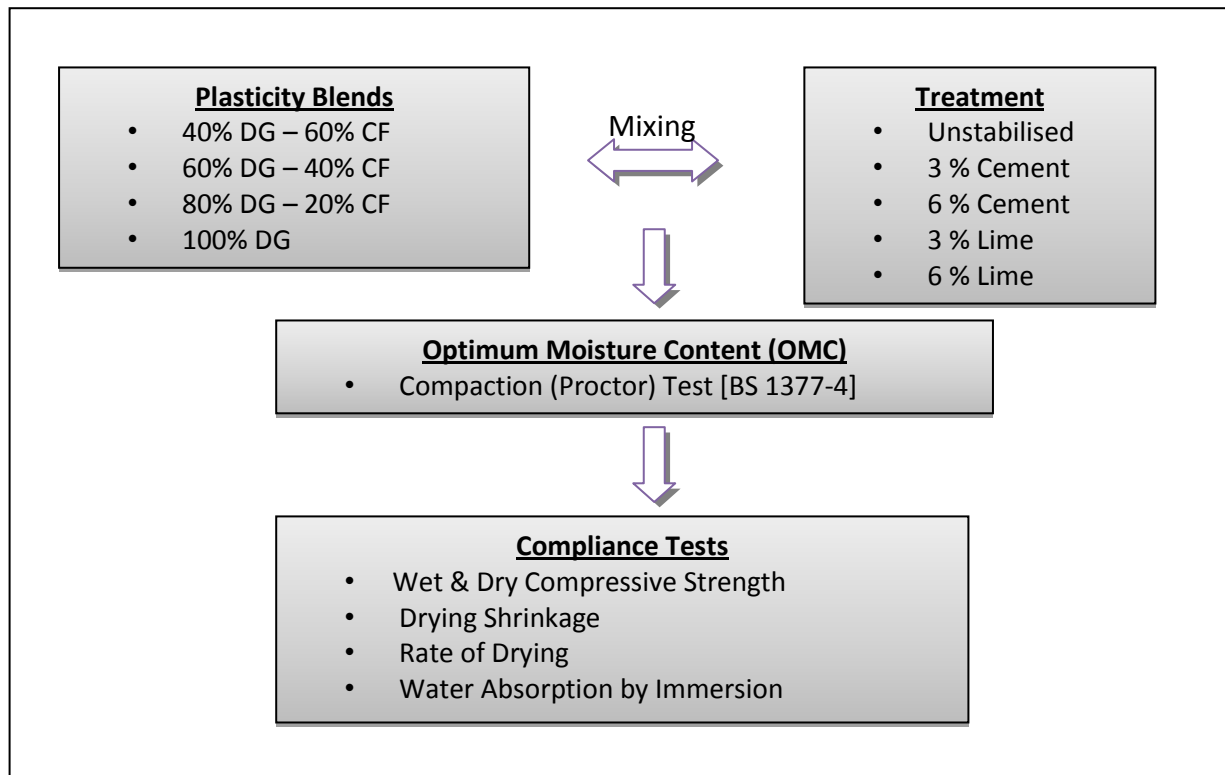


Figure 3.7: Rammed Earth Testing Methodology

3.3.1. Test Sample Preparation

A) Plasticity Blends

Specimens varying in plasticity using different proportions of Cape Flats sand (CF) and Decomposed Granite (DG) were constructed for the compliance tests. Trial Atterberg limits tests of various blends indicated that a minimum of 40% Decomposed Granite was required for the mixture to pass the tests and thus contain sufficient clay to be compacted and moulded into a wall. It was decided to construct 40% - 60%; 60% - 40%; 80% - 20% and 100% - 0% Decomposed Granite – Cape flats sand blends. Microscopic images of the blends were acquired and are displayed in 4.3.1.

B) Stabiliser Selection (Treatment)

It was decided to make unstabilised, cement stabilised and lime stabilised Rammed Earth specimens. SUREBUILD cement, manufactured by Pretoria Portland Cement (PPC), was used as it is the most commonly used cement in the Cape Town housing industry. According to PPC Cement (2011), SUREBUILD cement is a premium general purpose cement that is ideal for general building operations, structural concrete and the manufacture of cement-based products. SUREBUILD conforms to the 32,5R strength class of SANS 50197-1 for blended cements with limestone and slag additives, and is classified as a CEM II B-M (minimum clinker content

of 79%). Hydraulic building lime was used for lime stabilised specimens. From the literature review (2.2.4), cement is typically added in proportions between 2.5% and 15% (by mass) while lime dosages are between 3% and 12% (by mass). In the context of ‘sustainable development’ (2.1.3), it is important to limit environmental impacts by minimising the use of binder and thus it was decided to manufacture the stabilised specimens with 3% and 6% stabiliser.

C) Determination of the Optimum Moisture Content (OMC)

The Optimum Moisture Content test evaluated the moisture content at which the compacted soil achieves the greatest dry density. This is of importance, since dry density is proportional to compressive strength. Each Decomposed Granite – Cape Flats sand blend of varying plasticity will have a different Optimum Moisture Content (OMC) and thus it was essential to determine these values before the manufacture of test specimens. This test was performed for each soil blend, in accordance with BS1377-4 and is also explained in more detail in A.2.3.

D) Manufacture of the Rammed Earth Test Specimens (cylinders)

The cylinders were made for the four different blends of soil and were unstabilised, cement and lime stabilised. The 440 cylinders made were 57 mm diameter × 114 mm high following the recommendations of Walker *et al.* (2005) with a height to diameter ratio of 2. The smaller cylinder size was selected due to the quantity of cylinders to be manufactured. Apparatus required included the following (Figure 3.8):

- A well-ventilated drying oven capable of maintaining uniform temperature of 100 C.
- A Hobart mixer of 5 L capacity (Figure 3.9)
- Mould with an internal diameter of 57 mm and at least 250 mm in height
- A 2.5 kg cylindrical tamping rod
- Plastic Bags
- A metal base plate
- Lubricating oil
- A straight edge

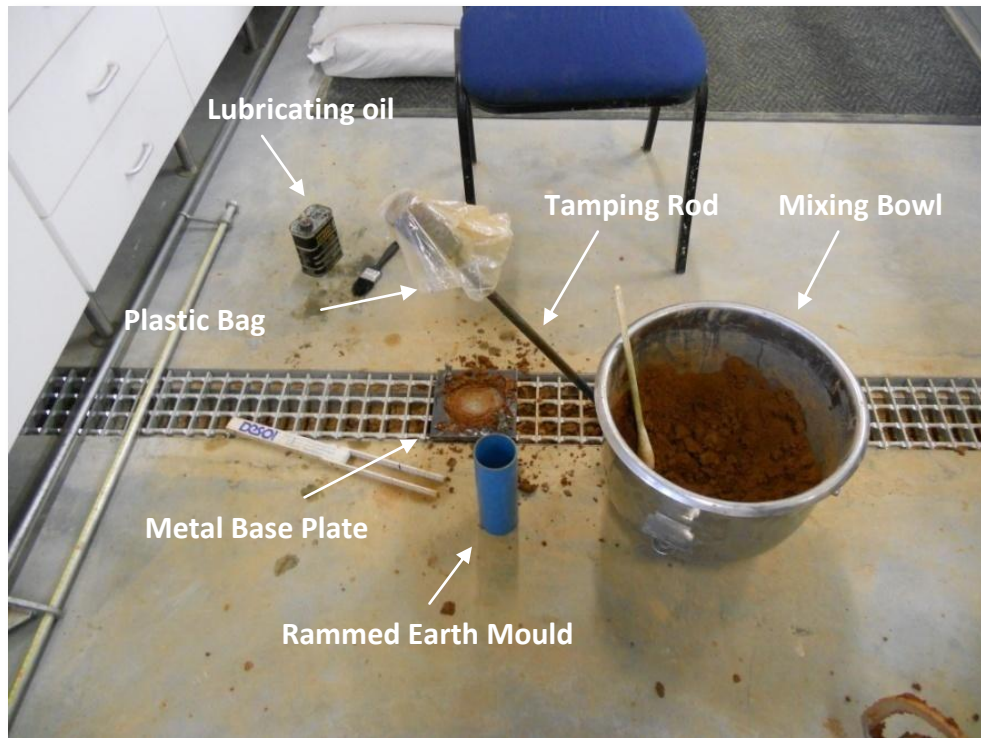


Figure 3.8: Specimen Construction Apparatus

Mixing Process

The Decomposed Granite and Cape Flats sand were firstly dried separately at 100 °C overnight and then left to cool for at least 12 hours. This is of importance as a soil which had not cooled or was moist would yield inaccurate OMC results. The appropriate soil blend was then mixed using a Hobart mixer (Figure 3.9); this was undertaken before adding any additives. In order to mix the lime and cement with the soil the following procedure was followed; the mass of soil required was calculated from the number of moulds and was placed in the Hobart mixer. The mass of soil required was estimated according to the average compacted density of material of 2000 kg/m³. The required percentage (by mass) of cement or lime was then added when the mixer was running.

All dried materials were thoroughly mixed together for 5 minutes before the addition of water. The pre-determined volume of water to reach Optimum Moisture Content (OMC) from results of the Proctor test (4.3.2) for the specific blend was then added gradually. Wet mixing occurred for at least 2 to 3 minutes and the drop test (see A.1.5) was then used to check that the OMC had been reached and ensure repeatability of results. The drop test consists of squeezing a handful of moist soil into a ball which is then dropped from shoulder height onto firm ground.

The manner in which the soil breaks on impact indicated whether the soil mix was at its Optimum Moisture Content.



Figure 3.9: Hobart Mixer

Compaction

Using the 2.5 kg cylindrical tamping rod, mixed material was compacted in 3 equal layers inside the mould until the specimen height reached 114 mm. The extra height on the mould helped with guiding the tamping rod which completely filled the mould. Lubricating oil was applied to the inner surface of the mould to promote an easier extrusion. A plastic sleeve was wrapped around the tamping rod to prevent the clay material sticking to the rammer during compaction. The specimens were then extruded using the tamping rod as shown in Figure 3.10. The specimens underwent 12 blows per layer at a constant height to maintain a consistent standard of work & repeatability of results. A specimen of excessive height was adjusted using a straight edge in the wet state or using a cutting machine (Figure 3.14) in the hardened state. This was to ensure flatness and perpendicularity of the ends and repeatability of results.



Figure 3.10: Extrusion of specimens

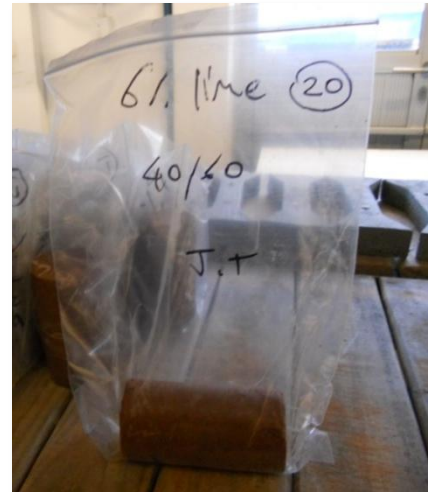


Figure 3.11: Curing of stabilised Specimens in sealed plastic bags

Curing

Curing for test specimens was followed according to recommendations of Walker *et al.* (2005). Unstabilised specimens were left to dry in air immediately after compaction while cement stabilised specimens were cured for 28 days and then left to dry in air for a further 28 days. Lime stabilised specimens were cured for 5 days and then left to dry. Sealed plastic bags to retain moisture were used as the curing method (Figure 3.11). All specimens left to dry were placed in a laboratory environment of 23°C and 50% Relative Humidity (RH). Cylinders were weighed and measured immediately after demoulding to establish material bulk densities.

3.3.2. Compliance Testing

The extent of testing of Rammed Earth materials depends on the specific application and the novelty of the material in use. A proven material improves confidence in its qualities and reduces the level of uncertainty and associated risks. Unconfined Compressive Strength (UCS), drying shrinkage, rate of drying and water absorption testing were undertaken and compared with minimum performance specifications in Table 2.7. Specimens for these tests were manufactured as mentioned earlier in section 3.3.1 in this chapter.

A) Wet and dry Compressive strength

Compressive strength was evaluated using a Zwick machine (Capacity of 100 kN) (Figure 3.12). The Zwick allowed a more accurate measure of compressive strength to be made than the other compressive strength machines in the laboratory, which was appropriate to the

relatively low strength of Rammed Earth. Compressive strength tests for Rammed Earth were performed according to recommendations of Standards Australia (2002) explained in A.2.8.

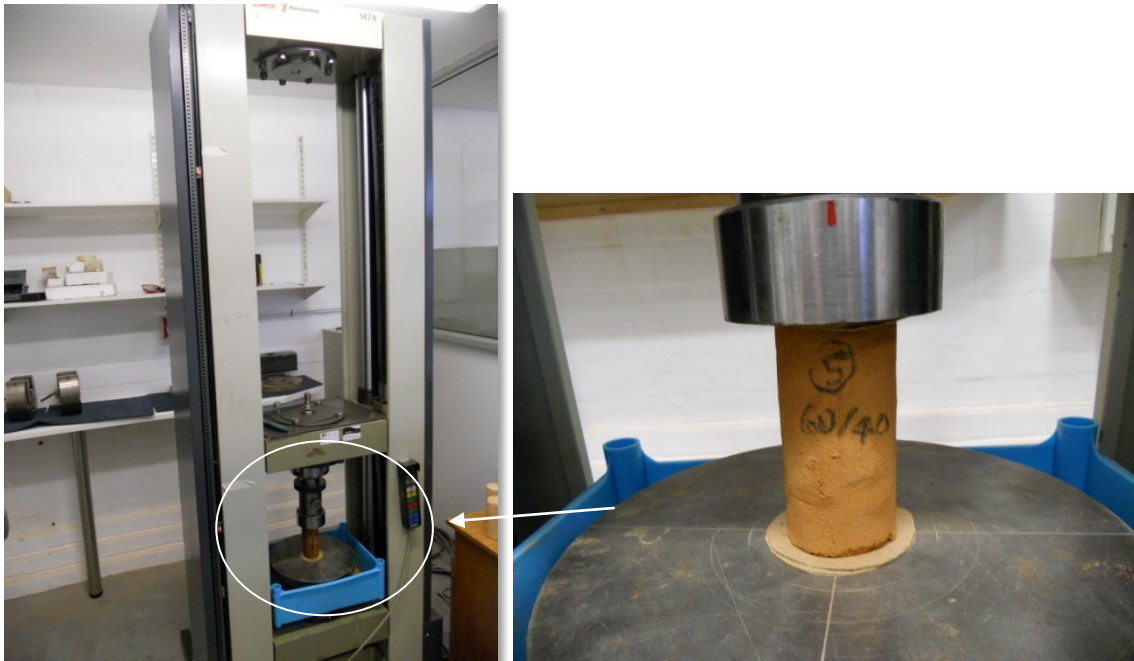


Figure 3.12: 100 kN Zwick Machine – Mechanical cross-head drive

The compressive strength of the cylinders was evaluated at 7, 14, 28 and 56 days after manufacture. It was decided to test at 56 days to observe the effect the slow release of moisture (drying) on compressive strength for the cement stabilised specimens cured for 28 days. This was also deemed necessary for lime stabilised specimens since from the literature, they achieve their final strength at an age typically 2-3 times longer than the 28 day curing period required for cement.

Specimens were tested for compressive strength in two moisture states: oven-dried (dry) and saturated surface dry (wet). Specimens were removed from their curing or drying regimes and either oven-dried (dry) or immersed in water (wet) before testing. Oven-dried (dry) specimens were dried according to recommendations from Standards Australia (2002) for 24 hours in a well-ventilated drying oven at 100°C to constant mass and allowed to cool to room temperature in a desiccator (Figure 3.13) before testing. Saturated surface dry (wet) specimens were immersed in water for 24 hours before testing following recommendations of Standards Australia (2002) in A.2.8.

According to Ciancio & Jaquin (2001), it was logical to assume that most of the pores in all oven-dried specimens were dry. The measured strength might have comprised of only particles interlocking and the clay cohesion. Ciancio & Jaquin (2001) suggested that it was thus reasonable to assume that specimens tested with moisture content different from zero and less than OMC showed higher compressive strength values than those obtained by oven dry specimens. Therefore, the measured oven dry strengths were believed to underestimate the real strength of all specimens. Wet compressive strength is of importance as wet conditions have a detrimental effect on the durability of a Rammed Earth wall, especially during construction where protection from water is minimal. It was also essential to observe the effect of the various stabilisers on the wet compressive strength.



Figure 3.13: Desiccator

Three nominally identical specimens of 114 mm \times 57 mm diameter were used for each test. The cylinders were capped using two cardboard circular cut-outs not exceeding 5 mm in thickness at either end as shown in Figure 3.12 before testing to provide two opposing parallel and flat surfaces to ensure repeatability of results. The specimens were also weighed and dimensioned; before oven-drying and water immersion and before testing to establish material

bulk densities. The opposing ends of some specimens which were not parallel and flat were prepared with a precision cutting machine (Figure 3.14) without affecting the dimensions.



Figure 3.14: Cutting Machine

B) Drying Shrinkage (Linear)

As mentioned in the literature review, clay shrinks and swells with the loss and addition of moisture. The deterioration of Rammed Earth walls occurs from contraction and expansion due to cyclic weather conditions. This problem can be limited with the construction of raised footings or eave overhangs. However, it was of importance to determine the value of drying shrinkage for a specific material and for the construction of movement joints (2.4.7). The material may also be deemed to be unsuitable if the drying shrinkage is excessive compared to minimum performance specifications (Table 2.7). Linear shrinkage is expressed as the ratio of change in length to original datum length and tests were performed according to recommendations of Walker *et al.* (2005) explained in A.2.5.

Three nominally identical specimens of 114 mm × 57 mm diameter were used for each test. Shrinkage measurements were recorded at 1, 3, 7, 14 and 28 days after specimens were left to dry i.e. following curing. Length measurements were initially recorded immediately after demoulding for unstabilised specimens and after curing (once plastic sleeves were removed) for stabilised specimens, using both the strain device (Figure 3.15) and the shrinkage apparatus (Figure 3.16). Both pieces of equipment were used as several linear shrinkage measurements exceeded the ± 0.5 mm range of the strain device. The strain device was favoured as it yielded more accurate results, measuring to the nearest 1 μm .



Figure 3.15: Drying Shrinkage strain device

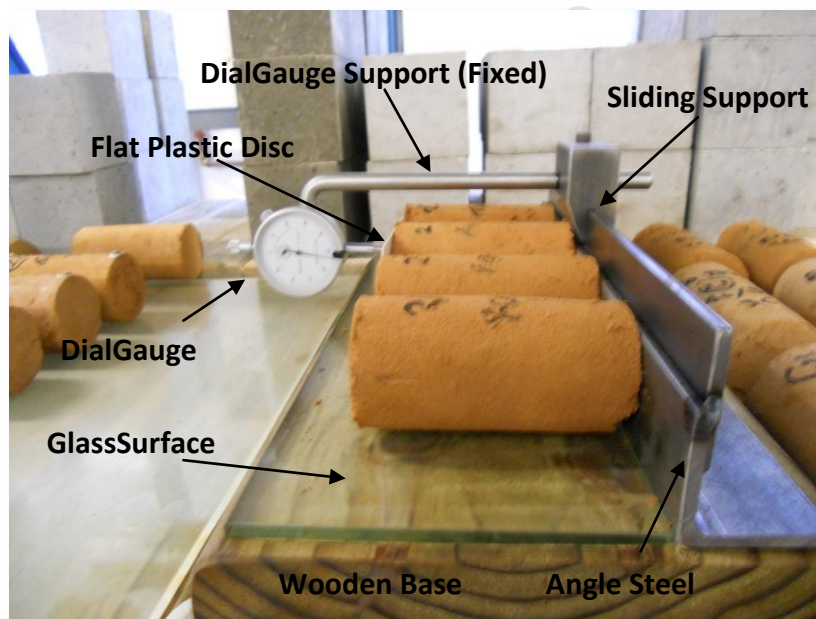


Figure 3.16: Drying Shrinkage Apparatus

Strain targets were glued longitudinally as shown in Figure 3.15 on two opposing sides of the specimens. However, some measurements exceeded the range of the strain device and then the shrinkage apparatus was used. The shrinkage apparatus had a range of 10 mm and measured to the nearest 10 μm . While using the shrinkage apparatus, a flat plastic disc shown in Figure 3.16 was used to ensure a flat surface when measuring. It was important to keep measurements consistent and thus specimens were modified before testing with a cutting machine to ensure

smooth parallel surfaces on both ends and also marked with a permanent marker to locate points of measurement.

C) Rate of Drying

The rate at which samples dried was measured so that the amount of time for a Rammed Earth wall to lose its moisture could be calculated. To explore this relationship between moisture content and time, the masses of two cylinders from each soil type were measured every time a shrinkage reading was recorded once the curing phase was completed. This established a rate of drying for each soil type.

D) Moisture Absorption by Immersion

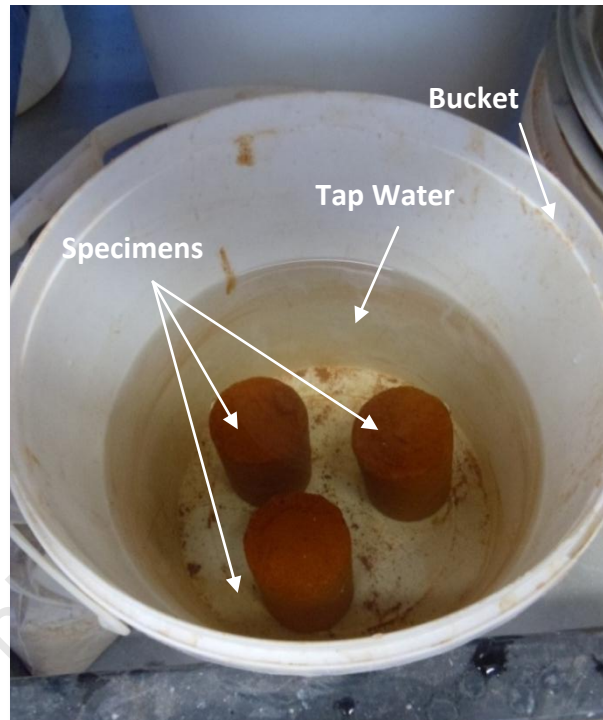


Figure 3.17: Moisture Absorption by Immersion

Durability tests were conducted by studying the effect of water absorption by immersion (Figure 3.17) on specimens with different stabilisers. This was a useful test in determining whether lime or cement was the most effective binder at reducing water ingress. Moisture absorption tests for Rammed Earth were performed according to recommendations of Standards Australia (2002) explained in A.2.6. The test involved testing cylindrical specimens where the increase in mass of oven-dried specimens due to immersion in water for 24 hours was determined and expressed as a percentage of the specimen's initial dry mass.

Three nominally identical specimens of 114 mm × 57 mm diameter were used for each test. The specimens were tested at 56 days after manufacture. Curing of all specimens was followed as mentioned in 3.3.1. Cylinders were weighed and dimensionally measured before testing to establish material bulk densities.

3.4. Conclusion

To conclude, Figure 3.18 shows an overview of all testing procedures. 16 Sites in the Cape Town Metropolitan area were selected and 16 sub-soils were acquired. These soils were each a series of tests demonstrated in Figure 3.18. The results from these tests, in conjunction with Rammed Earth literature, enabled the selection of a 'suitable' material for wall construction. Decomposed Granite was selected as the 'suitable' material and 'non-cohesive' Cape Flats sand was selected to manufacture specimens varying in plasticity.

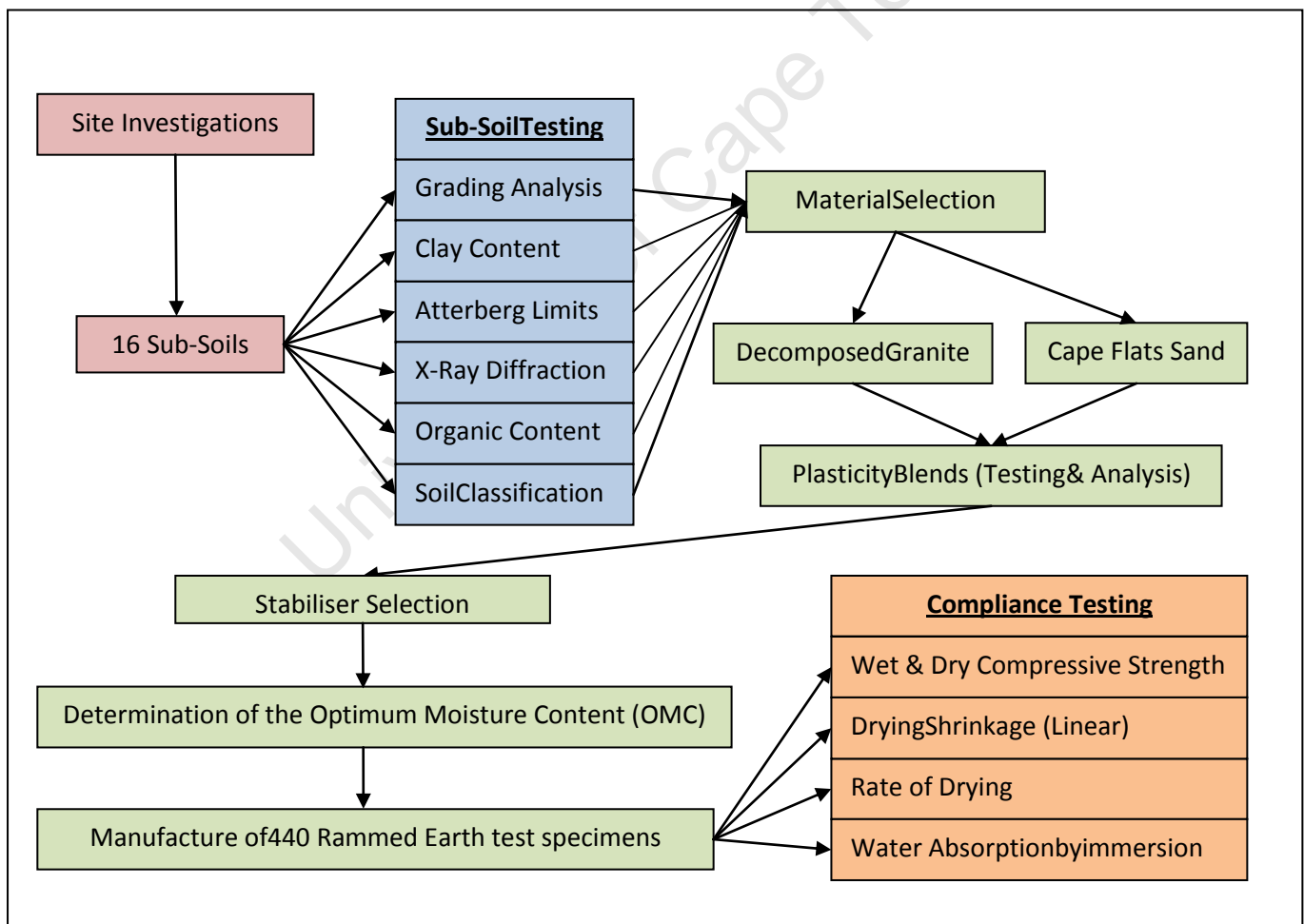


Figure 3.18: Overview of Testing Procedures

Tests were also undertaken on the different plasticity blends to determine the various blend characteristics. Stabilisers were then investigated and it was decided to make unstabilised, cement stabilised and lime stabilised Rammed Earth specimens. It was important to limit environmental impacts and thus it was decided to make the stabilised specimens with 3% and 6% stabiliser. The Optimum Moisture Content (OMC) had to be determined for each plasticity blend as each blend had a different OMC due to varying clay contents. A total of 440 Rammed Earth specimens were then manufactured and subjected to the compliance tests.

University of Cape Town

4. Results

4.1. Introduction

The results are presented in this chapter and discussed in chronological order of testing as described in chapter 3. The 16 sub-soils collected underwent various soil tests to select a 'suitable' material for Rammed Earth wall construction. The results of these soil tests are discussed and the selection process of the suitable material, Decomposed Granite (DG), is explained. The selection process of the non-cohesive soil, Cape Flats sand (CF), for the manufacture of the plasticity blends is also explained. The plasticity blends were then subjected to the same set of soil tests to determine the various blend characteristics. Abbreviations (Table 4.1) were used to discuss the various plasticity blends throughout this chapter. The Proctor test results evaluated the moisture content required for each blend at which the compacted soil achieved the greatest dry density. A total of 440 specimens were manufactured and compliance tests were undertaken on unstabilised, cement stabilised and lime stabilised cylinders. Unconfined Compressive Strength (UCS), water absorption and drying shrinkage assessments were undertaken. These results are all discussed and explained in this chapter, highlighting the relevant findings.

Table 4.1: Abbreviations used to identify the various Plasticity Blends made

Abbreviation	Description
40DG-60CF	Blend of 40% Decomposed Granite and 60% Cape Flats Sand
60DG-40CF	Blend of 60% Decomposed Granite and 40% Cape Flats Sand
80DG-20CF	Blend of 80% Decomposed Granite and 20% Cape Flats Sand
100DG	100% Decomposed Granite

This chapter used the Unified Soil Classification system in accordance with BS5930 to classify the 16 sub-soils collected into groups on the basis of grading and plasticity, so as to give each soil group a letter symbol representing main and qualifying terms. The system was described in (2.3.6) but all letter symbols and abbreviations are also explained further in this chapter.

4.2. Soil Properties

Sixteen soils were investigated from strategically selected sites in the Cape Town Metropolitan area. The aim was to select a suitable material that was readily available throughout Cape Town for Rammed Earth construction. A list of the 16 soils collected is presented in Table 4.2.

Soil number 17 from Sierra Leone was subsequently added to the list and the reasons are explained later in this chapter. All soils were photographed and identified in Figure 4.1.

Table 4.2: Soil Identification Table

Soil number	Soil Location
1.	Kommetjie
2.	Tokai
3.	Bishopscourt
4.	Newlands
5.	Vredehoek
6.	Constantia, Alphen road
7.	Kenilworth
8.	Constantia, Le Seuer avenue
9.	Hout Bay
10.	Pinelands
11.	Sea Point
12.	Monte Vista
13.	Bellville
14.	Blouberg
15.	Athlone
16.	Rondebosch
*17.	*Sierra Leone

* The Sierra Leone soil added subsequently



Figure 4.1: Colour Photograph of all Soils Collected

Following testing procedures given in Chapter 3 for all soil samples it was determined that the Atterberg limit test was the most useful test for deciding on Rammed Earth suitability since only soil number 3, 6 and *17 yielded results (Table 4.3) that showed some plasticity. All other soil samples contained insufficient clay content to produce liquid & plastic limit results and were termed 'Non-Plastic'(NP) as per SANS 3001 – GR10:2008.

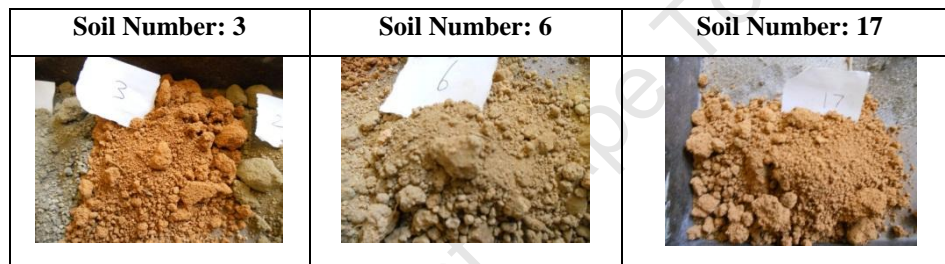
It was determined from the geology of Cape Town (2.3.1) that soils 3 and 6 were Decomposed Granites (DG). The Unified Soil Classification (USC) shows that all Decomposed Granites collected are poorly graded silty SANDS (silt of intermediate plasticity) (SP - SMI). The results (B.1) of the X-ray diffraction test show that all granites contained Kaolinite as the predominant clay mineral. All granites contained organic matter according to the organic content test which meant that a detrimental effect during hydration and clay bonding might be expected during testing. It was decided to proceed with testing as this effect was uniform for all test specimens and represented conditions in practice, even for the subsoil levels at which the specimens were taken. Furthermore, the Organic Content test was deemed to be a 'rough' test and does not always correlate with an unsuitable material.

It was noticed that soil 3 was similar in colour to soil 17 from Sierra Leone which had already been classified as Decomposed Granite according to Collis (2011). It was thus decided that all material selection tests be undertaken for soil 17 since it was being evaluated simultaneously in the lab for another project. The results for the Decomposed Granites are displayed in Table 4.3.

Results showed that soil 3 and soil 17 were similar for all material selection tests undertaken. It was thus decided that soil 3 would be selected as the clay soil for Rammed Earth testing due to its distinct easily identifiable red colour (Figure 4.2) and availability throughout Cape Town. Soil 6 was somewhat different to soils 3 & 17 as it was brown in colour but contained traces of red. It also had lower clay content, plasticity index, liquid limit and linear shrinkage. Soil 6 was collected 2 km from where soil 3 was collected. This suggested that soil 6 was a mixture of the distinctly red Decomposed Granite (DG) with an unidentified brown soil, possibly hill wash of non-cohesive properties or lower clay content. This suggested an explanation for the lower plasticity results, brown colour and similar mineralogical properties.

Table 4.3: Comparison of Soil Properties for Decomposed Granites

Properties	Soil number:	3.	6.	17.
1. Grading Analysis (%)				
Sand (4.75 – 0.075 mm)		56.4	58.4	59.8
Silt (0.075 – 0.002 mm)		35.8	37.9	31.3
Clay (< 0.002 mm)		7.8	4.2	8.6
2. Atterberg Limits				
Liquid Limit (%)		45.6	42.3	49.2
Plastic Limit (%)		29.1	34.9	30.7
Plasticity Index (%)		16.5	7.3	18.5
Linear Shrinkage (%)		7.2	5.0	7.6
3. Unified Soil Classification (USC)		SP - SMI	SP - SMI	SP - SMI
4. Predominant Clay Mineral(XRD)		Kaolinite	Kaolinite	Kaolinite
5.Organic Content Test		Fail	Fail	Fail

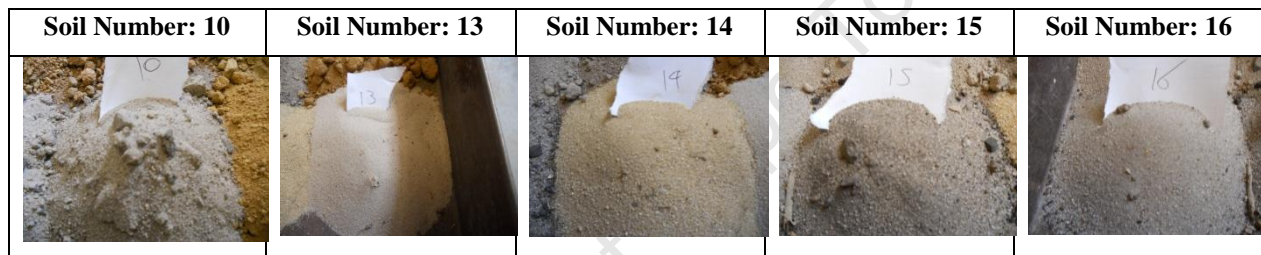
**Figure 4.2 Colour Photographs of Decomposed Granites**

The next phase of material selection included selection of a ‘non-plastic’ or ‘non-cohesive’ soil to construct Rammed Earth cylinders of varying plasticity. The purpose was to select a soil which would be readily available and easily identifiable. It was thus decided to compare the properties of various soils from the Cape Flats area. Therefore, soils 10, 13, 14, 15 and 16 were selected and compared. All material selection tests were undertaken and the results for all Cape Flats sands are displayed in Table 4.4.

Results showed that all soils from the Cape Flats area exhibited similar properties. They had no non-cohesive properties and were termed Non-Plastic (NP) according to Atterberg limits testing. According to the Unified Soil Classification (USC), all soils were described as uniformly graded SANDS (SPu). The results of the X-ray diffraction test showed that all Cape Flats soils contained Quartz as the predominant mineral. All Cape Flats soils contained organic matter according to the organic content test. It was decided that a soil with lower silt content be selected, hence the choice of soil 13 as the non-cohesive soil for Rammed Earth testing.

Table 4.4: Comparison of Soil Properties for Cape Flats Aeolian Sands

Properties	Soil Number:	10.	13.	14.	15.	16.
1. Grading Analysis (%)						
Sand (4.75 – 0.075 mm)		95.6	97.4	97.3	91.6	98.0
Silt (0.075 – 0.002 mm)		4.4	2.6	2.7	8.4	2.0
Clay (< 0.002 mm)		0	0	0	0	0
2. Atterberg Limits						
Liquid Limit (%)		NP	NP	NP	NP	NP
Plastic Limit (%)		-	-	-	-	-
Plasticity Index (%)		-	-	-	-	-
Linear Shrinkage (%)		-	-	-	-	-
3. Unified Soil Classification (USC)						
		SPu	SPu	SPu	SPu	SPu
4. Predominant Mineral (XRD)						
		Quartz	Quartz	Quartz	Quartz	Quartz
5. Organic Content Test						
		Fail	Fail	Fail	Fail	Fail

**Figure 4.3: Photographs of Cape Flats Aeolian Sands**

4.3. Properties of Plasticity Blends

The selected Decomposed Granite (DG) and Cape Flats sands (CF) were blended to manufacture Rammed Earth specimens of varying plasticity. It was thus important that all blends also underwent the same material selection testing to fully document the materials used for Rammed Earth compliance testing. The results from testing for all soil blends are displayed and compared with DG and CF in Table 4.5.

As expected, the grading analysis and clay content results showed decreasing clay content with a decreasing percentage of Decomposed Granite (DG). This was also represented in the Atterberg limits results with decreasing plasticity percentages. The Unified Soil Classification (USC) termed Decomposed Granite as poorly graded silty SAND (silt of intermediate plasticity) (SP - SMI) and as expected, a lower DG percentage termed the soil blends as a poorly graded silty SAND (silt of low plasticity). It was initially thought that the granite blends comprised of a higher clay content due to its 'stickiness' during testing but Kalumba (2011) stated that in some cases, the silt fraction could behave in a similar manner to clay particles and

contribute towards cohesion. The predominant clay mineral was, as expected, determined to be Kaolinite and all blends failed the organic matter test. As discussed earlier, it was decided to proceed with testing as this effect was uniform for all test specimens and represented conditions in practice.

Table 4.5: Properties of Type of Selected Soils and Soil Blends

Properties	DG	CF	40DG-60CF	60DG-40CF	80DG-20CF
1. Grading Analysis (%)					
Sand (4.75 – 0.075 mm)	56.4	97.3	88.4	79.1	67.4
Silt (0.075 – 0.002 mm)	35.8	2.7	8.4	16.1	26.0
Clay (< 0.002 mm)	7.8	0	3.2	4.8	6.4
2. Atterberg Limits					
Liquid Limit (%)	45.6	NP	16.4	22.8	32.0
Plastic Limit (%)	29.1	-	14.1	17.4	23.0
Plasticity index (%)	16.5	-	2.3	5.4	9.0
Linear Shrinkage (%)	7.2	-	1.2	4.3	6.4
3. Unified Soil Classification (USC)					
	SP - SMI	SPu	SP - SML	SP - SML	SP - SMI
4. Predominant Mineral					
	Kaolinite	Quartz	Quartz	Kaolinite	Kaolinite
5. Organic Matter					
	Yes	Yes	Yes	Yes	Yes
6. Compaction Characteristics					
Maximum Dry Density (kg/m ³)	1570	-	1730	1710	1670
Optimum Moisture Content %	18.2	-	14.4	15.8	16.2

4.3.1. Microscopic images of Selected Soils and Blends

In order to better understand the mechanisms affecting the properties of the Rammed Earth samples, representative samples were viewed under a microscope and their magnified images captured. A table showing the images of each soil and soil blend used is shown in Figure 4.4. Note that all images are to the same scale. The horizontal red line in the images represents a length of 1 mm.

From the images, it was noted that Decomposed Granite (DG), although containing 40% less particles between 4.75 and 0.075 mm, had a larger percentage of particles greater than 0.5 mm. This corresponded with the results from the grading analyses (B.4). The grading curves indicated that 95% of the Cape Flats sand (CF) particles were between 0.075 and 0.425 mm in size which corresponded with the images. Looking at the various blends, it was noted that the increase of CF in DG would improve the overall grading.

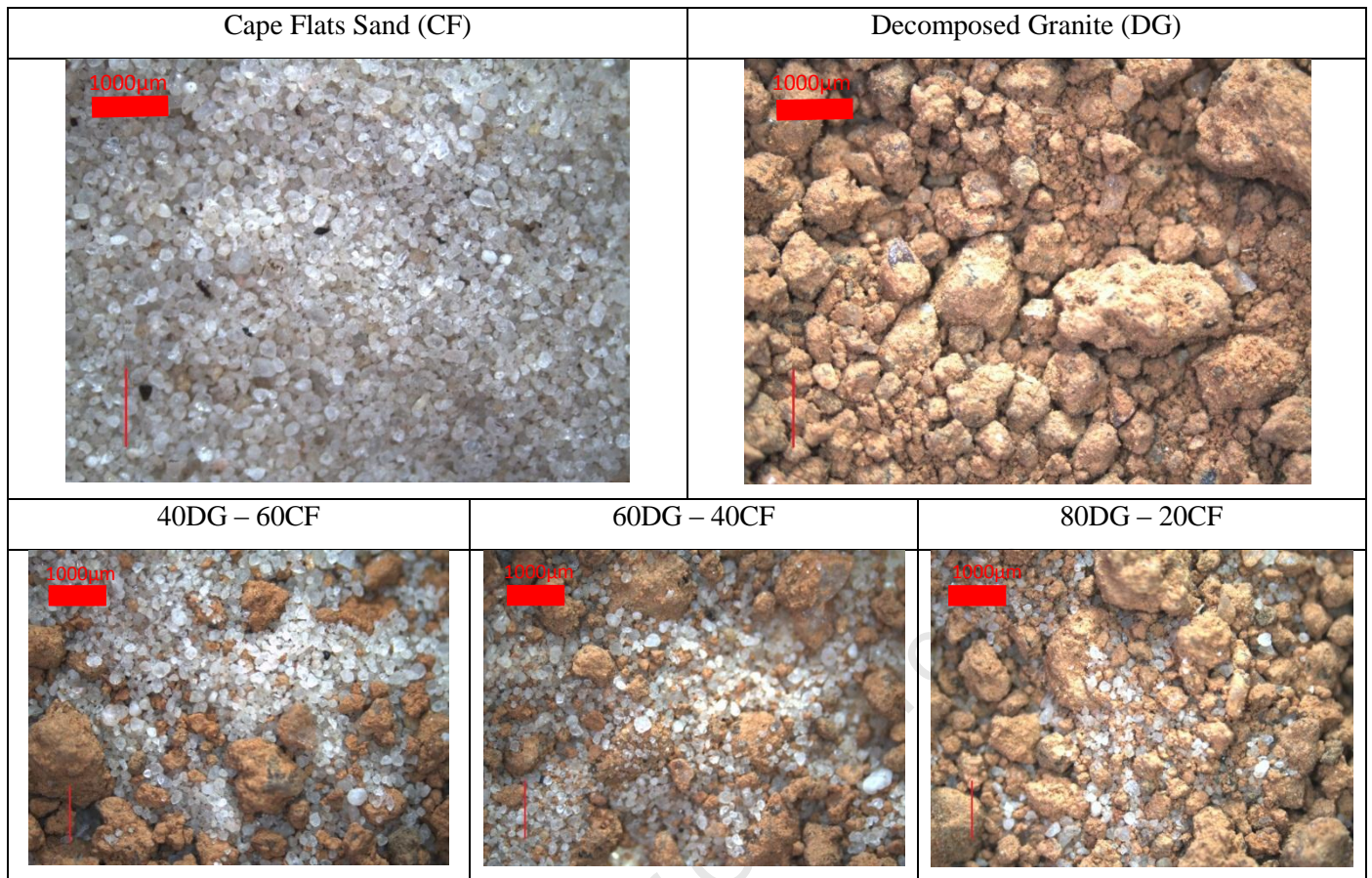


Figure 4.4: Microscopic images of Rammed Earth samples

4.3.2. Determination of the Optimum Moisture Content (OMC)

The Optimum Moisture Content (OMC) needed to be determined for the manufacture of Rammed Earth specimens of varying plasticity. The results of the OMC tests are shown in Figure 4.5 and Table 4.6. Results (Figure 4.5) showed that an increase of Decomposed Granite (DG) resulted in a higher OMC (see B.3 for detailed experimental results). This was expected as an increase in clay content yielded higher moisture absorption according to literature (2.3.3). Interestingly, results also showed that a decrease of DG results in a higher maximum dry density. This was because the finer CF particles improved the overall grading and hence the particle packing. The OMC results shown in Table 4.6 were used during the manufacture of the various Rammed Earth specimens.

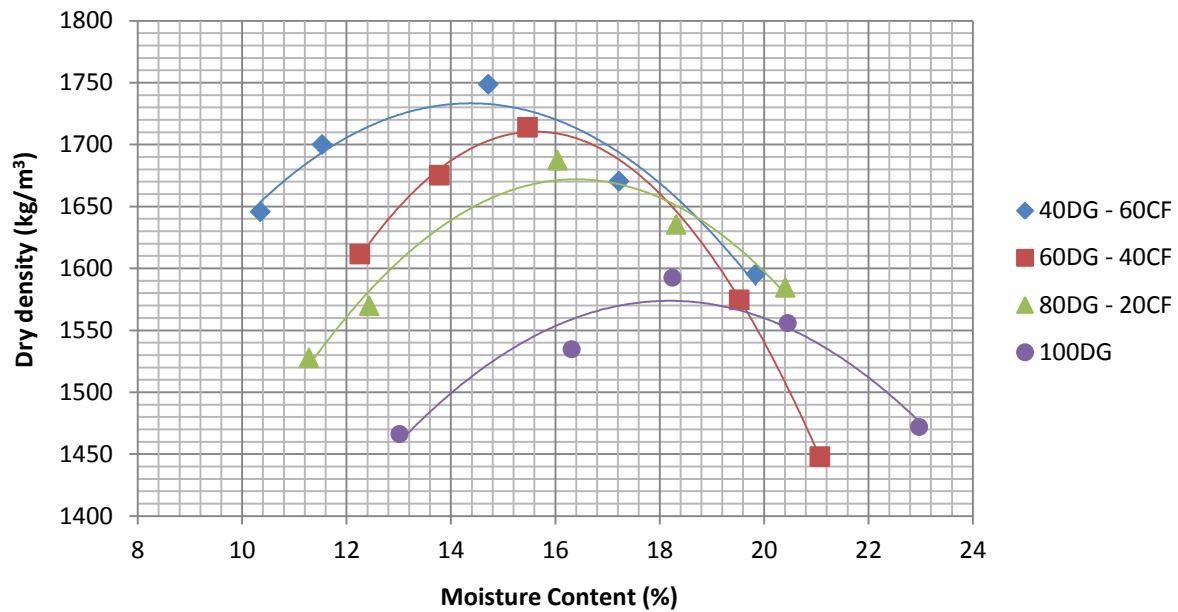


Figure 4.5: Relationship between Dry Density and Moisture Content

Table 4.6: Compaction Characteristics

	Optimum Moisture Content (%)	Maximum Dry Density (kg/m ³)
40% DG - 60% CF	14.4	1730
60% DG - 40% CF	15.8	1710
80% DG - 20% CF	16.2	1670
100% DG	18.2	1570

4.3.3. Workability

It was to be noted from laboratory observations that the lower plasticity blends were easier to manufacture in terms of compactive effort than the higher plasticity blends. For example, the increase of clay content in the blend caused the fresh specimen to stick to the sides of the mould even when lubricated with oil. Furthermore, mixing became difficult due to the buildup of clay lumps in the Hobart mixing bowl. This was not the case with the 40DG – 60CF & 60DG – 40CF blends.

However, the lower the clay content, the lower the plasticity index. This meant that on a construction site, there will be a higher probability for the blend to behave as a liquid if the moisture content added to the mixture marginally exceeded OMC. Conversely, if the moisture content was marginally below OMC, there will be a higher probability that the lower plasticity blend would crumble and not hold its shape after manufacture due to a minimal activation of the clay minerals. The higher the plasticity index, the higher the range of moisture content at which a soil blend will exhibit a plastic behaviour.

Compaction time was almost doubled for the manufacture of the 100DG specimens compared with the 40DG – 60CF specimens. However, the 100DG fresh specimens were noticeably stronger immediately after extrusion compared to the 40DG – 60CF fresh specimens.

4.4. Rammed Earth Compliance Testing

Specimens were manufactured from combinations of soil and stabiliser and tested for dry & wet compressive strength, drying shrinkage and moisture absorption according to the methods described in Chapter 3. The results are discussed in this section and show that the 40DG – 60CF and 60DG – 40CF blends often recorded similar results, as was the case with the 80DG – 20CF and 100DG blends. For this reason, the 40DG – 60CF and 60DG – 40CF blends will be termed ‘lower plasticity blends’ while the 80DG – 20CF and 100DG blends are termed ‘higher plasticity blends’ to simplify the discussion of results in this Chapter.

4.4.1. Compressive Strength

A total of 20 soil combinations varying in plasticity and stabiliser were used. Cylinders were manufactured from these combinations and were tested for wet & dry compressive strength at 7, 14, 28 and 56 days after manufacture. Variables such as compactive effort, moisture content and density for the compaction of Rammed Earth were difficult to keep constant compared to the compaction of concrete. Every effort (see 3.1.1 & 3.1.2) was made to keep these variables constant to ensure consistent results. Specimens were compacted at a pre-determined Optimum Moisture Content (OMC) and all points on the graphs that followed represented an average of 3 specimens. However, with specimens of low stabiliser content and low strengths, certain experimental variations were observed where it appeared that specimens decreased somewhat in strength over time.

Figure 4.6 shows results for compressive strength of the sample at 56 days after manufacture. Strength developments over time for each soil combination is discussed in detail later in section under ‘Relationship between Compressive strength and Time’. Note the minimum acceptable value of 2 MPa & 1 MPa for loadbearing and non-loadbearing applications respectively in Rammed Earth construction according to Walker *et al.* (2005).

In the case of the unstabilised specimens, it was apparent that strength was gained over time due to drying i.e. the gradual loss of moisture. As the specimens dried, the clay fraction of the soil began to contract and the clay particles bonded to one another. As the soil dried, this bonding became stronger. This effect is also discussed in more detail further in this section. In the case of cement stabilised specimens, strength was gained as a result of chemical and

mechanical bonding. The chemical bonding occurred between the cement particles due to hydration reactions. The products of this reaction were calcium silicate hydrates, calcium aluminate hydrates and hydrated lime. These products bond mechanically and cement together the particles in the soil increasing the overall strength of the soil (O'Flathery, 1974).

When soil was stabilised with lime, unlike cement which worked with the coarse particles of a soil, lime directly worked with the clay minerals in a soil. Hydrated lime reacted with clay particles and transforms them into a strong cementitious matrix. A pozzolanic reaction was mainly responsible for improvement in soil properties.

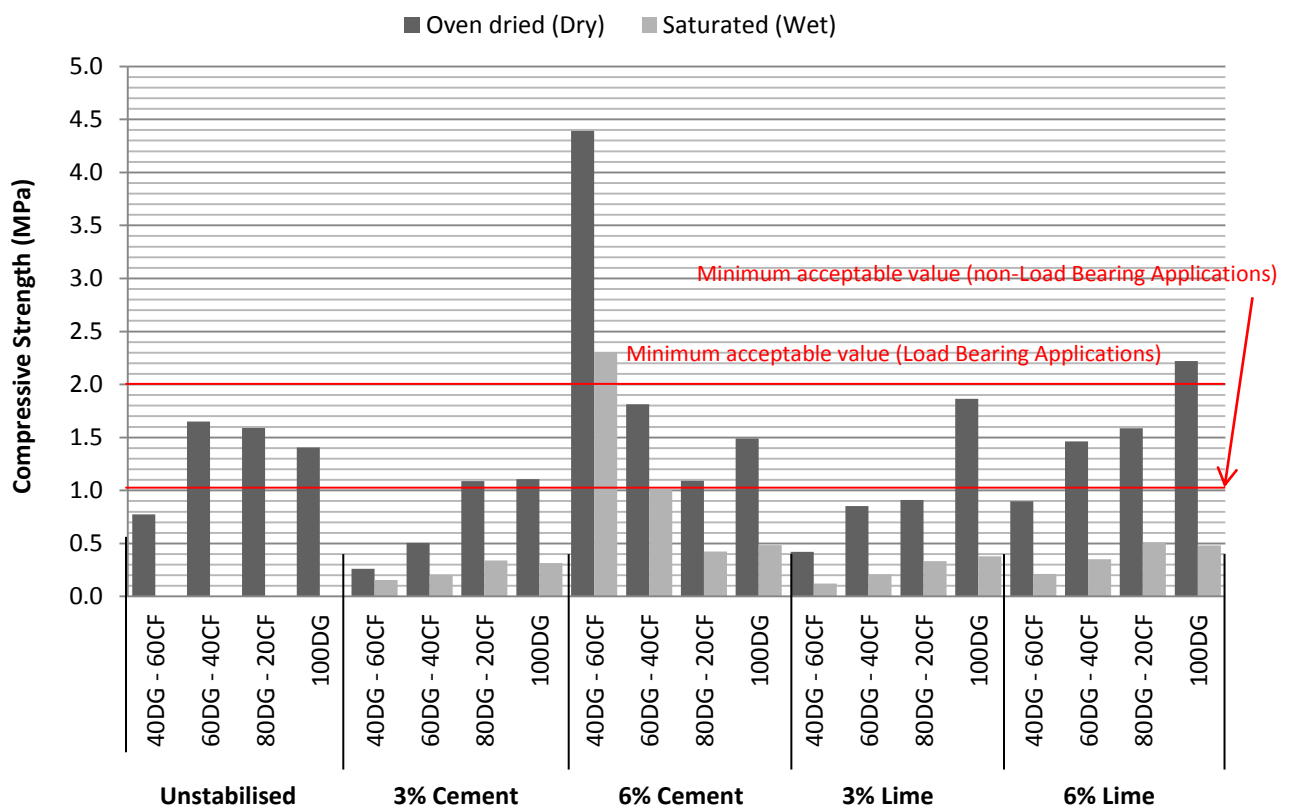


Figure 4.6: Results for Compressive Strength at 56 Days

At 56 days, it was noted that about half of all stabilised soil combinations gave lower dry strength results than the unstabilised specimens. This was not expected as the literature indicated that the addition of stabiliser generally increased the compressive strength of specimens. This could not be explained wholly by the presence of organic content retarding the hydration reaction of cement and pozzolanic reaction of lime. These reactions might have reduced the strength gain rate but should not have had a negative effect on the later strength of the specimen. It was initially thought that this was related to moisture retention in the stabilised

specimens. To explain further, the curing period of stabilised specimens involved storing them in plastic bags, keeping moisture content high thus facilitating hydration and pozzolanic reactions. Unstabilised specimens were left to dry immediately after manufacture as they had no stabilising reactions that required moisture but relied on the force between clay particles, stronger at lower moisture contents. It was thus thought that stabilised specimens, containing high moisture content immediately after curing, retained a higher moisture content during the drying process due to the previous 28 days and 5 days of curing for the cement and lime stabilised specimens respectively. Higher moisture contents in the stabilised specimens explained the lower strength results. This gave some indication that cement stabilised specimens may not have been hydrating much; one might have expected a lower moisture content if that had occurred.

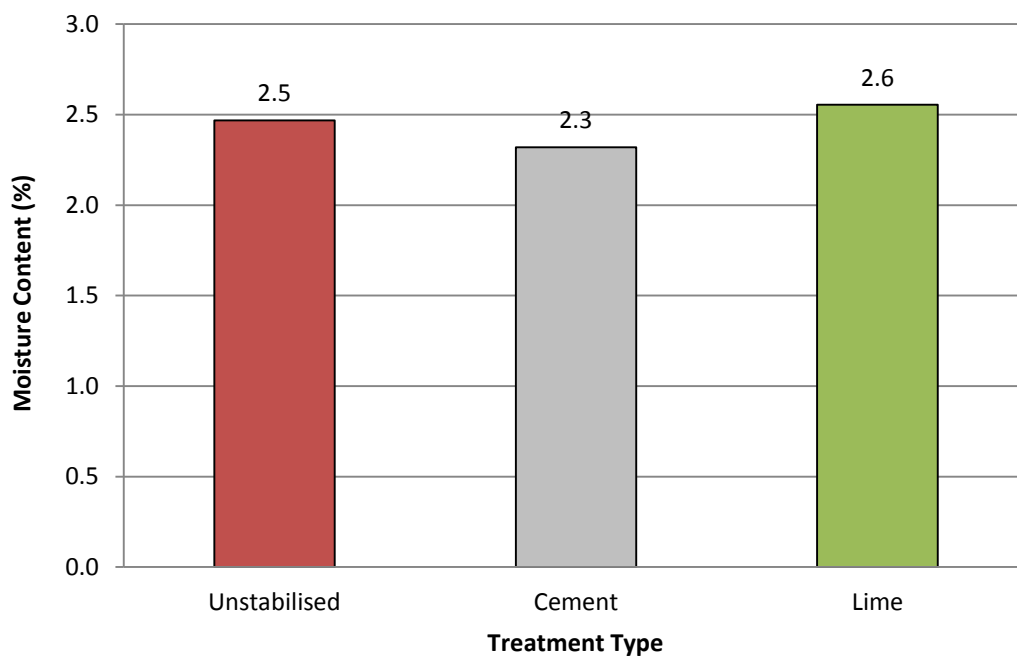


Figure 4.7: Average Unstabilised & Stabilised Specimen Moisture Contents (%) after 56 days

However, results in Figure 4.7 showed that at all specimens at 56 days contained similar moisture contents and thus could not have explained the lower strength results. A possible explanation was that 3% stabiliser content was insufficient to have had a significant effect on the compressive strength combined with the swelling/weakening of clay particles during sealed curing. This combined initial effect may have had a negative effect on the compressive strength during the drying process. However, this was not clear and further research is recommended on this phenomenon.

The results in Figure 4.7 were obtained by averaging all dry specimen moisture contents per treatment at 56 days. It was interesting to notice that the unstabilised specimens which were left to dry for the longest period of time yielded similar results thus implying that all specimens whether unstabilised or stabilised lost moisture to a certain moisture content under similar laboratory conditions. This effect is investigated further in this section under “Relationship between moisture content and time”. The literature stated that the addition of stabiliser significantly improved wet compressive strength and general durability. This was confirmed as all unstabilised ‘wet’ specimens disintegrated in the presence of water as opposed to stabilised specimens. Powrie (2005) stated that clays sustain large pore water suctions resulting in large effective stresses, hence frictional strength. However, for unstabilised specimens, this strength was lost when the clay was immersed in a body of water.

Figure 4.8 & 4.9 show a more detailed direct comparison between the cement and lime stabilised specimens for wet & dry compressive strength at 56 days. Looking at the 3% cement & lime stabilised specimens, it was noted that all specimens tended to increase in strength with increasing clay content. However, considering the 6% stabilised specimens, there was a trend that cement stabilised specimens decreased in strength with increasing clay content.

Firstly, it was thought that the stabiliser content at 3% was too low to have had a significant effect on the compressive strength which was primarily associated with the bond of the clay particles in this case. However, 3% stabiliser remained necessary to protect specimens against disintegration when immersed in water. At 6% stabiliser, it was apparent from results and literature that the amount of stabiliser present was sufficient to provide higher compressive strengths for the various soil combinations. The results implied that increasing clay content promoted pozzolanic reactions in lime stabilised specimens while retarding hydration reactions in cement stabilised specimens.

The only soil combination to pass the minimum acceptable value specified for both wet & dry compressive strength was the 40DG – 60CF blend stabilised with 6% cement. Comparing this combination with the 40DG – 60CF unstabilised specimens; there was a 400% increase in dry strength which was unexpected. In comparison, this unexpected high dry strength result of 4.4 MPa was supported by a significantly high wet strength result of 2.3 MPa. This correlated with the results of the Compaction test (Table 4.6) which demonstrated that the 40DG – 60CF combination exhibited the highest maximum dry density (1730 kg/m^3) at Optimum Moisture

Content (OMC). Grading curves (see B.4) also showed the 40DG – 60CF blend to contain a higher spread of particle size.

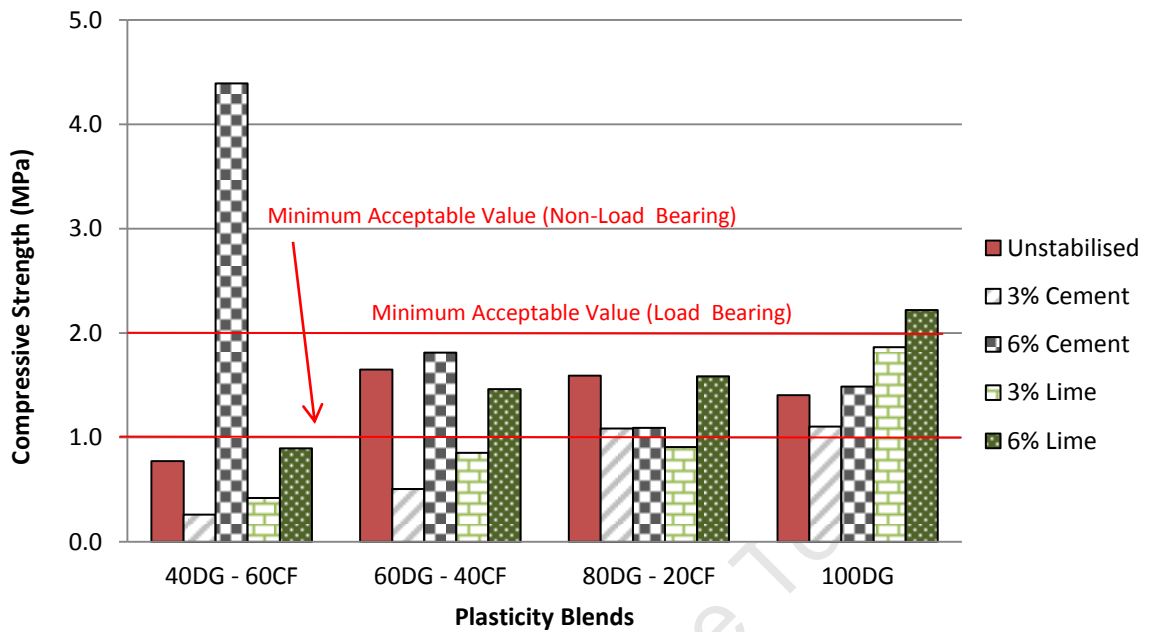


Figure 4.8: Dry Compressive Strength at 56 days)

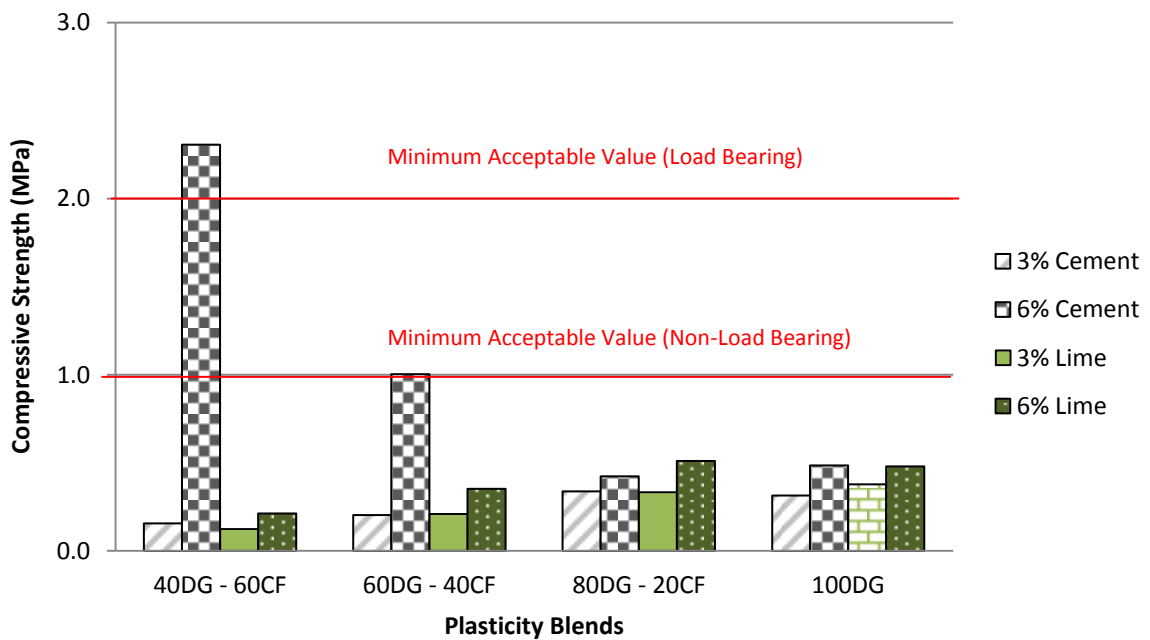


Figure 4.9: Wet Compressive Strength at 56 days

According to Powrie (2007), when a soil is well-graded and compacted, it will pack together well to fill all the voids because it contains a wide range of particle sizes. This ultimately would lead to a higher compressive strength which would explain the results of the 40DG – 60CF 6% cement specimens. However, this was contradicted by the 40DG – 60CF Lime stabilised and unstabilised specimens having recorded the lowest compressive strengths. This implied that there was insufficient clay content available to bond particles together but did not explain the high 40DG – 60CF strength results. A reason could have been that only the higher (6%) cement content and the content of hydration products associated were sufficient to make up for the lack of clay particles and as a result this specific soil combination was packed into a denser water-stable matrix.

In addition, the 40DG – 60CF soil blend had the highest maximum dry density when compacted at OMC. It also contained the least clay content and as implied earlier from results, this was less detrimental to hydration reactions due to the apparent retarding effect that clay has on cement. The combination of all these factors was advanced as the most plausible explanation for the unexpected high strength, but more research would be required to fully understand this phenomenon. All unstabilised specimens disintegrated during water immersion and it was thus impossible to record any wet compressive strength results for these specimens.

Relationship between Moisture Content and Time

Results in this section demonstrate the relationship between moisture content and time in more detail. Strength results were recorded at 7, 14, 28 and 56 days after manufacture. Each graph has been divided into the various specimen treatment types (unstabilised, 3% and 6% cement, 3% & 6% lime) and shows the relationship between moisture content and time for the various curing methods. Moisture content for specimens was calculated from mass losses recorded before testing (before oven-drying and water immersion). Initially, all specimens recorded Optimum Moisture Content readings for their respective treatment types. Results are shown in Figures 4.10 to 4.14.

Results showed that unstabilised, 7 day & several 14 day lime stabilised specimens all disintegrated when immersed in water for 24 hours which made moisture content impossible to record and therefore these results were omitted. Sealed curing for lime stabilised specimens ended at 5 days and there was no 5 day moisture content results recorded. Thus, moisture

content was assumed to be constant at OMC until the plastic bags were removed (Figures 4.13 & 4.14).

All results displayed in Figures 4.10 – 4.14 showed that specimens did not fully dry and moisture reached a ‘plateau’ at an equilibrium moisture content. It was determined earlier (Figure 4.7) that on average, all specimens dried to constant mass at similar moisture content irrespective of the treatment type. This effect is investigated in more detail in this section.

As shown in Figure 4.10, specimens took between 7 and 14 days to dry to approximately constant mass. This effect is well illustrated with lime specimens (Figures 4.13 & 4.14) where specimens were left to dry after 5 days of curing; after only 2 days, specimens lost between 2-3% moisture. It was also interesting to note for the cement stabilised specimens (Figure 4.11 & Figure 4.12), the effect of plastic bags on retaining moisture during the curing process. Results for these specimens showed that the largest moisture content loss during the curing process was 0.5%. The rate of moisture loss for the unstabilised & lime specimens was similar, according to results. Moisture loss in cement stabilised specimens was less rapid and is discussed further under “Drying Shrinkage” due to the lack of intermediate readings between 28 and 56 days in this section.

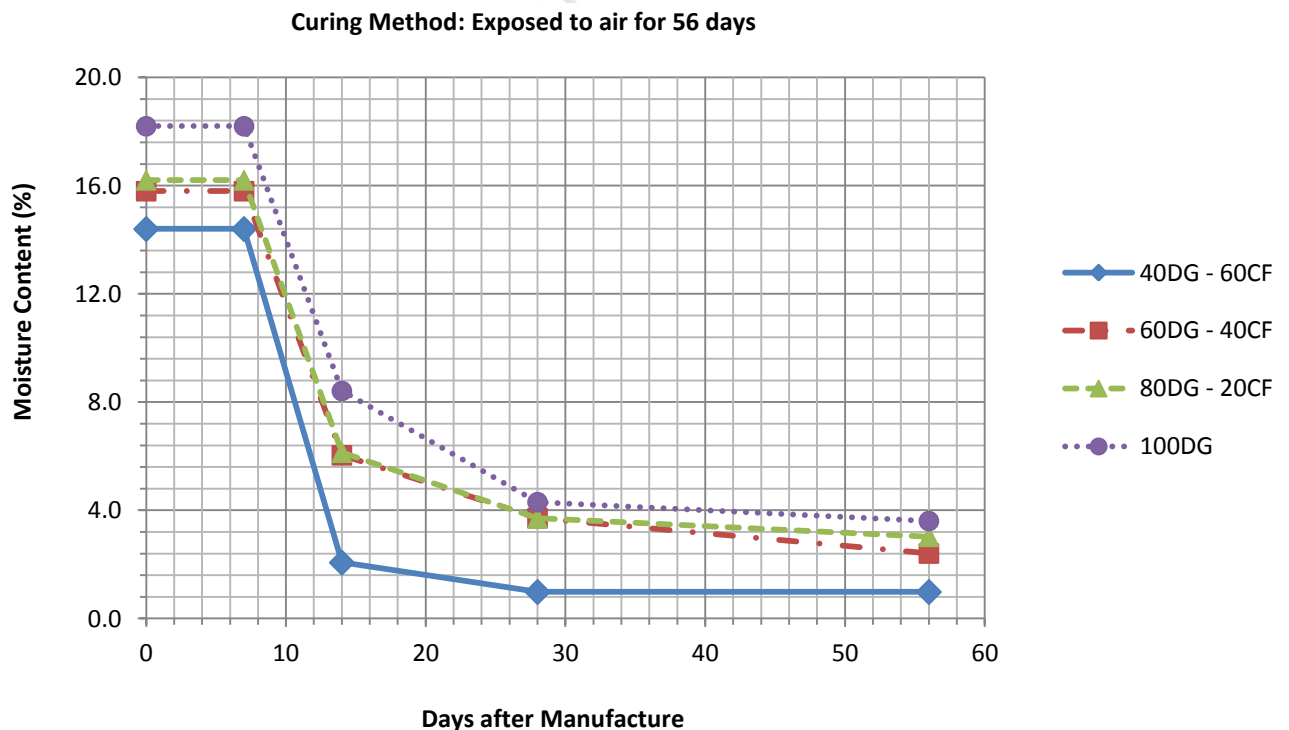


Figure 4.10: Relationship between Moisture Content and Time – Unstabilised

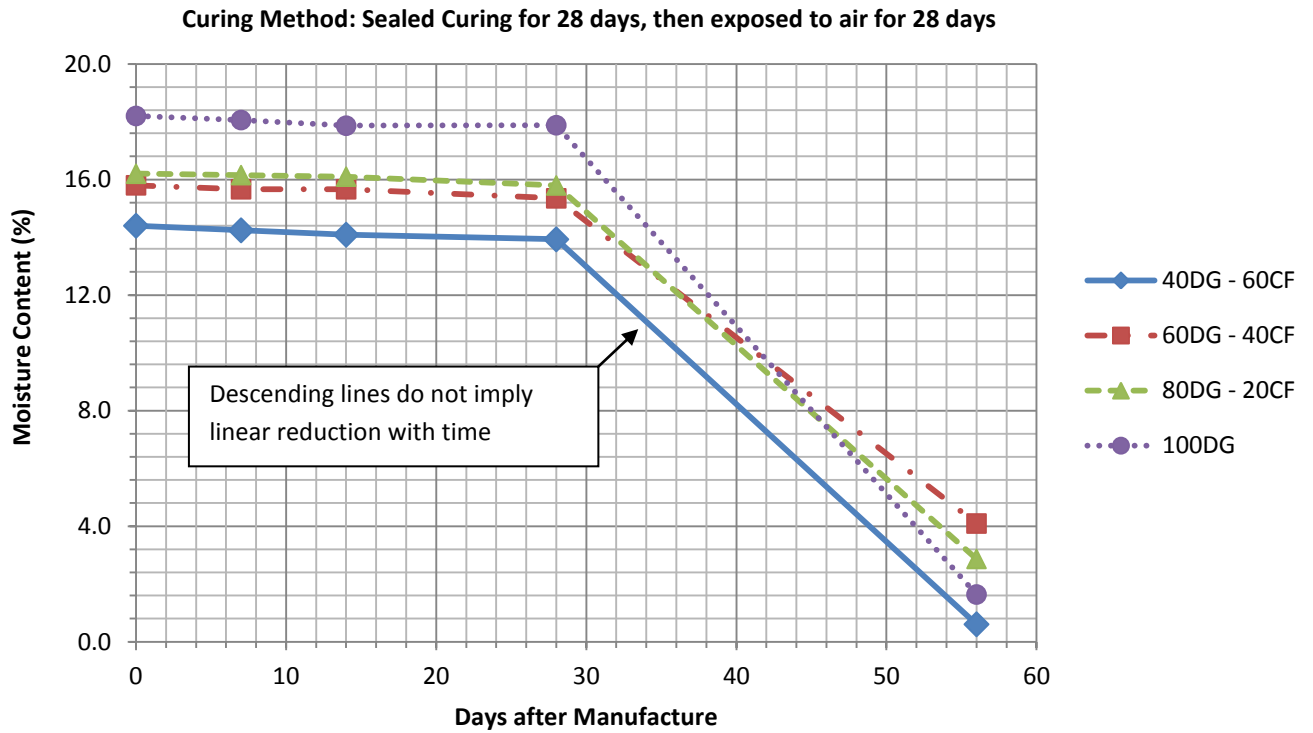


Figure 4.11: Relationship between Moisture Content and Time – 3% Cement

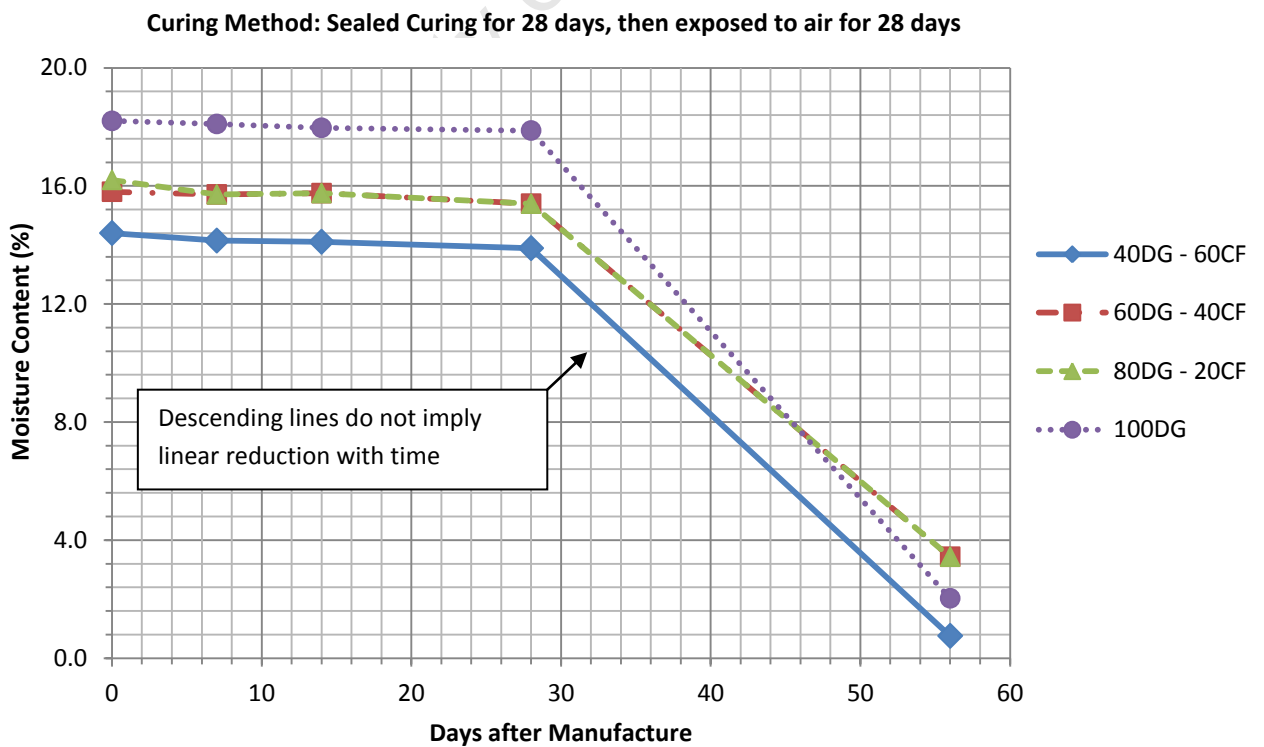


Figure 4.12: Relationship between Moisture Content and Time – 6% Cement

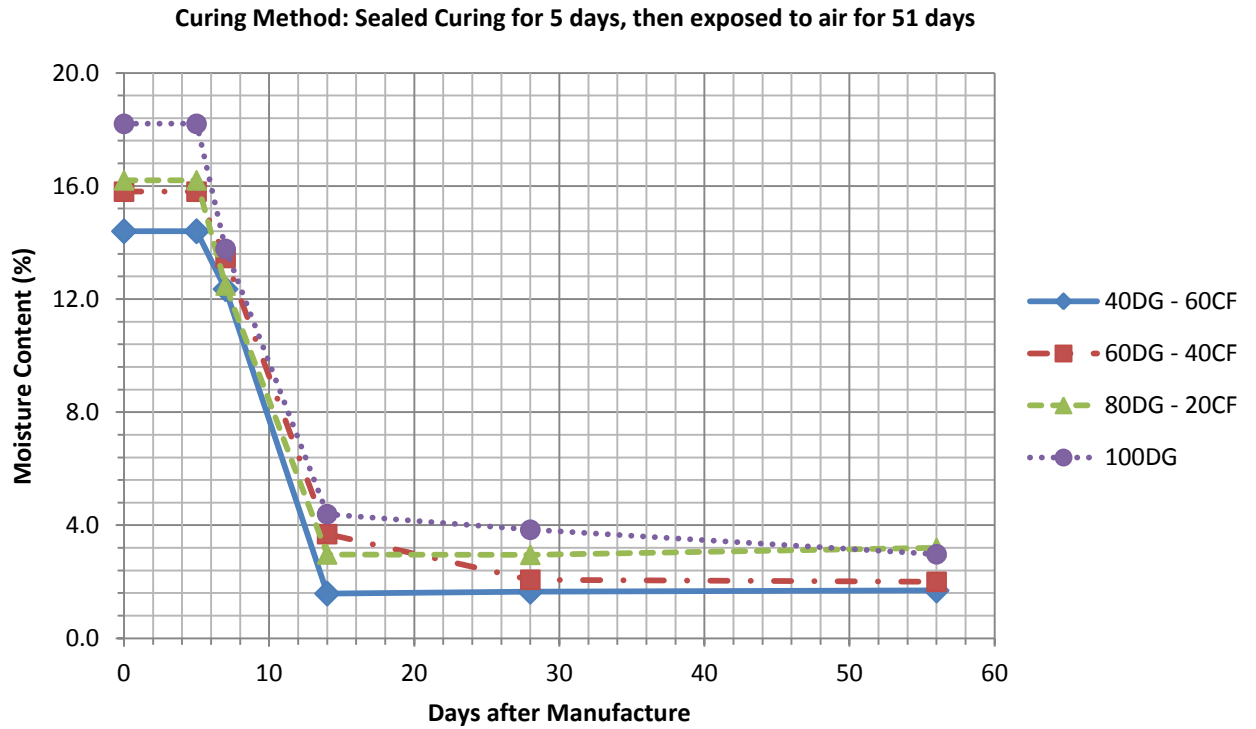


Figure 4.13: Relationship between Moisture Content and Time – 3% Lime

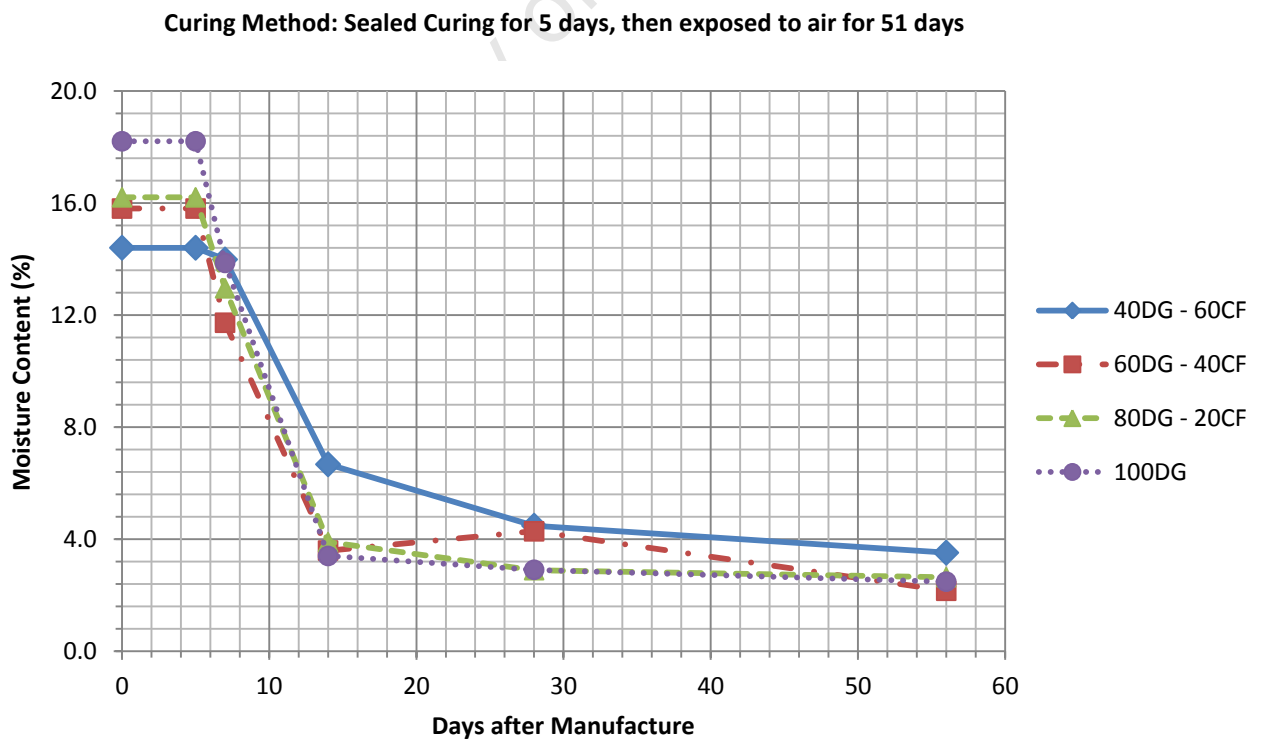


Figure 4.14: Relationship between Moisture Content and Time – 6% Lime

Relationship between Compressive Strength and Time

Results in this section demonstrate the relationship between compressive strength and time in more detail. Strength results were recorded at 7, 14, 28 and 56 days after manufacture and each point represents an average of 3 results. Each graph has been divided into the various specimen treatment types (unstabilised, 3% and 6% cement, 3% & 6% lime) and shows the relationship between compressive strength and time for the various curing methods. The ordinate axis of Figures 4.15 to 4.19 and Figures 4.20 to 4.23 was kept constant to facilitate comparisons between each graph. See (B.5) for variability of these results.

Note specifically in this section that variables such as compactive effort, moisture content and density for the compaction of Rammed Earth were difficult to keep constant. Every effort (see 3.1.1 & 3.1.2) was made to keep these variables constant to ensure consistent results. Specimens were compacted at a pre-determined Optimum Moisture Content (OMC). However, in some cases there were certain experimental variations where it was observed that specimens appeared to decrease somewhat in strength over time. These cases involved specimens of low stabiliser content and lower compressive strengths where the overall strength development over time was relatively low (< 1 MPa). Note the various curing regimes per treatment are displayed above each of the figures.

Dry Compressive strength over Time

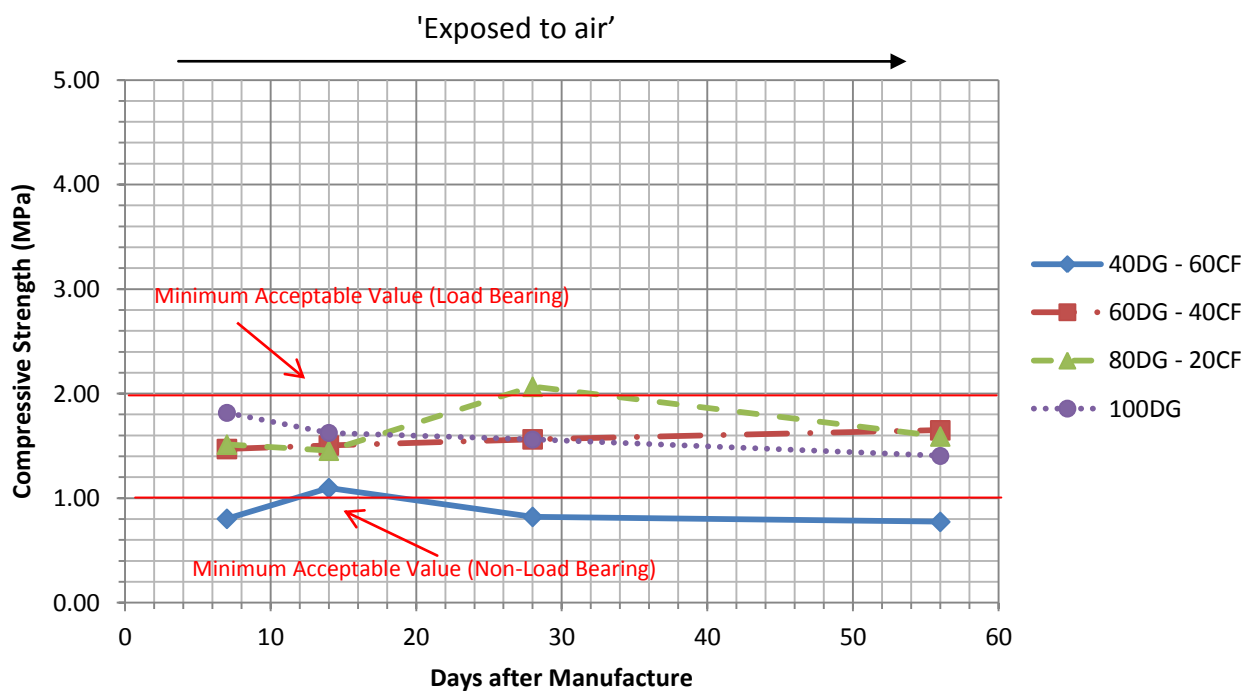


Figure 4.15: Relationship between Dry Compressive Strength and Time – Unstabilised

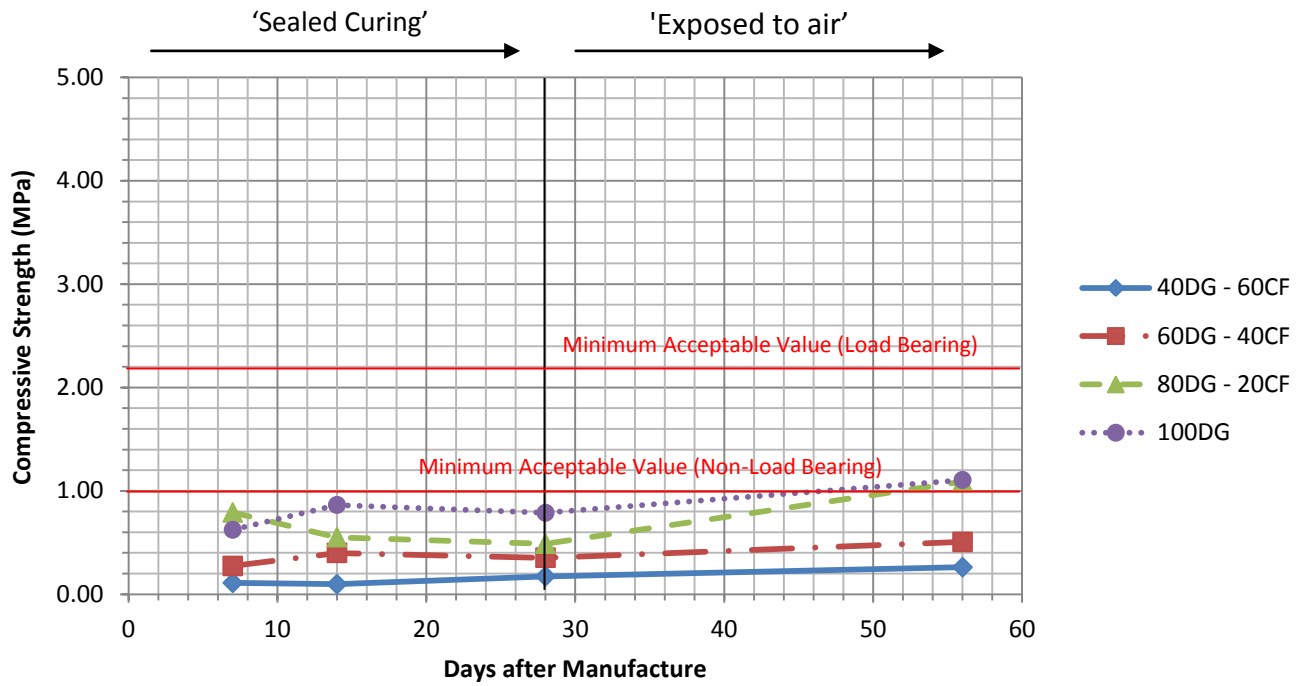


Figure 4.16: Relationship between Dry Compressive Strength and Time - 3% Cement

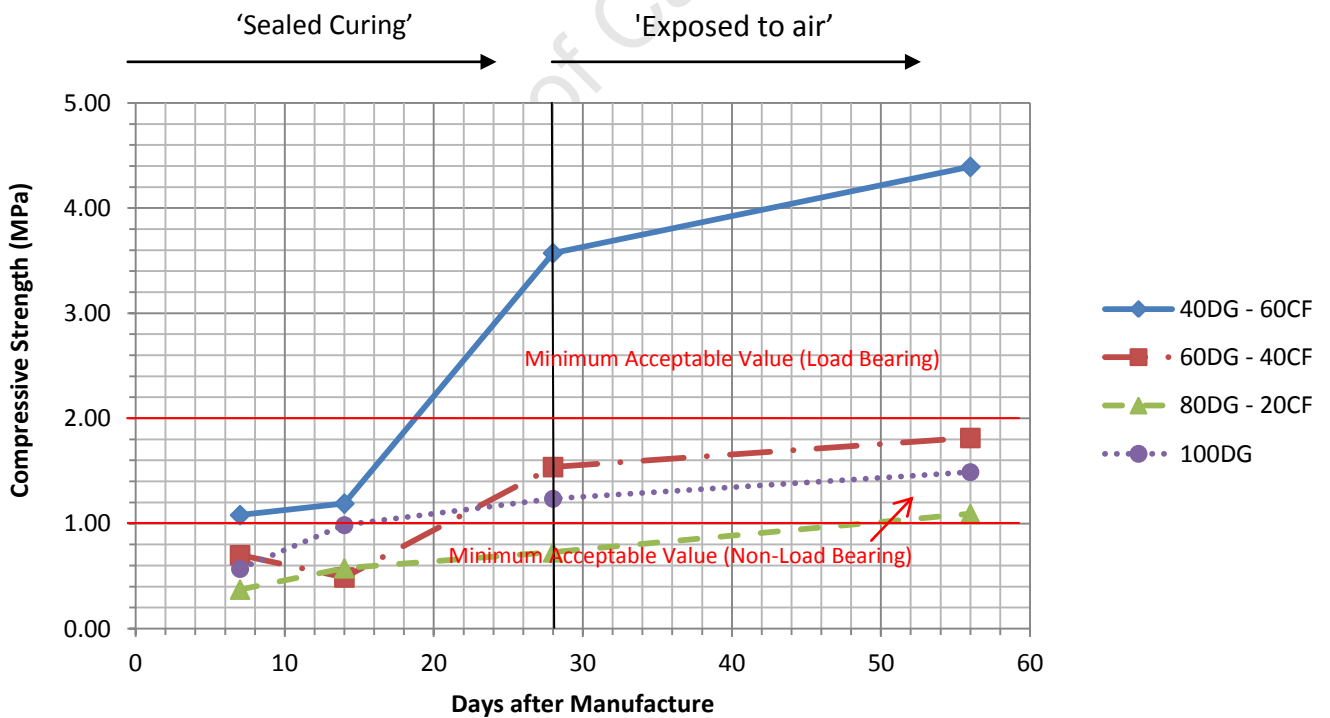


Figure 4.17: Relationship between Dry Compressive Strength and Time - 6% Cement

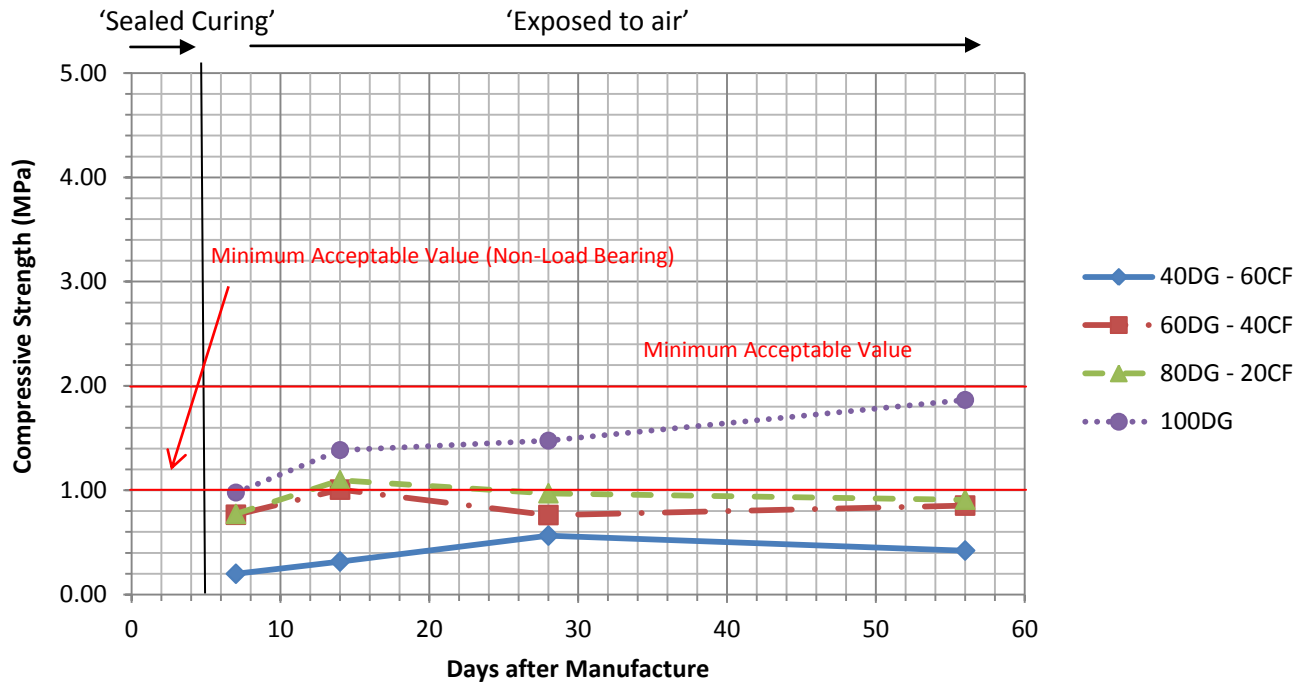


Figure 4.18: Relationship between Dry Compressive Strength and Time - 3% Lime

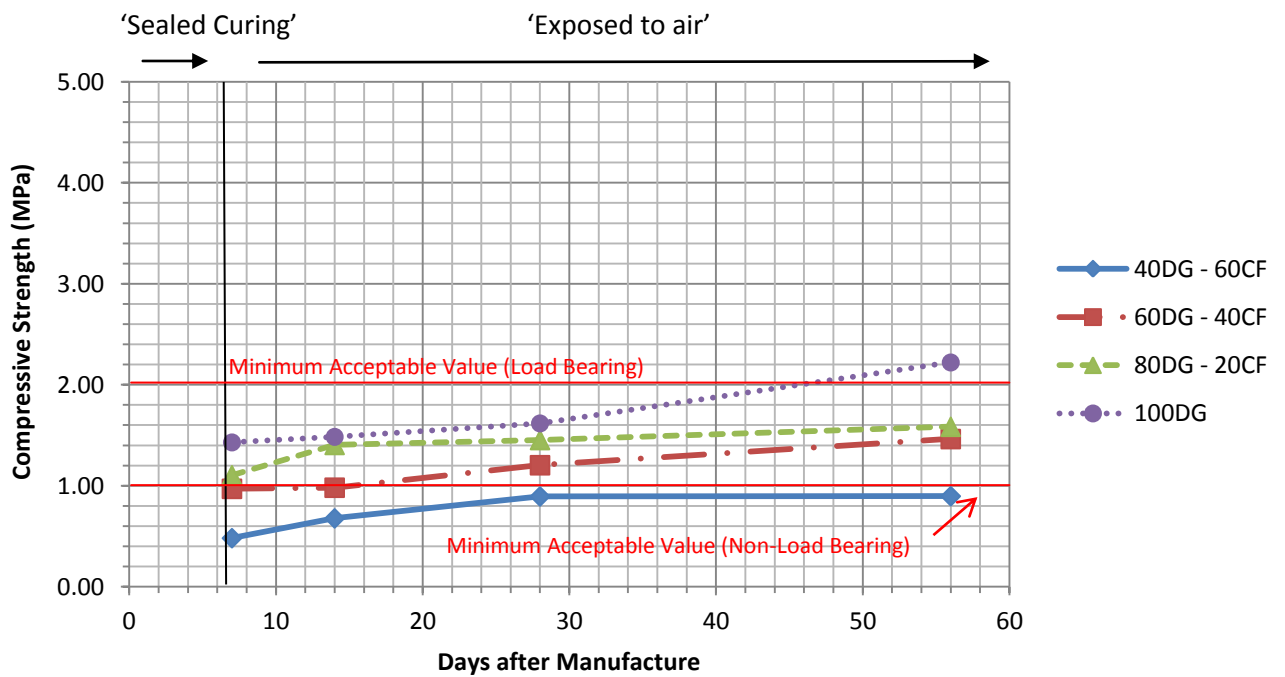


Figure 4.19: Relationship between Dry Compressive Strength and Time - 6% Lime

Wet Compressive Strength over Time

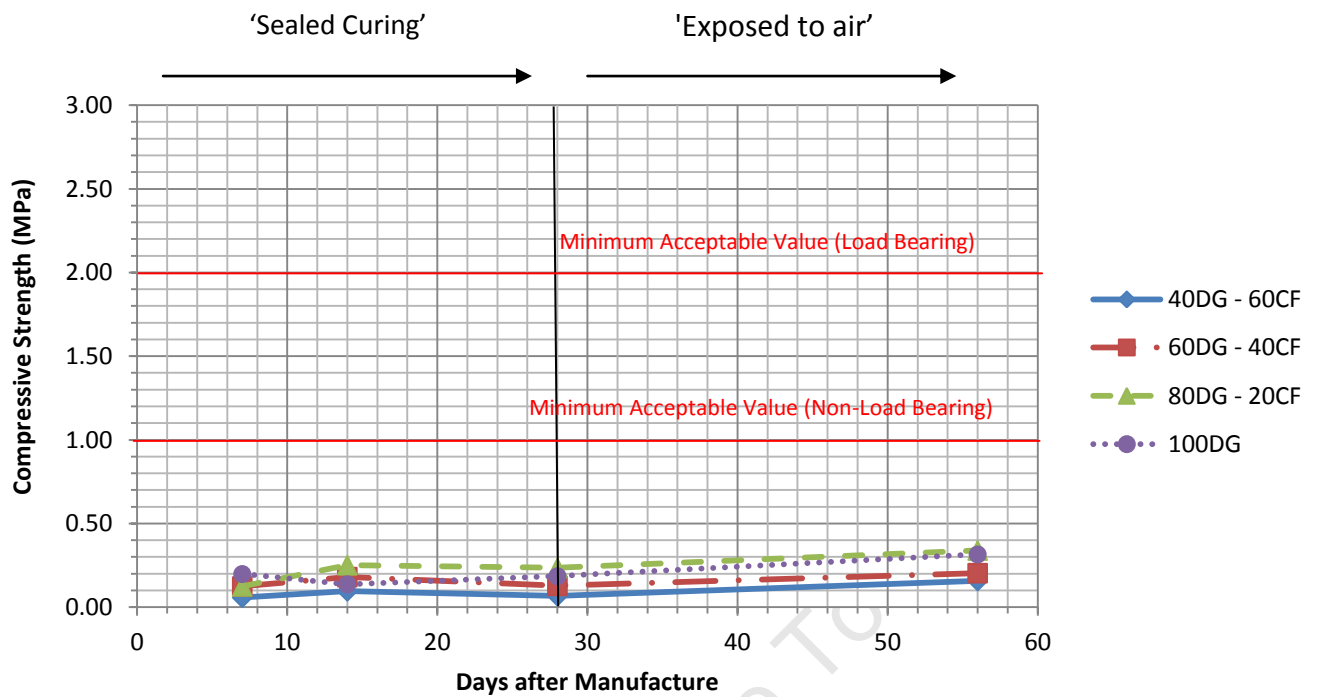


Figure 4.20: Relationship between Wet Compressive Strength and Time - 3% Cement

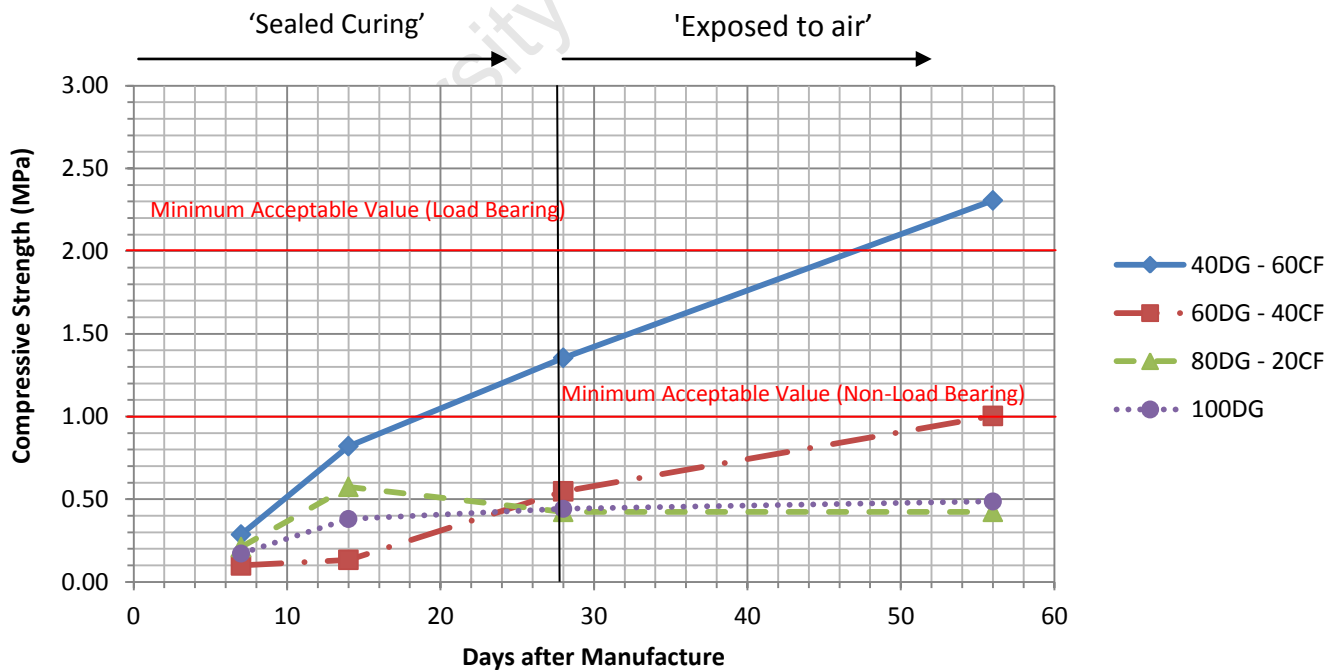


Figure 4.21: Relationship between Wet Compressive Strength and Time - 6% Cement

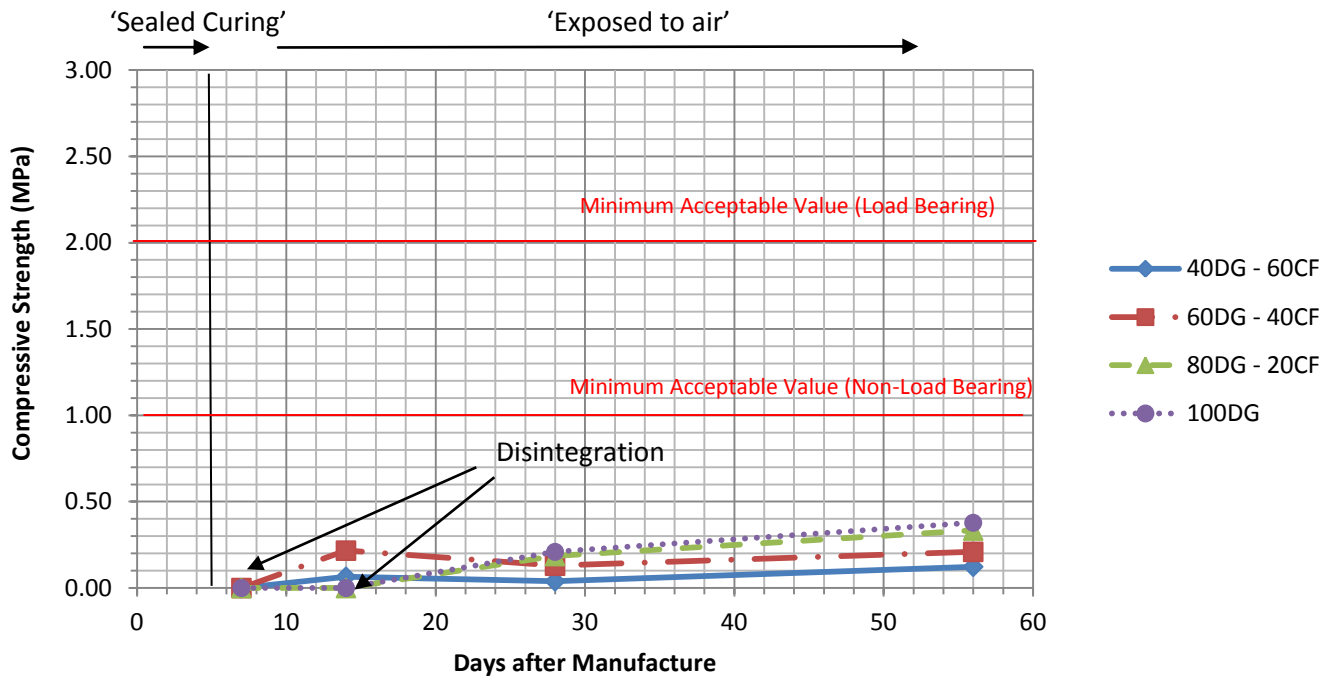


Figure 4.22: Relationship between Wet Compressive Strength and Time - 3% Lime

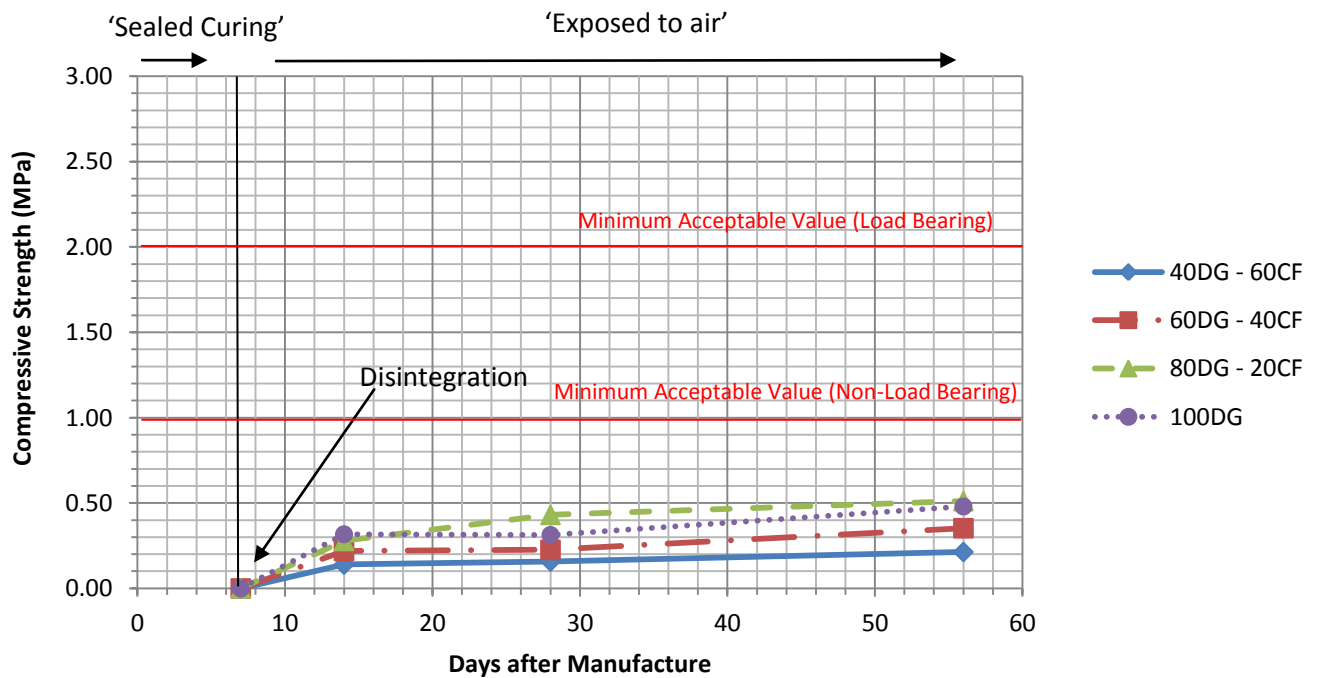


Figure 4.23: Relationship between Wet Compressive Strength and Time - 6% Lime

Results showed that unstabilised specimens (Figure 4.15) showed no further increase in compressive strength from 7 days after manufacture. The moisture loss for unstabilised specimens over time (Figure 4.10) correlates in the sense that the specimens were relatively close to reaching equilibrium moisture content at this time period.

As discussed earlier, the compressive strength of unstabilised specimens was primarily due to the bonding forces between clay particles. The closer the particles are to one another, the higher the compressive strength. The results thus suggested that the loss of moisture over time contributed to a denser soil matrix, hence greater compressive strength. It was also apparent that once the specimens had reached equilibrium moisture content, no further progression in strength was observed.

Considering the 3% stabilised specimens (Figures 4.16, 4.18, 4.20 & 4.22) it was observed that the majority of results were similar to the unstabilised specimen results in terms of strength development over time. This suggested that the lower stabiliser content in the specimens was insufficient to have an effect and the compressive strength derived primarily from bonds between clay particles. This correlated with the 3% cement stabilised specimens (Figure 4.16) where it was observed that only the higher plasticity blends recorded an increase in strength only when sealed curing had been removed. In the case of 3% lime stabilised specimen (Figure 4.18), it was observed that the 100DG blend was the only blend to record an increase in strength. This correlated with the discussion in this paragraph but the strength increase progressed for 51 days. This was interesting as this suggested that, although the initial strength was primarily contributed by the bond of clay particles, pozzolanic reactions may have occurred in the later stages as it is known from literature that lime stabilised specimens achieve their final strength typically 2-3 times longer than the 28 day curing period required for cement.

It was discussed earlier under that the results implied that increasing clay content promoted pozzolanic reactions in lime stabilised specimens while retarding hydration reactions in cement stabilised specimens. This suggests that the higher clay content present in the 100DG was sufficient to promote pozzolanic reactions. In general it was noted that specimens of low (3%) stabiliser content behaved in a similar manner to the unstabilised specimens in terms of strength development over time.

It was interesting to notice that 'wet' specimens stabilised with 3% cement contained sufficient cement to prevent disintegration (Figure 4.20), even after only 7 days of curing. This was not

the case with 'wet' lime stabilised specimens, some of which disintegrated after 7 days. In the case of 3% lime, the higher plasticity blends (80DG-20CF & 100DG) disintegrated even after 14 days (Figure 4.22) i.e. 5 days of curing and then exposed to air for 9 days. This implied that the lower lime content is insufficient to bind the increasing amount of weak clay particles into a solid matrix. It was only after 28 days that all 'wet' lime stabilised specimens recorded compressive strength results after water immersion. This suggested again that the pozzolanic reactions associated with lime stabilisation were acting at a later stage in comparison to the hydration reactions associated with cement.

Considering the 6% stabilised specimens (Figures 4.17, 4.19, 4.21 & 4.23) it was observed that the majority of specimens, compared with unstabilised and 3% stabilised specimens, showed an increase in compressive strength over time. As discussed earlier, it was observed that the cement stabilised lower plasticity blends and lime-stabilised higher plasticity blends recorded the highest compressive strengths. This suggested that the presence of clay retarded cement hydration reactions while promoting pozzolanic reactions in the specimens.

It was observed that the 'wet' & 'dry' lower plasticity cement-stabilised specimens (Figures 4.17, 4.21) significantly increased in compressive strength after the 28 day curing period where the hydration reactions in the specimens would end. This suggested that the increase in compressive strength was been primarily due to by the gradual loss of moisture. Higher plasticity blends demonstrated a lower increase in strength over time which suggested that clay particles were retarding cement hydration reactions and perhaps hindering the bonding process in the associated specimens. This suggested an explanation to the lower compressive strengths when comparing results with the unstabilised specimens (Figure 4.15).

Furthermore, it was observed that the 'wet' higher plasticity blends did not show any increase in strength once sealed curing had been removed (Figure 4.21). This was not expected as it was initially thought that the gradual loss of moisture would contribute to an increase in strength once hydration reaction had ended. A possible explanation was that these specimens, containing higher clay content, were prone to weakening (swelling of clay particles) due to the higher absorption of moisture after water immersion and before testing for compressive strength.

Considering the 6% lime stabilised specimens in more detail (Figures 4.19 & 4.23), it was observed that, as opposed to cement stabilised specimens, the 'wet' & 'dry' higher plasticity blends recorded higher compressive strengths over time. This suggested that the increased

presence of clay particles promoted the pozzolanic reactions occurring in the specimens. Moisture loss in lime stabilised specimens was similar to unstabilised specimens (Figures 4.10, 4.13 & 4.14) where the specimens had reached equilibrium moisture content 14 days after sealed curing had been removed i.e. exposed to air. Moisture loss in cement stabilised specimens was less rapid and is discussed further under “Drying Shrinkage” due to the lack of intermediate readings between 28 & 56 days. For lime specimens, it was interesting to note that although the specimens had reached equilibrium moisture content and no further moisture loss occurred, the specimens continued to increase in compressive strength over time. This suggested that pozzolanic reactions were occurring in the later stages of the 56 day time period.

Relationship between Compressive Strength and Dry Density

According to Craig (2005), the degree of compaction of a soil is measured in terms of dry density, i.e. the mass of dry solids per unit volume of soil. The dry density of a given specimen after compaction depends on the moisture content and the energy supplied by the compaction equipment (compactive effort). Dry density (ρ_d) is given by equation 2.12 in 2.3.7 where ρ is the bulk density and w is the moisture content.

Masses were recorded before each compressive test to calculate the respective dry densities, i.e. after oven drying & water immersion. Therefore no dry density calculations were required for the ‘dry’ specimens as they were already dried to constant mass. Dry densities for the ‘wet’ specimens were calculated by equation 2.12 after water immersion according to their respective moisture contents.

Results are displayed per treatment type at an age of 56 days in Figures 4.24 to 4.32. Each point represents an average of 3 specimens. The ordinate axis was kept constant to facilitate comparisons. Note that variables such as compactive effort, moisture content and density for the compaction of Rammed Earth were difficult to keep constant compared to the compaction of concrete. Every effort (see 3.1.1 & 3.1.2) was made to keep these variables constant to ensure consistent results. See (B.5) for variability of these results.

The results (Figures 4.24 – 4.32) seemed to show little by way of sensible or expected relationships between the different variables. According to Standards Australia (2002), the dry density of soil in Rammed Earth applications is dependent on soil type, the moisture content during compaction and compactive effort and a broad range of values are quoted for Rammed Earth, varying from 1700 kg/m^3 to 2200 kg/m^3 . Comparison of results between Proctor tests and actual construction practice are difficult due to the variations in compactive effort. This

suggested an explanation for the quoted higher dry densities compared with Proctor test results in Table 4.6 as a higher compactive effort was employed for the Rammed Earth specimens. Additionally, it was noted in most cases the higher plasticity blends recorded lower dry densities in the Proctor test results, discussed in more detail in 4.3.2.

According to literature, a higher dry density in specimens will lead to a more compact matrix, closer bonded particles and hence a higher compressive strength. However, it was interesting to note that in some cases, results seemed to somewhat contradict the literature suggesting that the compressive strength was primarily contributed by the strength of bonds between particles contributed by cement or lime as opposed to closer bonded particles. It was observed that lower plasticity blends with higher dry densities recorded higher compressive strengths for 6% cement stabilised specimens (Figures 4.26 & 4.30). It was observed that higher plasticity blends with lower dry densities recorded higher compressive strengths for 6% lime stabilised specimens (Figure 4.28 & 4.32). A possible explanation was the added cementitious products during hydration reactions for blends with lower clay content, an assumed retardant to hydration, contributed to a higher dry density while there was an indication that the pozzolanic reactions acting directly with clay particles for blends with higher clay content contributed to a lower dry density. This suggested that the dry density was also dependent on stabiliser type. This was interesting as this indicated that lighter (mass) Rammed Earth walls of a similar compressive strength could be built using lime as opposed to cement. More research would need to be undertaken on this effect.

Considering the 3% stabilised specimens, there was little to be observed in terms of expected relationships. It was discussed earlier that the lower stabiliser content failed to have a significant effect on the compressive strengths and these stabilised specimens recorded similar results to the unstabilised specimens. It was only with specimens of higher stabiliser content that significant effects were observed.

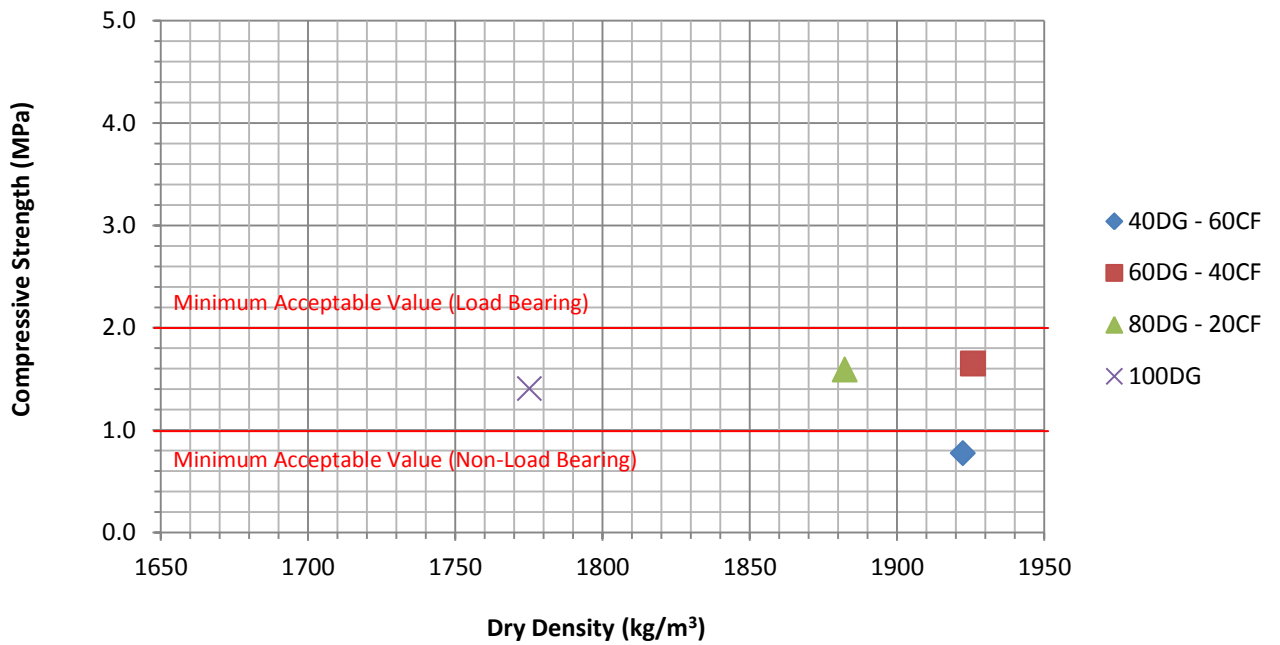


Figure 4.24: Relationship between Dry Compressive Strength and Dry Density at 56 days – Unstabilised

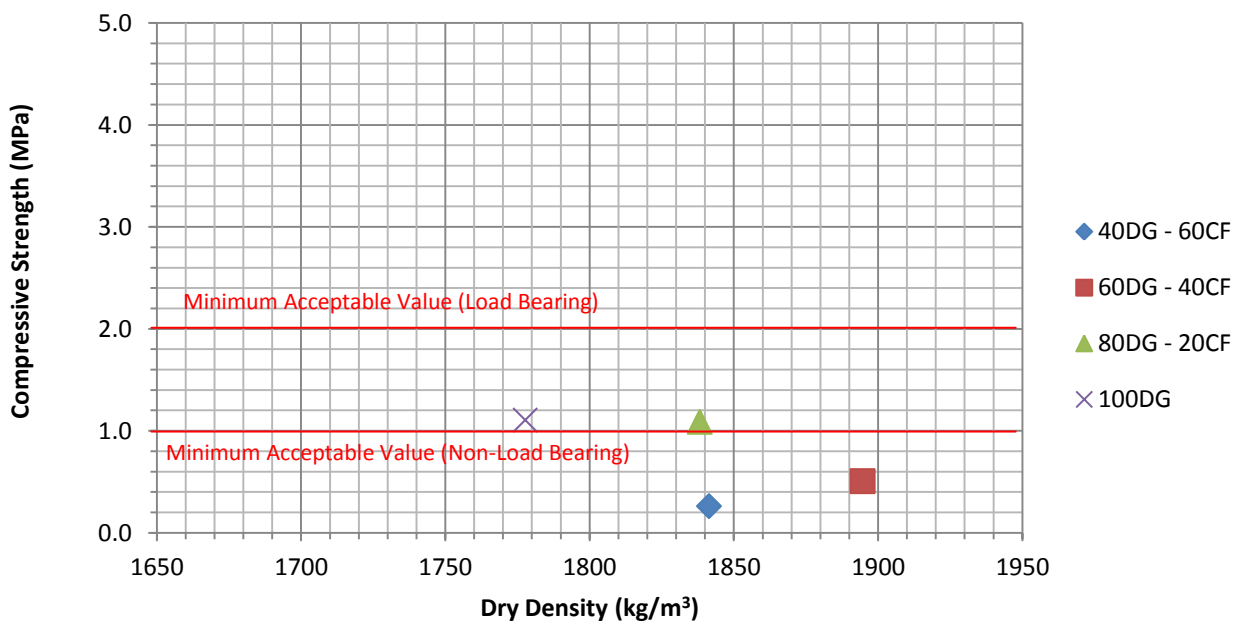


Figure 4.25: Relationship between Dry Compressive Strength and Dry Density at 56 days – 3% Cement

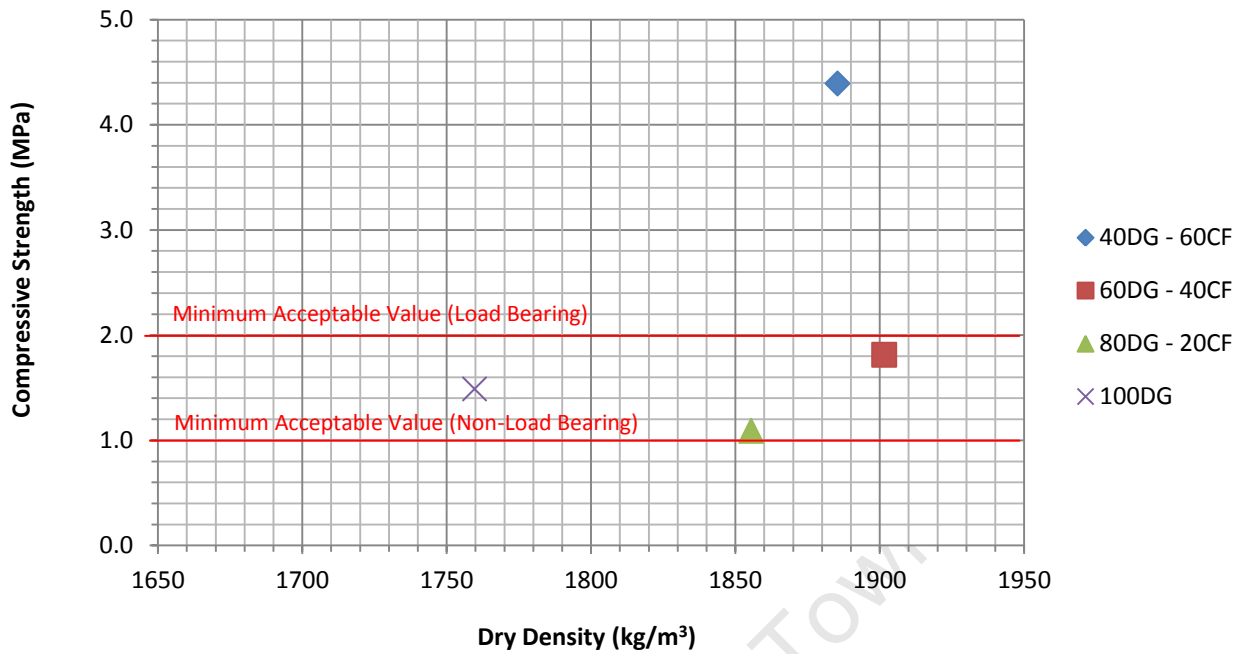


Figure 4.26: Relationship between Dry Compressive Strength and Dry Density at 56 days – 6% Cement

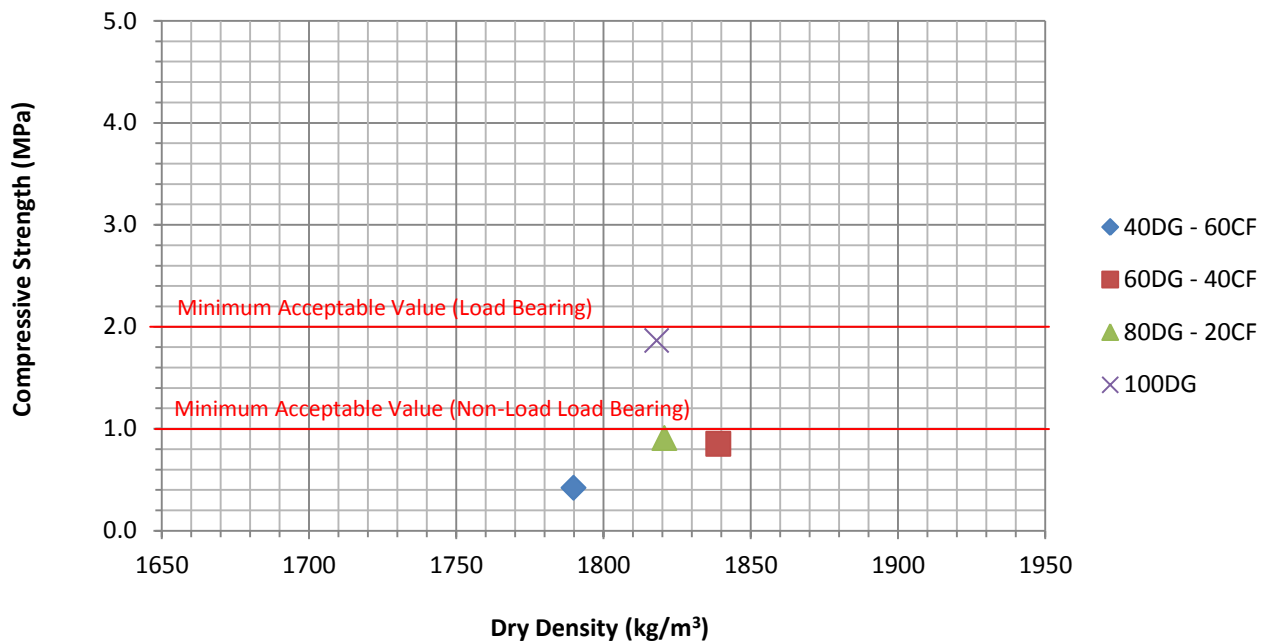


Figure 4.27: Relationship between Dry Compressive Strength and Dry Density at 56 days – 3% Lime

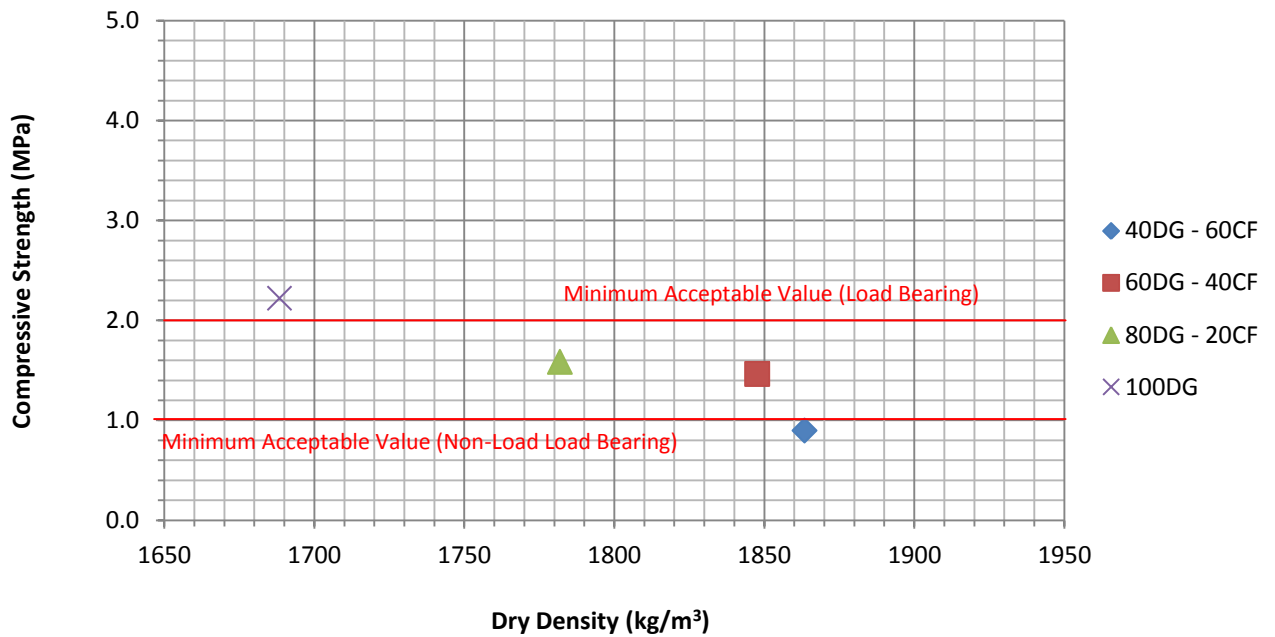


Figure 4.28: Relationship between Dry Compressive Strength and Dry Density at 56 days – 6% Lime

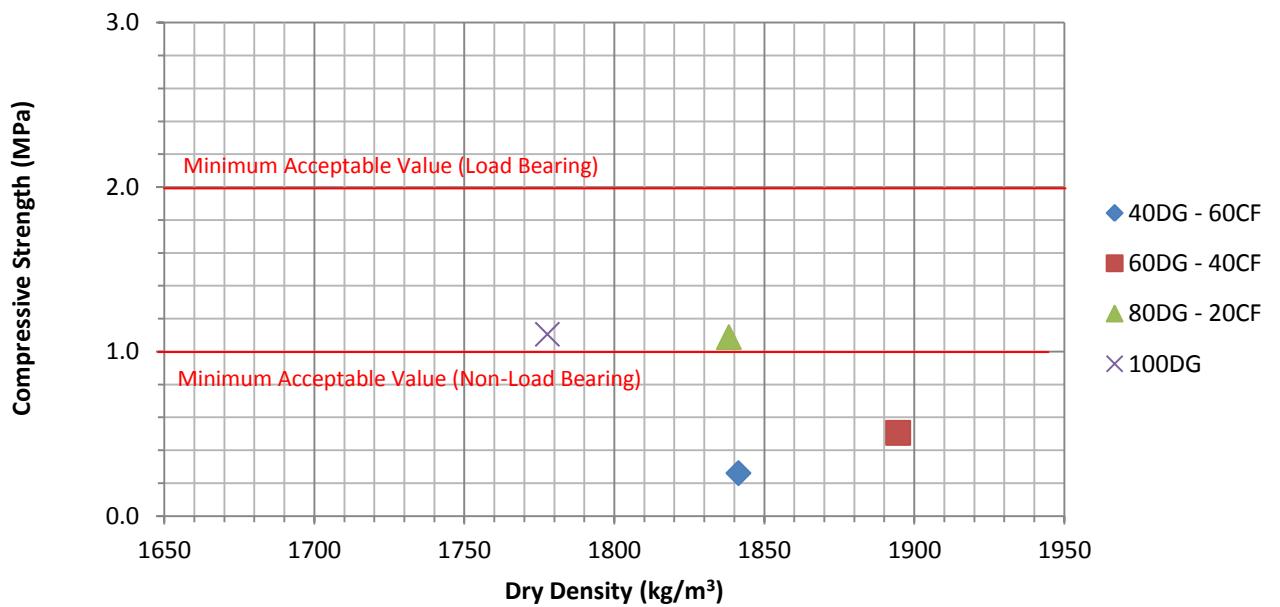


Figure 4.29: Relationship between Wet Compressive Strength and Dry Density at 56 days – 3% Cement

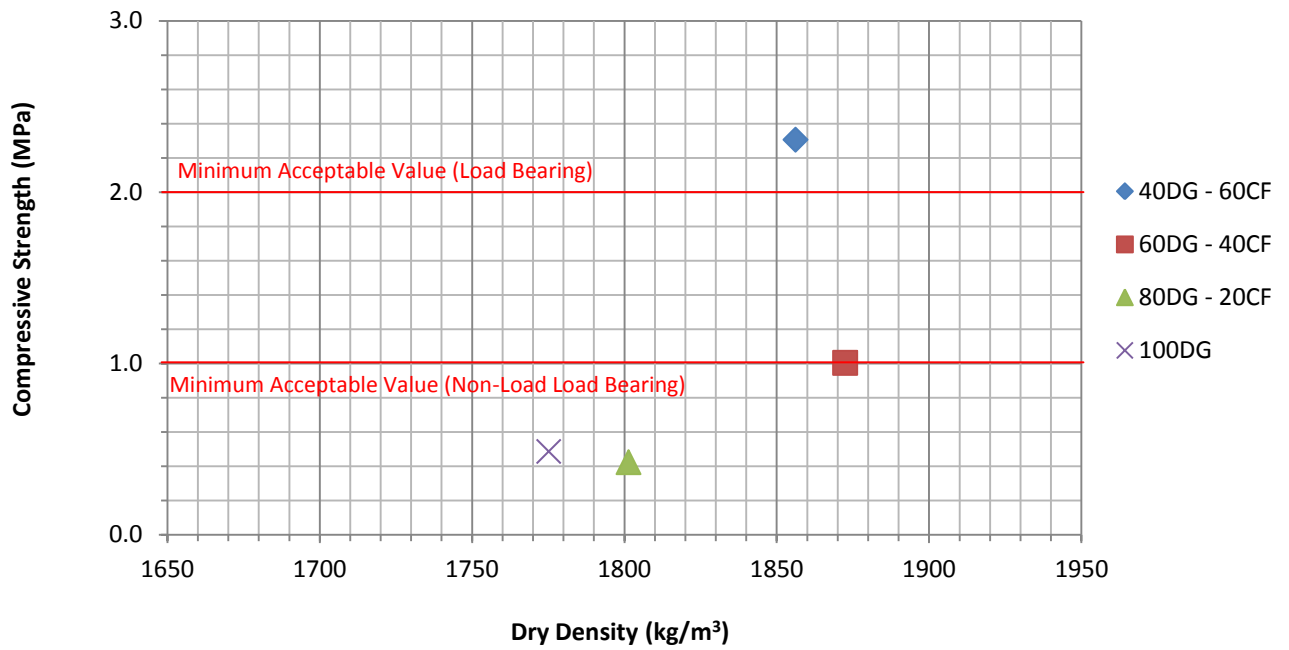


Figure 4.30: Relationship between Wet Compressive Strength and Dry Density at 56 days – 6% Cement

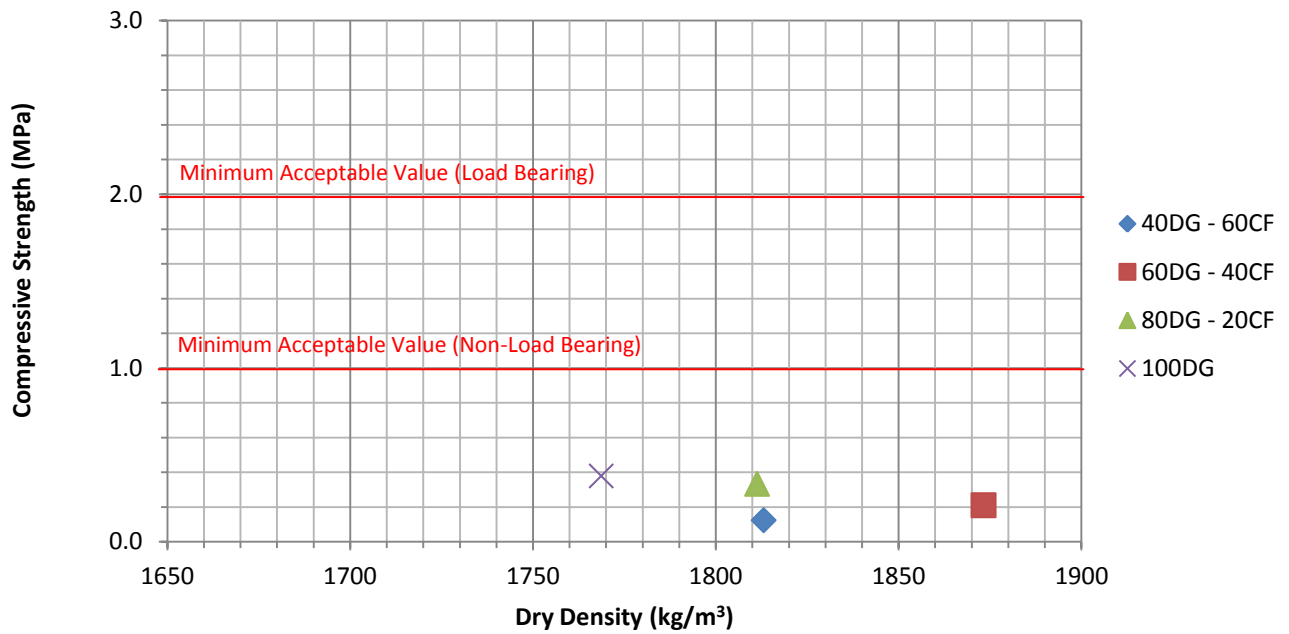


Figure 4.31: Relationship between Wet Compressive Strength and Dry Density at 56 days – 3% Lime

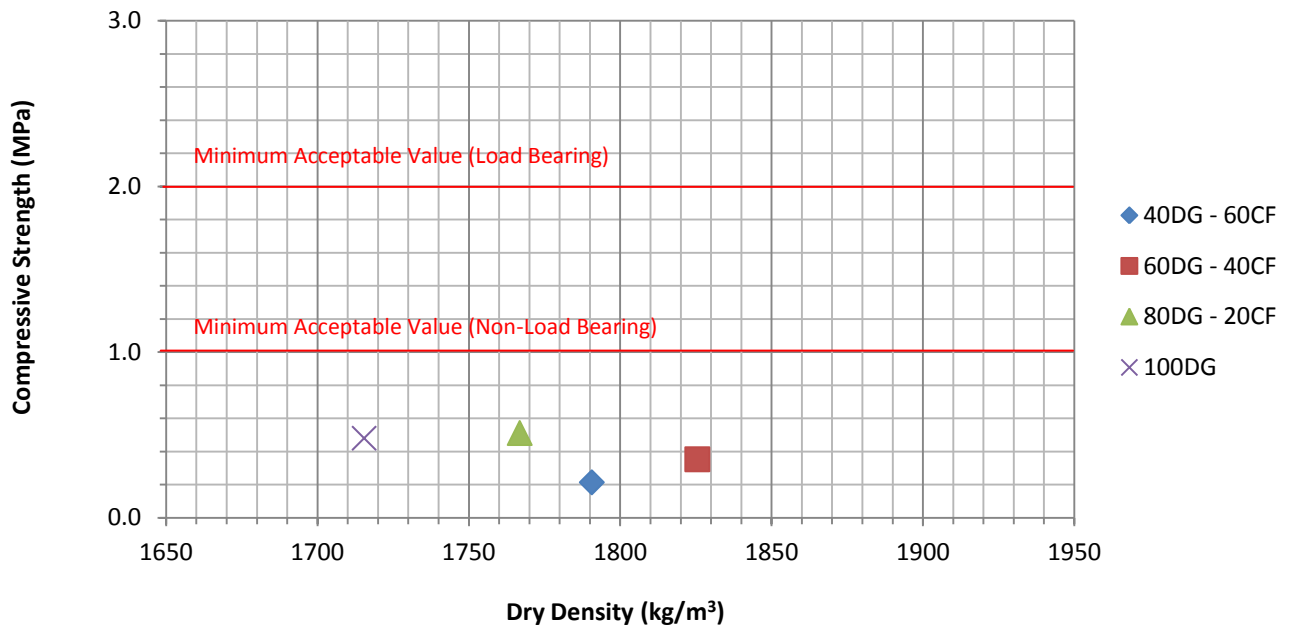


Figure 4.32: Relationship between Wet Compressive Strength and Dry Density at 56 days – 6% Lime

4.4.2. Drying Shrinkage (Linear)

Drying shrinkage for all blends was measured as a percentage according to the described methodology in Chapter 3. Figure 4.33 shows an overall summary for drying shrinkage after 28 days of drying following curing (i.e. by measuring at days following curing, as relevant). Figures 4.34 – 4.38 show shrinkage developments over time. According to Walker *et al.* (2005), the limiting value or typical minimum performance specification for loadbearing and non-loadbearing applications is a shrinkage value of 0.5% and 1% respectively. See (B.5) for variability of these results. The trend observed for all soil combinations was higher shrinkage with increasing clay content which was expected. The 100 DG soil combination recorded the highest shrinkage of all blends as there was more moisture absorbed by the higher clay content during compaction. This suggested that during drying, there was a higher loss of moisture which led to higher drying shrinkage results.

As the clay minerals underwent shrinkage with the gradual loss of moisture, the unstabilised specimens naturally recorded the highest shrinkage readings of all treatment types. This was because the clay particles were not bound into a strong soil - binder matrix and none of the unstabilised soil blends could therefore be used for loadbearing applications. However, the high shrinkage readings for the unstabilised specimens were useful for determining and comparing the effect of cement and lime on limiting drying shrinkage.

Results showed that cement, overall, was the most effective stabiliser at reducing drying shrinkage. Primary and secondary cementitious reactions created a stable soil cement matrix

which 'locked' the clay minerals and limited their shrinkage. It was observed that there was a large difference between 3% cement (Figure 4.35) and 6% cement (Figure 4.36) stabilisation results with the latter recording significantly lower shrinkages.

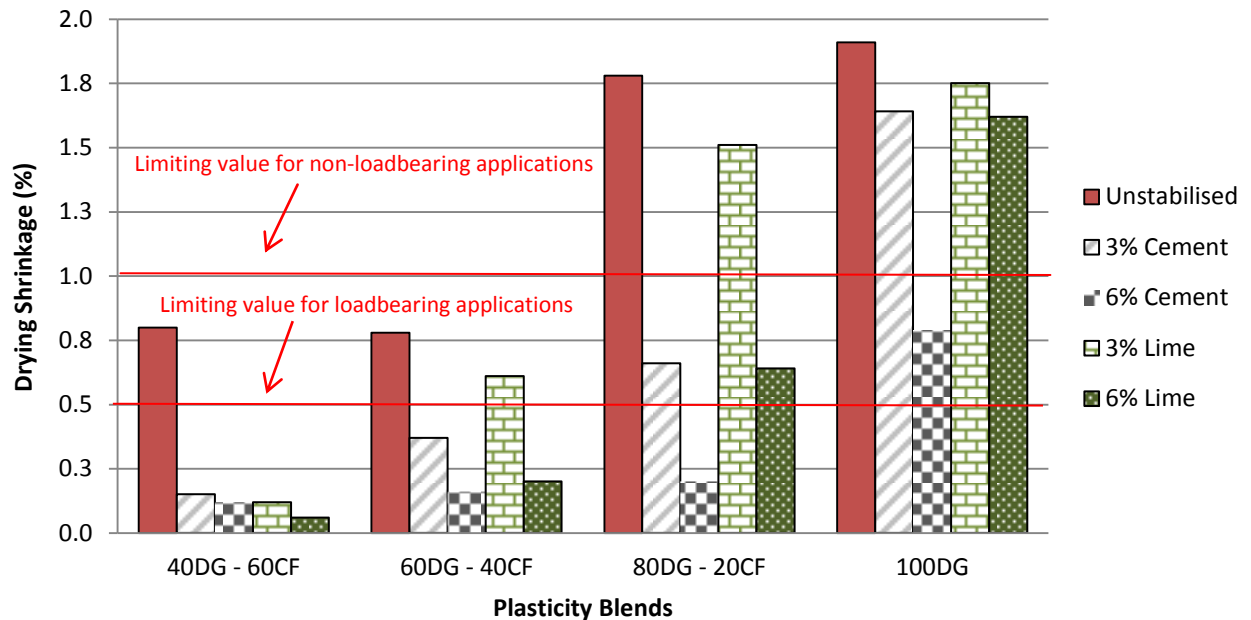


Figure 4.33: Relationship between Drying Shrinkage and Time (after 28 days of drying allowing curing)

Lime stabilisation, although not as effective as cement stabilisation was still useful for lower plasticity blends. As opposed to cement stabilisation, results suggested that the lime reacted with clay particles to form cementitious products with time and formed a matrix that contributed to limiting drying shrinkage. There was a significant difference between 3% lime (Figure 4.37) and 6% lime (Figure 4.38) results although it appeared that such a limiting effect did not occur with a soil of high clay content (100DG) which implied that the clay particle content was too excessive for the amount of lime that can limit drying shrinkage. Therefore, both combinations would exhibit shrinkage behaviours close to that of unstabilised specimens as shown (Figure 4.34). It was also interesting to note that the results for all blends stabilised with 3% cement were similar to all blends stabilised with 6% lime. This suggested that lime was not as effective as cement as a stabiliser for limiting drying shrinkage. However, considering the 40DG – 60CF blend it was observed that lime was slightly more effective at limiting shrinkage for soils of low clay content.

From the literature review, water-related weathering and mechanical abrasion of surfaces are the primary agents of decay in Rammed Earth buildings. Rainfall causes damage through kinematic impact at the surface, washing out of fines and the cyclic swelling and shrinkage of the clay fraction over time. The plasticity in walls will be more effective in preventing cracks

when clay minerals shrink at a lower rate. This is why it was important to also determine the rate of shrinkage. The rate in this case was described as the time it takes for the specimens to record constant shrinkage readings. It was observed, with the exception of the 100DG blend, that specimens exhibited the most drying shrinkage within the first 7 days, especially after day 1 and reached equilibrium within 14 days after manufacture.

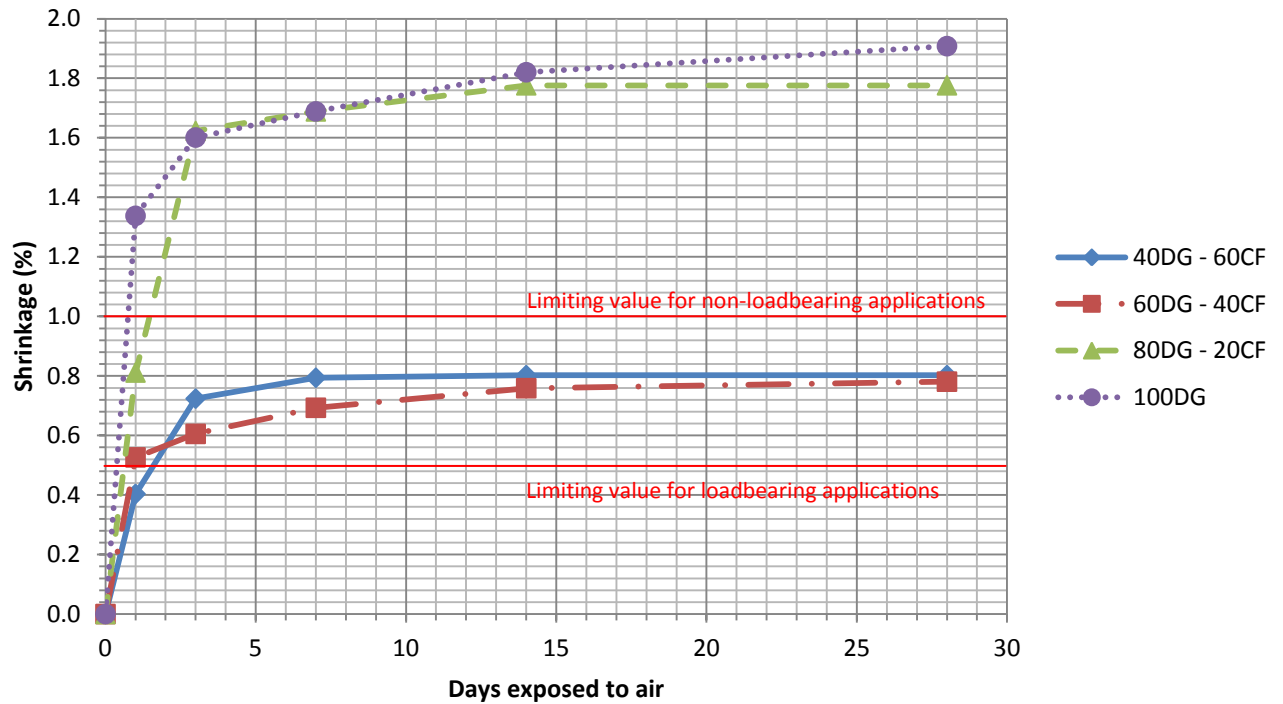


Figure 4.34: Relationship between Drying Shrinkage and Time – Unstabilised

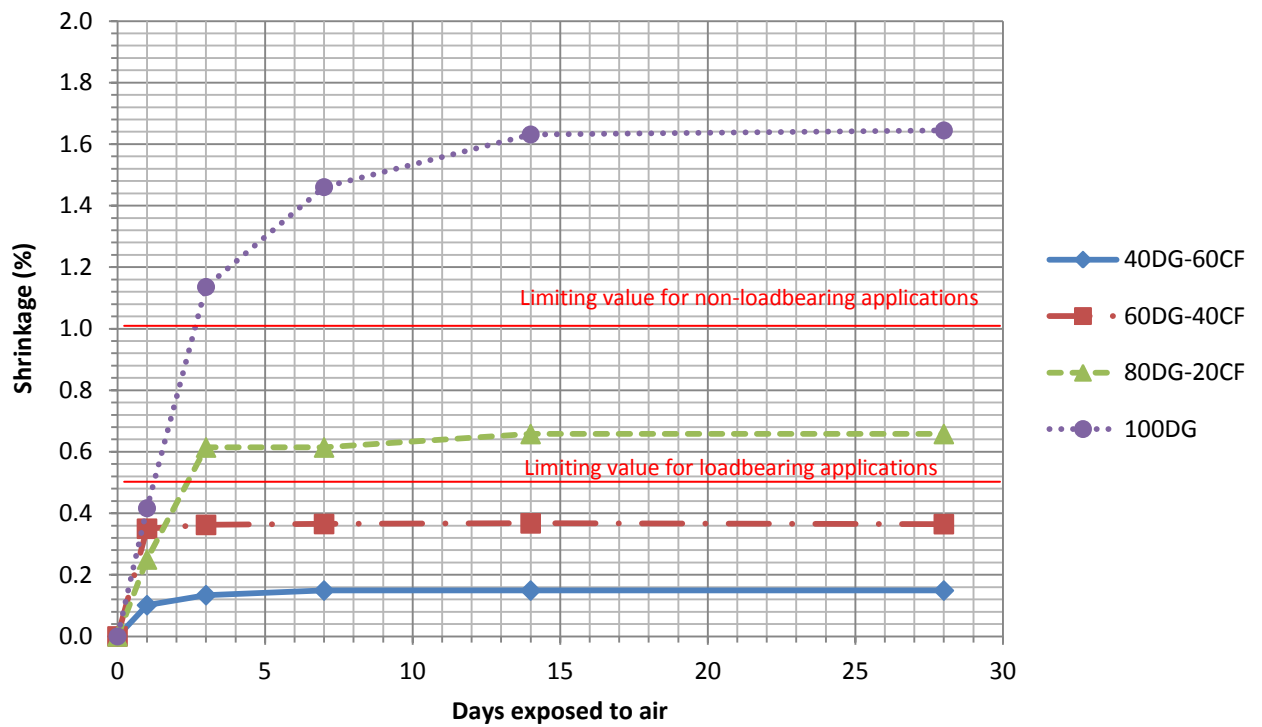


Figure 4.35: Relationship between Drying Shrinkage and Time - 3% Cement

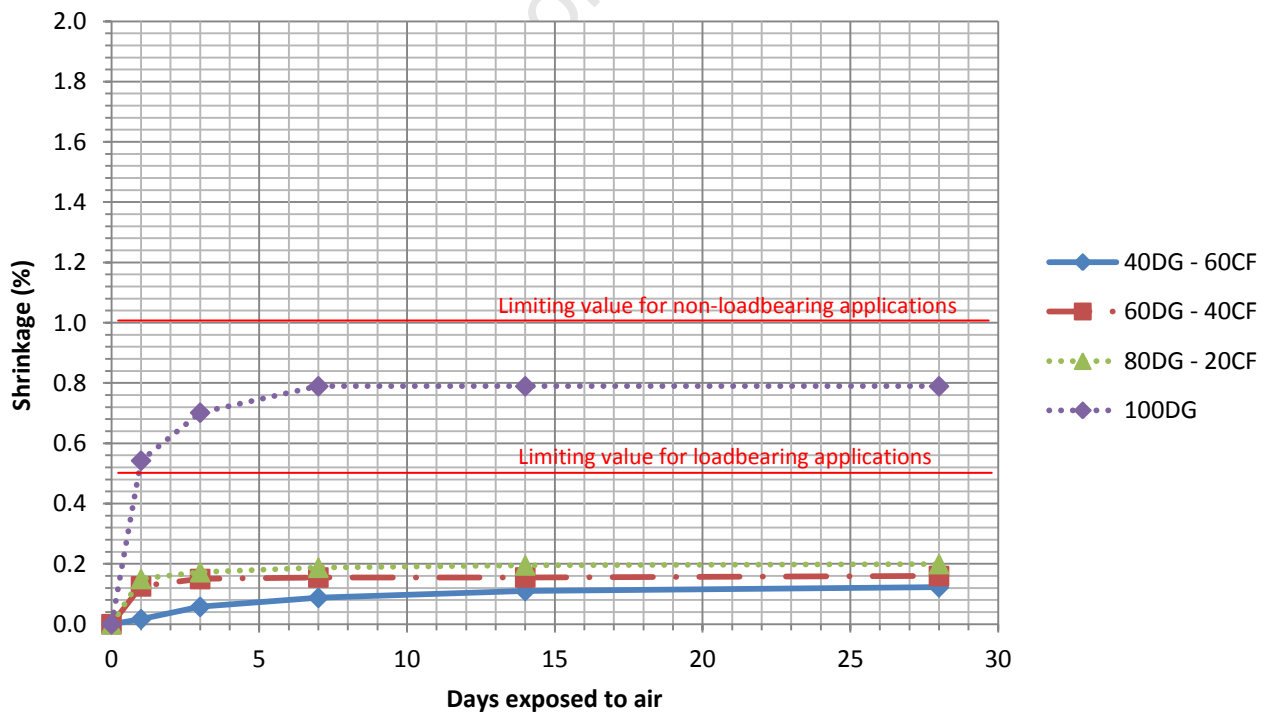


Figure 4.36: Relationship between Drying Shrinkage and Time - 6% Cement

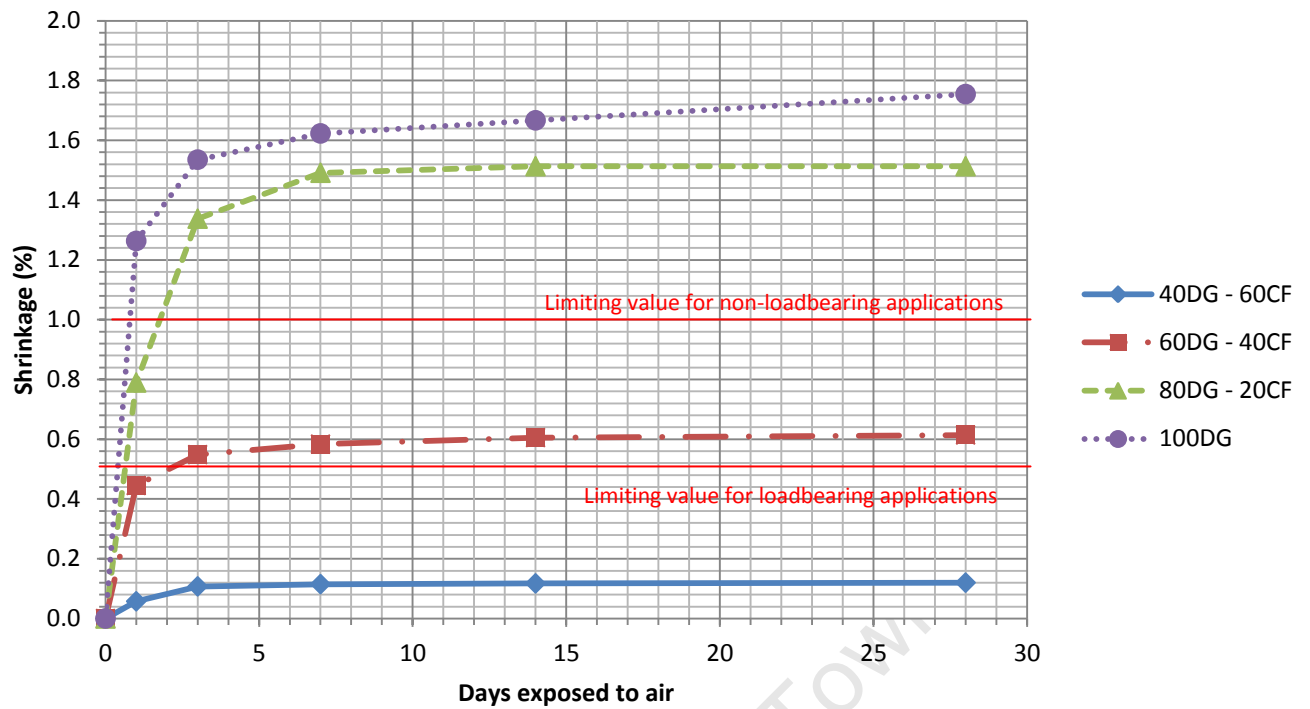


Figure 4.37: Relationship between Drying Shrinkage and Time - 3% Lime

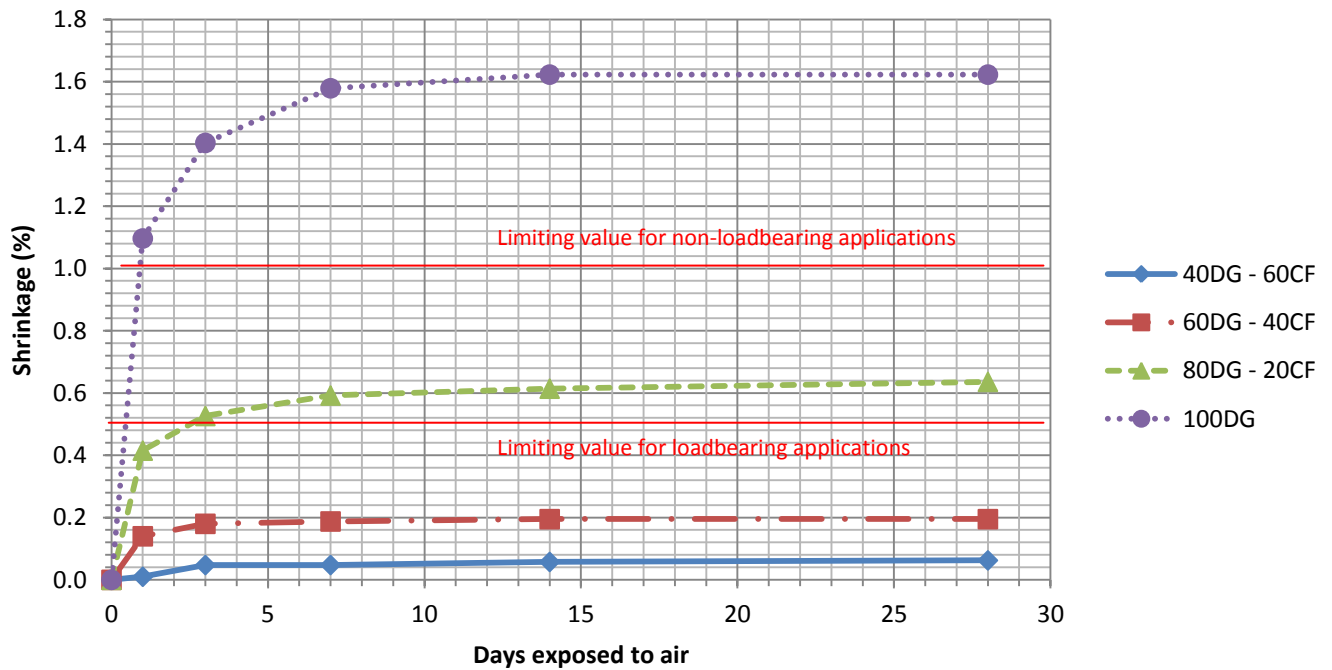


Figure 4.38: Relationship between Drying Shrinkage and Time - 6% Lime

Due to the fact that moisture loss exhibits a significant role in drying shrinkage, it was important to investigate for the relationship between the two. As discussed earlier, results for drying shrinkage were taken at 1, 3, 7, 14 and 28 days from when specimens were exposed to air. Correlating moisture loss results were calculated from recorded masses. The ordinate and abscissa axis of figures 4.39 – 4.43 were kept constant to facilitate comparisons.

Results (figures 4.39 – 4.43) showed that in general, all blends lost between 2 - 4% moisture within 1 day and was when the highest drying shrinkages took place. Similarly, most specimens had lost a further 8 – 12% moisture by day 3 and the majority of drying shrinkage had taken place. In comparison, little moisture was lost from day 7 onwards but unstabilised specimens and 3% stabilised specimens of higher clay content continued to exhibit drying shrinkage. These results suggested that drying shrinkage was dependant on moisture loss, especially within the first 3 days. It was observed that drying shrinkage was also dependant on clay content and stabiliser type & content with 6% cement being the most effective stabiliser at reducing moisture loss and drying shrinkage within the first 3 days for lower plasticity blends.

The rate of moisture loss for the unstabilised & lime specimens was similar, according to results (Figure 4.39 – 4.43). Moisture loss in cement stabilised specimens was less rapid and is clearly seen in lower plasticity blends for 6% cement stabilisation. A possible explanation was that because there was sufficient time (28 days of hydration reactions before the removal of sealed curing) for hydration reactions to bind soil particles into an insoluble, relatively impermeable matrix. Therefore, the moisture was trapped in between soil particles and the drying effect was retarded. This effect is investigated in more detail later under “Rate of Drying”

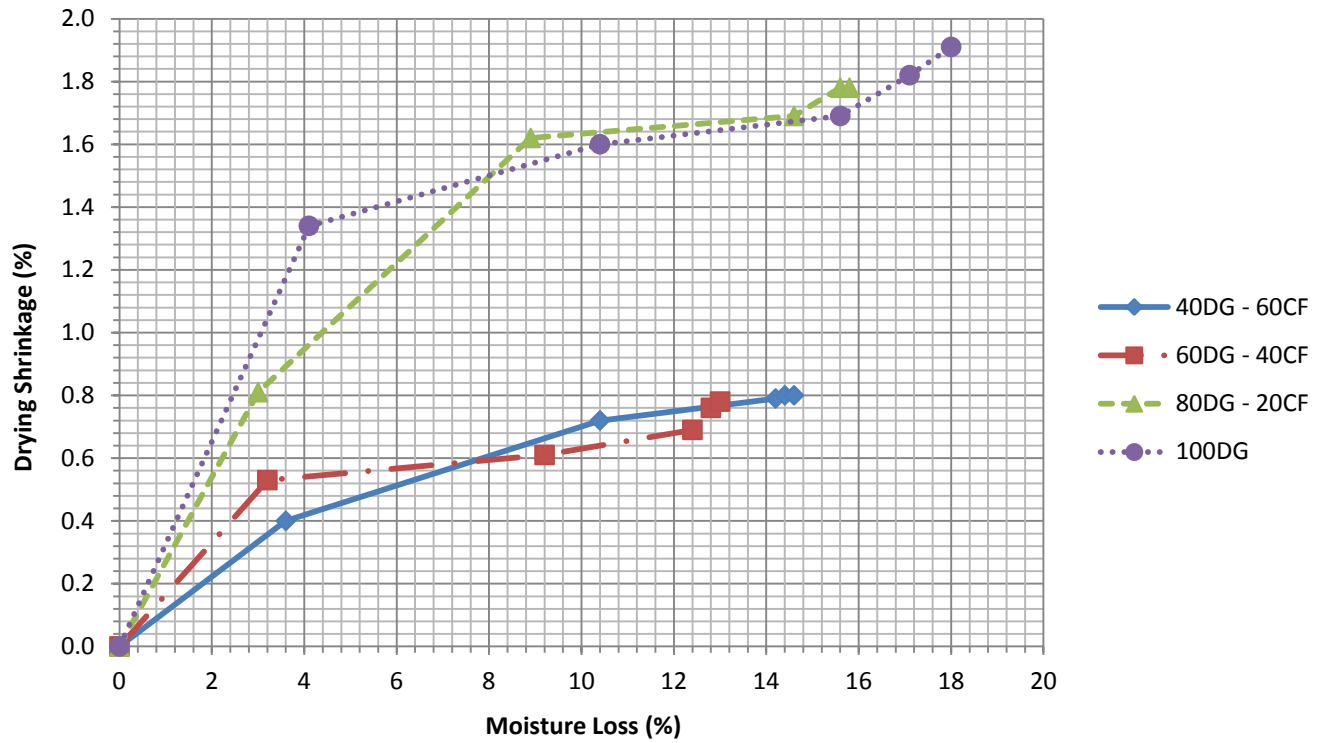


Figure 4.39: Relationship between Moisture Loss & Drying Shrinkage – Unstabilised

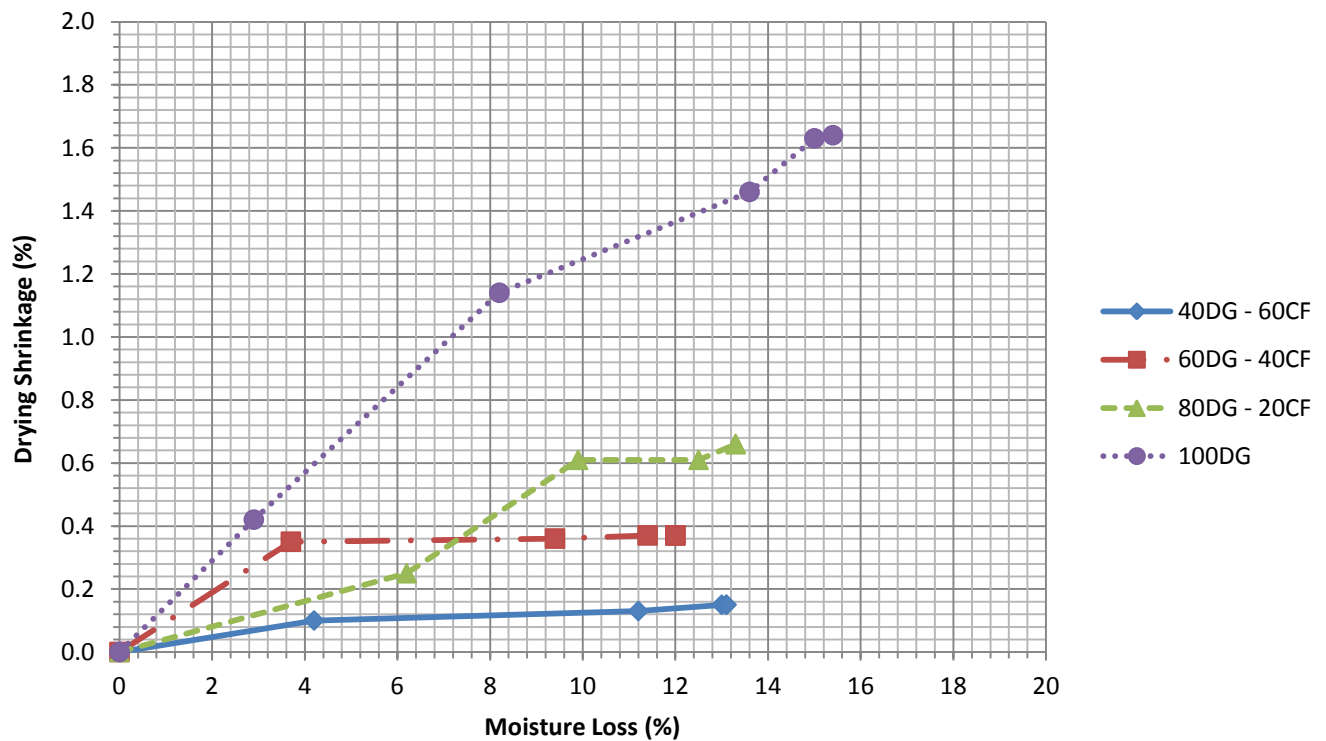


Figure 4.40: Relationship between Moisture Loss & Drying Shrinkage – 3% Cement

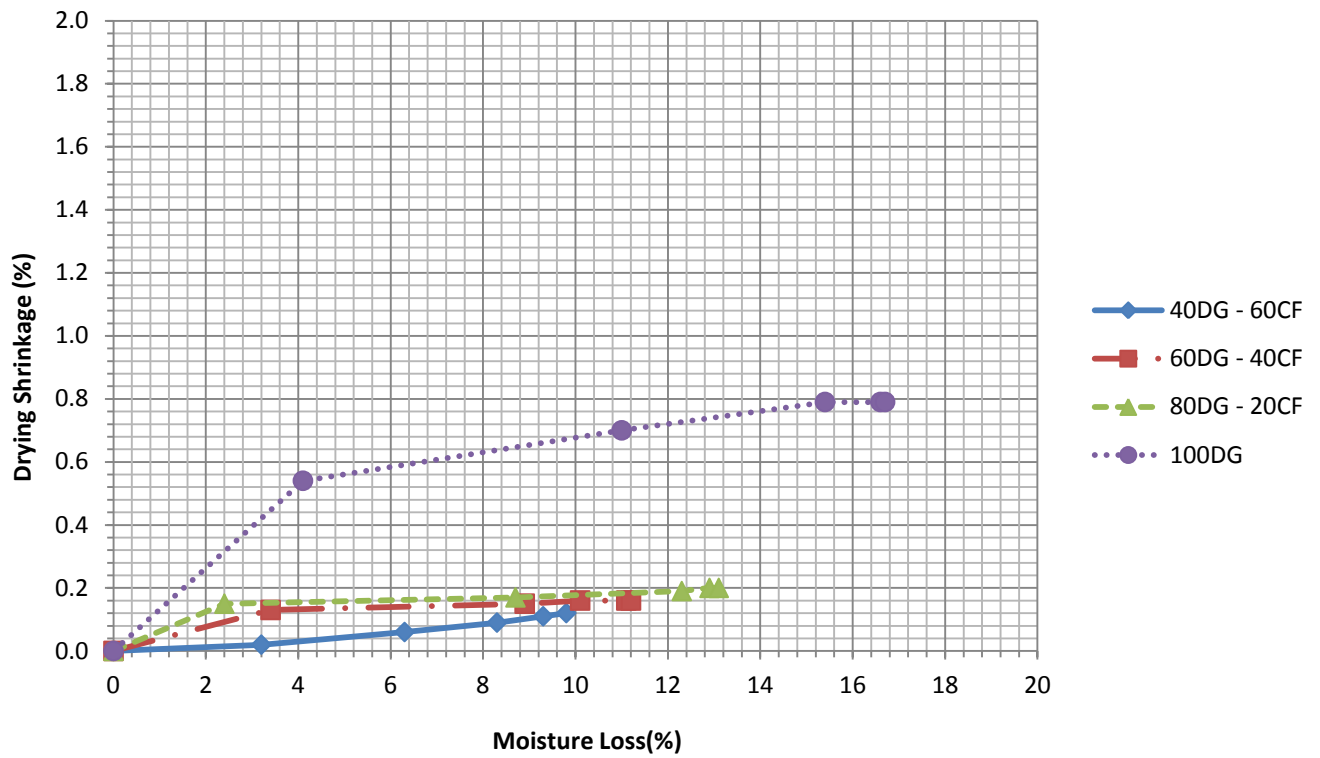


Figure 4.41: Relationship between Moisture Loss & Drying Shrinkage – 6% Cement

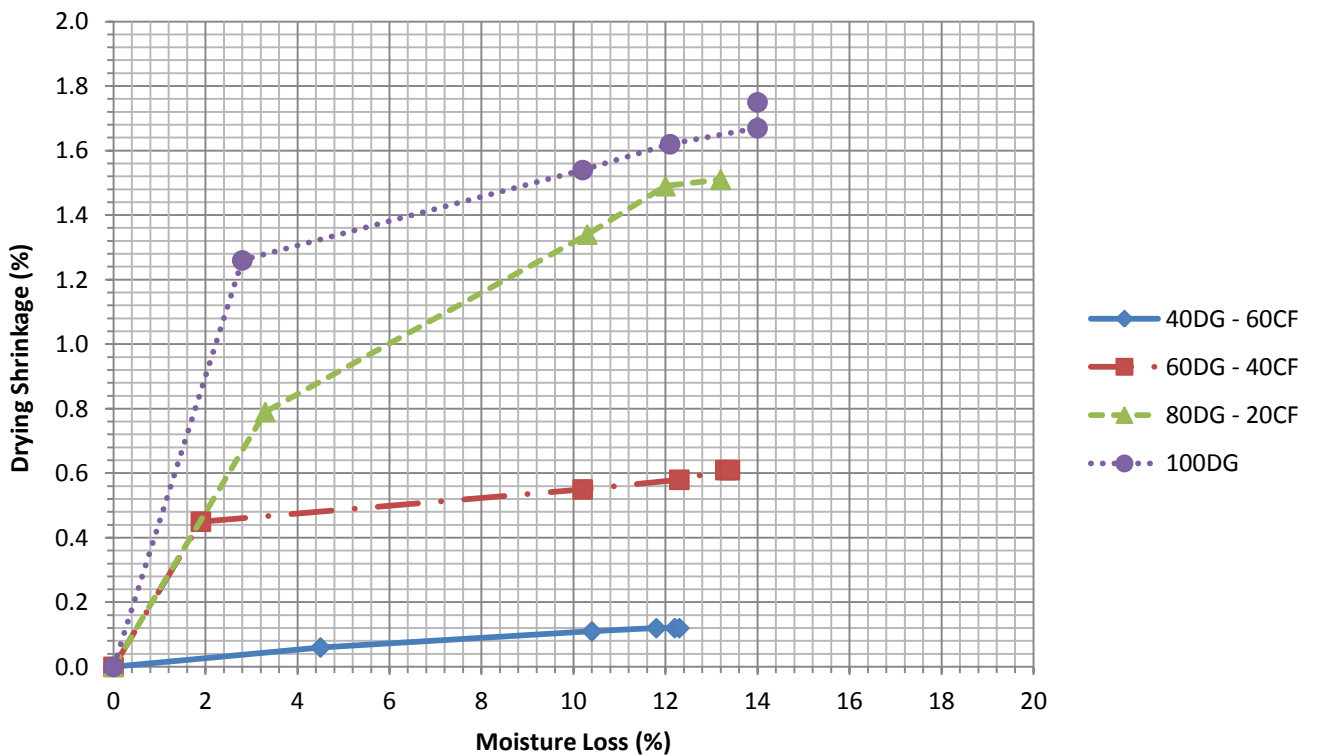


Figure 4.42: Relationship between Moisture Loss & Drying Shrinkage – 3% Lime

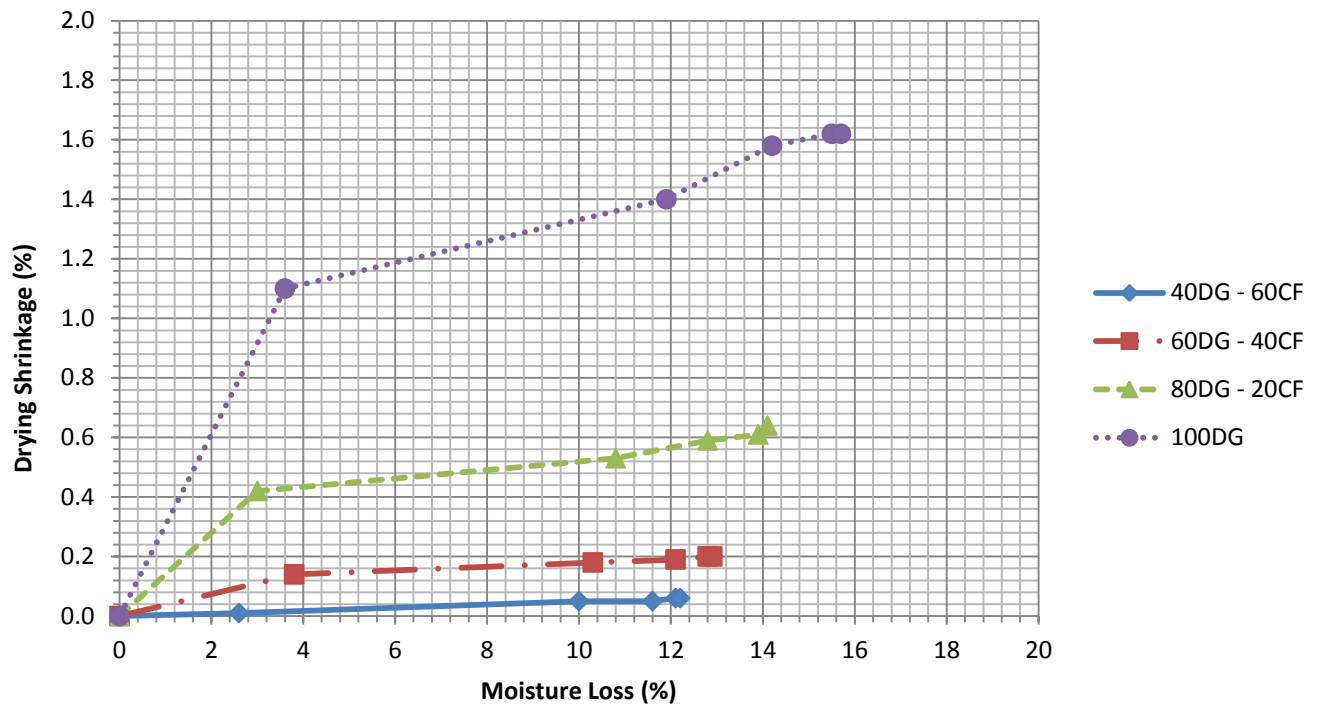


Figure 4.43: Relationship between Moisture Loss & Drying Shrinkage – 6% Lime

4.4.3. Rate of Drying

Rate of drying was measured according to the methodology described by recording the mass loss at 1, 3, 7, 14 and 28 days. The same specimens that were used for drying shrinkage were also used for rate of drying measurements.

The trend observed from Figures 4.44 – 4.48 was a higher loss of mass, in the form of moisture, for blends with higher clay content for all soil combinations. This was expected as a higher percentage of clay minerals present in the specimen resulted in higher Optimum Moisture Content (OMC) during mixing. According to literature, moisture loss was directly related to drying shrinkage due to the contraction / shrinking of clay minerals and thus blends with low moisture loss improved Rammed Earth durability.

As discussed earlier, all blended specimens (on average) reached similar moisture contents after 28 days of drying. The results on the following graphs confirmed the similar moisture loss. However, it was noted that the 6% cement stabilised specimens (Figure 4.46) retained more moisture for the lower plasticity blends over time. This could be a result of a combination of two effects. Firstly, the lower plasticity blends contained less clay, absorbed less moisture to reach OMC during manufacture and thus lost less mass in the form of moisture during drying. (Note that this was not to be confused with the fact that specimens of all combinations would

dry to constant mass at similar moisture contents. Secondly, the results demonstrated that 6% cement proved the optimum binder type and quantity to produce strong interlocking forces between soil particles and insoluble hydration products to retain moisture for soils low in clay content. 6% cement stabilised specimens high in clay content recorded lower strength results which suggested that the extra moisture had a detrimental effect on the bonding between clay particles. Lime proved to be less effective than cement at retaining moisture.

The rate of moisture loss between all blends and combinations was similar but as time proceeded it was noted that the range between the various blends for cement stabiliser was greater than for the lime and unstabilised specimens. This indicated that immediately after curing (beginning of drying) and before the carbonation reaction occurred between the lime and the CO_2 in the air, the moisture in the specimens was lost at a rate independent of the presence of lime. However, it was noted from results that for cement stabilised specimens, the rate of moisture loss was dependent on the cement due to the hydration reaction acting earlier. This demonstrated that lime virtually had no effect on moisture retention as carbonation reactions are slow and unlikely to progress far by the end of the 7-14 day period. This suggested that cement was more effective than lime in reducing moisture loss primarily because of more rapid hydration reactions.

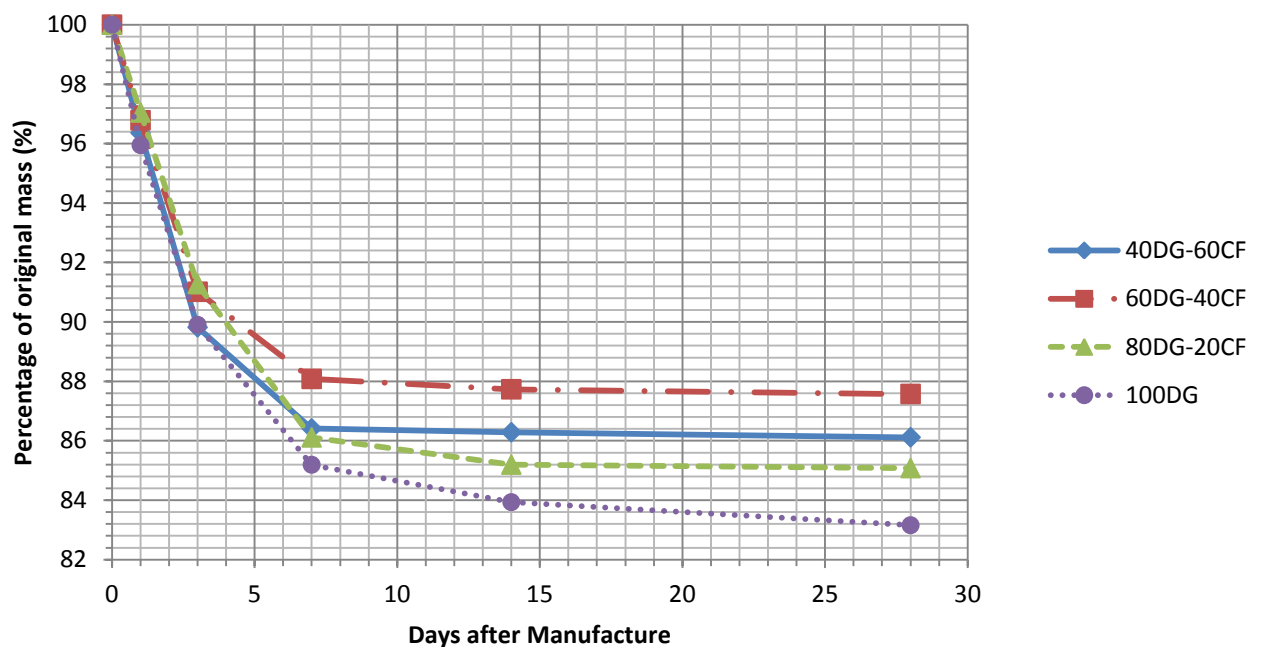


Figure 4.44: Relationship between Percentage of Original Mass and Time - Unstabilised

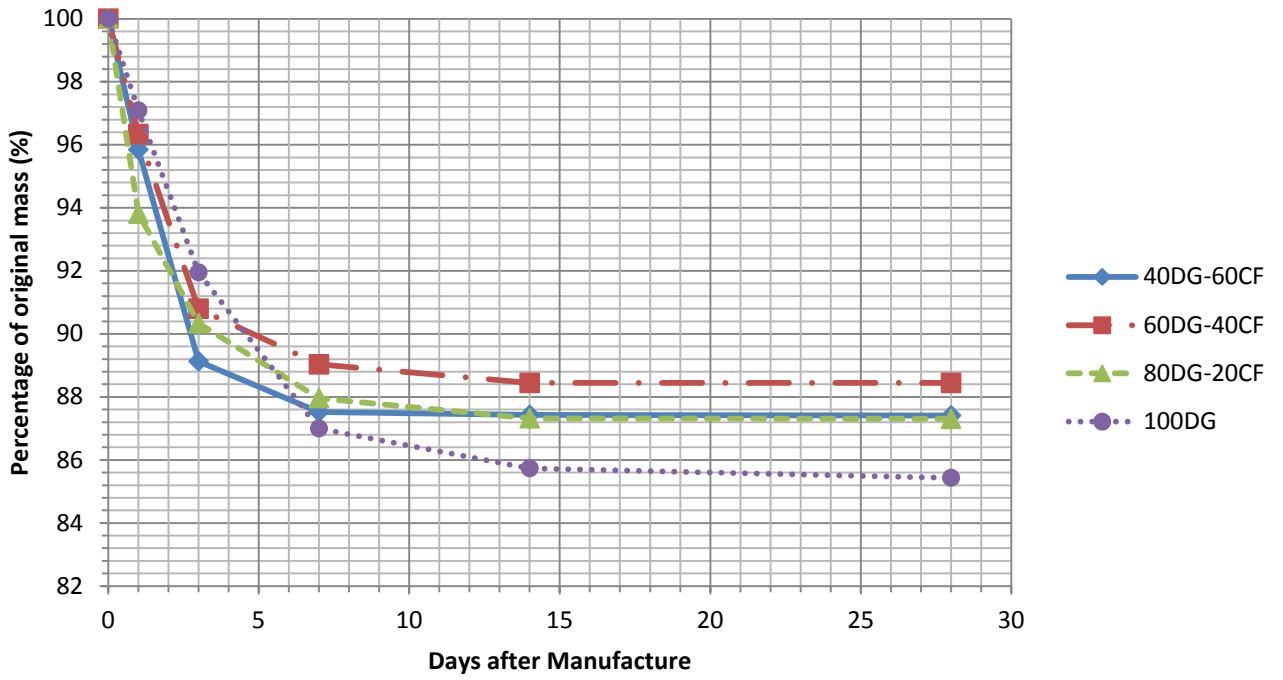


Figure 4.45: Relationship between Percentage of Original Mass and Time - 3% Cement

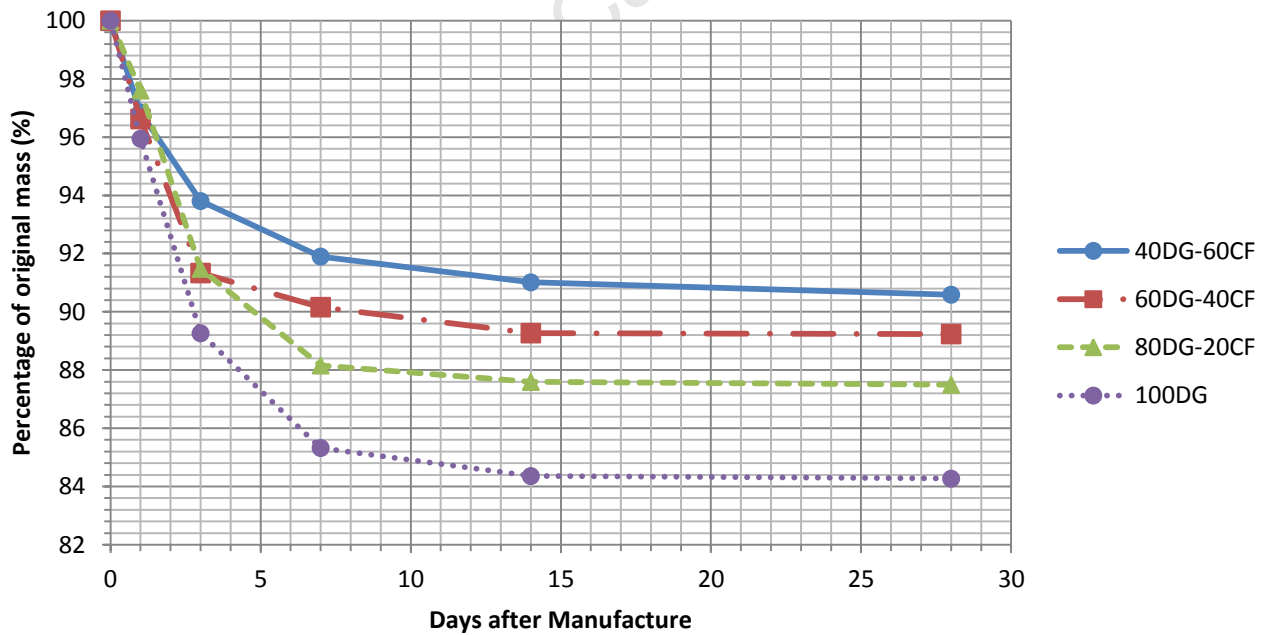


Figure 4.46: Relationship between Percentage of Original Mass and Time - 6% Cement

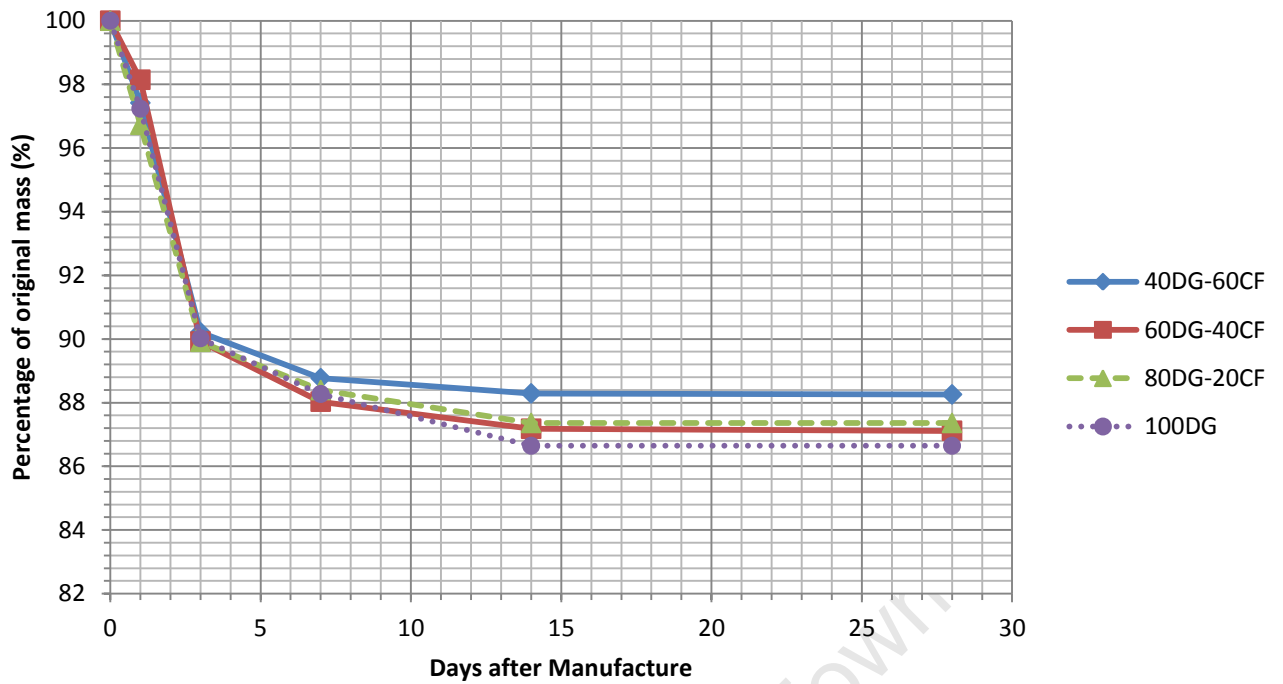


Figure 4.47: Relationship between Percentage of Original Mass and Time - 3% Lime

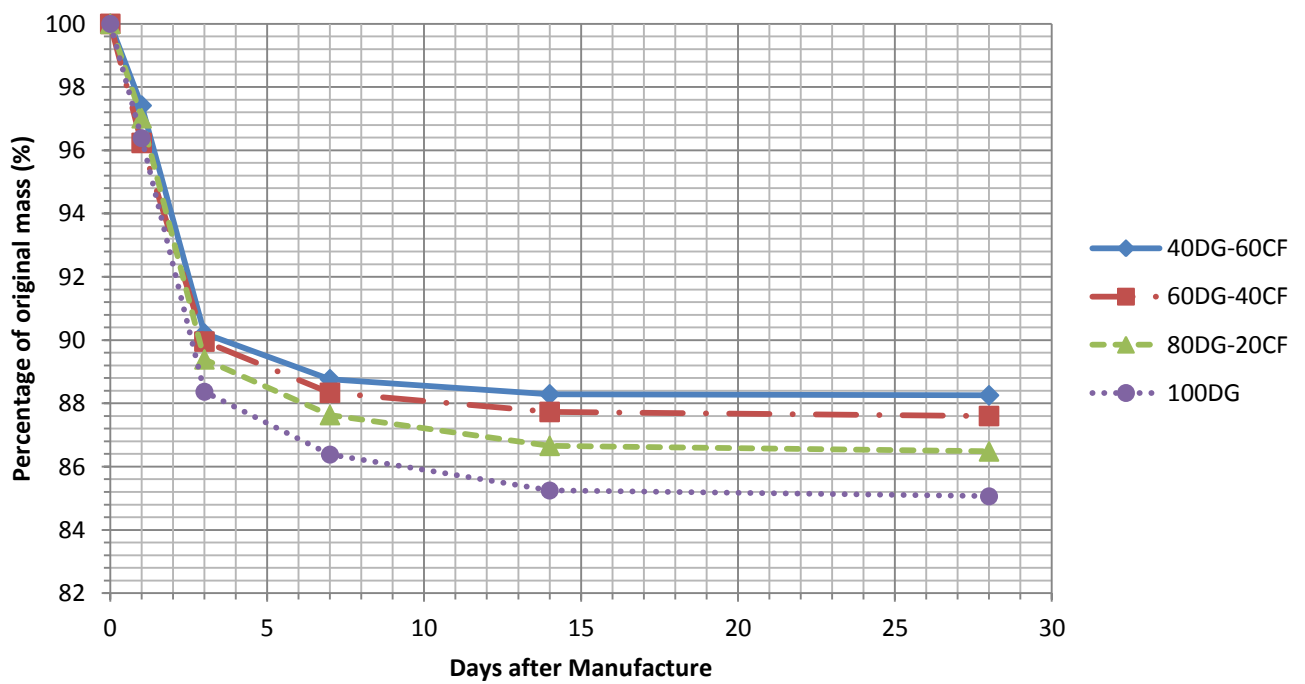


Figure 4.48: Relationship between Percentage of Original Mass and Time - 6% Lime

4.4.4. Moisture Absorption by Immersion

Moisture absorption was measured according to the methodology described in Chapter 3, by testing cylindrical specimens where the increase in mass of oven-dried test specimens due to immersion in water for 24 hours, was determined and expressed as a percentage of the specimen's initial dry mass. See (B.5) for variability of these results. According to the literature review, water absorption is directly related to drying shrinkage as clay minerals swell and shrink under cyclic weather conditions which ultimately would lead to the failure of a Rammed Earth wall. Therefore, low moisture absorption readings indicated improved Rammed Earth durability.

As expected, the trend observed was a higher water absorption with increasing clay content due to the increase in clay minerals absorbing more moisture. It was determined from Figure 4.49 that stabilisers were more effective at limiting absorption when used in combination with lower plasticity blends, due to less clay present in the specimens to absorb moisture. Furthermore, the unstabilised specimens all disintegrated under water immersion and were omitted from the graph, which confirmed the fact that unstabilised Rammed Earth walls, unless protected, were not durable in the presence of water.

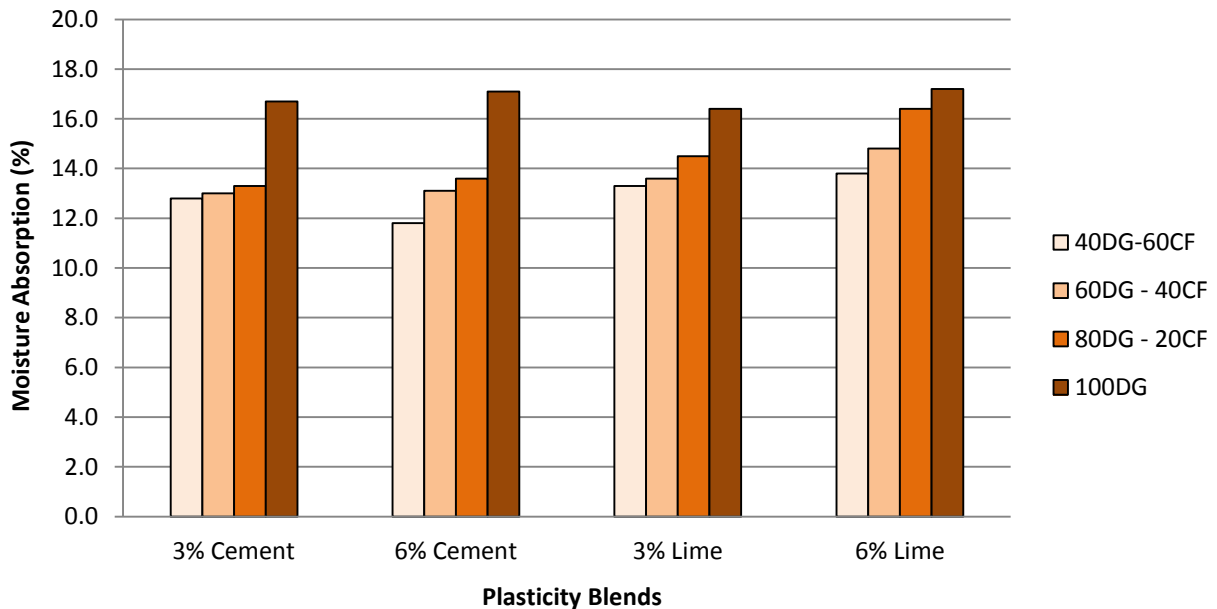


Figure 4.49: Moisture Absorption Results for all Blends and Stabiliser Combinations

Cement was more effective than lime at reducing water absorption due to stronger interlocking forces i.e. tighter packing of soil particles that prevent moisture ingress and filling of void space by cement hydration products. However, there was a point (100DG) where an increase in

clay minerals resulted in similar water absorption values. A possible explanation was the ‘insufficient’ stabiliser content to prevent absorption with the higher clay content present in the specimen.

4.5. Conclusion of Results

This Chapter indicated that the various soil combinations showed great variability in their performances. This section gives a list of conclusions based on the results discussed earlier in this Chapter for each engineering property.

4.5.1. Compressive Strength

From the investigations into the wet & dry compressive strength of Rammed Earth specimens made using the various soil combinations, the following conclusions were made:

- On the basis of literature and the observation, unstabilised specimens gained strength due to the gradual loss of moisture over time i.e. contraction of clay minerals within the specimen.
- Cement stabilised specimens gained strength as a result of chemical & mechanical bonding and the gradual loss of moisture over time. The chemical bonding occurred between the cement particles and was a hydration reaction. The products of the hydration bonded mechanically and cemented the particles in the soil increasing the overall strength of the specimen.
- Lime stabilised specimens gained strength as a result of hydrated lime reacting (pozzolanic reactions) with clay particles transforming them into a matrix.
- All unstabilised specimens disintegrated when immersed in water as the water dispersed the clay minerals and resulted in a weakening of the specimens
- 3% stabiliser content for the various blends was too low to have a significant effect on the compressive strength of all soil combinations. Results suggested that strength in these cases remained primarily associated with the bond between clay particles. However, it was observed that 3% stabiliser was sufficient to prevent disintegration when immersed in water.
- 6% cement stabiliser content for the various blends was sufficient to result in higher compressive strengths for lower plasticity specimens only. This suggested that the clay minerals were retarding hydration reactions in higher plasticity blends.

- Conversely, 6% lime stabiliser content for the various blends was sufficient to result in higher compressive strengths for higher plasticity blends only. This suggested that the higher clay mineral content was promoting pozzolanic reactions within the specimens.
- Unstabilised & lime stabilised specimens took a maximum of 14 days to dry to similar equilibrium moisture content when exposed to drying. The loss of moisture over time for cement stabilised specimens was lower which suggested that there was sufficient time before the removal of sealed curing for hydration reactions to bind soil particles into a water-stable, relatively impermeable matrix. This implied that the moisture was trapped in between soil particles and the drying effect was retarded. This directly correlated with the compressive strength of 6% cement stabilised specimens which showed an increase in strength with gradual loss of moisture over time after hydration reactions had occurred which implied that strength was gained due to the gradual loss of moisture over time.
- The compressive strength of 6% lime stabilised specimens increased gradually over the 51 day drying period even though the specimens had reached equilibrium moisture content within 14 days after curing had been removed. This suggested that 6% lime stabilised specimens achieved their final strength typically 2-3 times longer than the 28 day curing period required for cement stabilised specimens. The same principle applied to the time required for pozzolanic reactions to occur to prevent separation of clay particles (disintegration) during water immersion.
- Specimens recorded higher dry densities than corresponding Proctor test results due to the higher compactive effort employed during manufacture. There was a range of 160 kg/m³ between the maximum dry densities of the various soil combinations. This related with the literature which stated that the dry density of soil in Rammed Earth is dependent on soil type, the moisture content during compaction and the compactive effort.
- Results showed 6% lime stabilised specimens with higher compressive strengths (higher plasticity blends) to have lower dry densities. Conversely, results showed 6% cement stabilised specimens with higher compressive strengths (lower plasticity blends) to have higher dry densities. This contradicted the literature which stated that a higher dry density would ultimately lead to a higher compressive strength suggesting that the compressive strength could be contributed by the strength of bonds between particles as opposed to closer packed particles.

- The higher dry densities for cement stabilised specimens with lower clay content was thought to be due to the addition of cementitious products during hydration. As discussed earlier, clay was a possible retardant to hydration reactions and thus fewer cementitious productions could be present in blends higher in clay content. Conversely, it seemed that pozzolanic reactions acting directly with clay particles for blends with higher clay content contributed to a lower dry density. More research would be required on this effect.
- Unexpectedly, the only soil combination to pass the minimum acceptable value for load-bearing applications according to Walker *et al.* (2005) for both wet & dry unconfined compressive strength in Rammed Earth was the 6% cement stabilised 40DG – 60CF blend. The wet & dry compressive strengths were 4.4 and 2.3 MPa respectively. It was initially expected that soil blends higher in clay content would exhibit the highest compressive strengths, much like the behavior of lime stabilised specimens.

4.5.2. *Drying Shrinkage (Linear)*

From the investigations into the drying shrinkage of Rammed Earth specimens, the following conclusions were made:

- Higher clay content present in a specimen leads to higher drying shrinkage.
- Unstabilised specimens recorded the highest shrinkage because clay particles were not restrained by a strong soil - binder matrix.
- 6% Lime stabilised specimens recorded similar shrinkage results as the 3% cement stabilised specimens. There were more cement stabilised combinations that could be used for loadbearing applications (shrinkage results < 0.5%). This demonstrated that cement was more effective at limiting drying shrinkage than lime.
- Primary and secondary cementitious reactions created a strong soil cement matrix which ‘locked’ the clay minerals and limited the shrinking of clay minerals, hence drying shrinkage.
- Results suggested that lime, unlike cement, reacted with the clay particles to form cementitious products that crystallised with time and form a matrix that contributed to limiting drying shrinkage.
- Moisture loss in cement stabilised specimens was less rapid resulting in lower drying shrinkage.

4.5.3. Rate of Drying

From the investigations into the rate of drying of Rammed Earth specimens, the following conclusions were made:

- Higher clay content in specimens resulted in a higher rate of moisture loss due to the increased moisture content required to reach Optimum Moisture Content during mixing, unless stabilised with cement.
- Observations showed that drying shrinkage was dependant on moisture loss, especially during the first 3 days from exposure to air when the highest shrinkages were experienced.
- Drying shrinkage was also dependant clay content and stabiliser type & content with 6% cement being the most effective stabiliser at reducing moisture loss and drying shrinkage for lower plasticity blends. A possible explanation was the insoluble hydration products and soil particles producing strong interlocking forces between them, trapping moisture and thus retarding moisture loss. It was suggested that 6 % cement was less effective for higher plasticity blends due to the possible retarding effect clay had on hydration reactions.
- Lime appeared to be less effective than cement as a stabiliser at retaining moisture in Rammed Earth specimens. Specimens dried to constant mass after 7-14 days and during this time period the carbonation reactions would be minimal according to literature.

4.5.4. Moisture Absorption

From the investigations into the moisture absorption of Rammed Earth specimens, the following conclusions were made:

- From literature, clay minerals swell and shrink under cyclic weather conditions which ultimately would lead to the failure of a Rammed Earth wall. Therefore, blends with lower moisture absorption readings improved Rammed Earth durability.
- Unstabilised specimens disintegrated under water immersion which demonstrated that unstabilised Rammed Earth walls, unless protected, were not durable under in the presence of water.
- Cement was more effective than lime at reducing water absorption due to stronger interlocking forces i.e. tighter bonding of soil particles that prevented moisture ingress into the specimen. A possible explanation was the effectiveness of the insoluble cement

hydration products which proved cement to be more effective than lime at limiting water absorption.

- The stabiliser effect of limiting moisture absorption decreased for blends with increasing clay content.

University of Cape Town

5. Discussion

5.1. Introduction

This chapter provides an overall discussion of the relevant findings from Chapter 4. It draws together all the results from the experimental work, discusses them in a broad setting and draws essential insights and understanding about how the materials behaved and why. The findings are contextualised for use in practice and optimal soil combinations that give the most advantageous set of physical and mechanical engineering properties for load bearing & non-loadbearing applications are investigated. To conclude this chapter, a list of recommendations for further research & evaluations is presented.

5.2. Discussion

Results discussed in Chapter 4 were analysed to determine the optimal soil combination for the construction of Rammed Earth walls in the Cape Town metropolitan area. It was important to define a list of criteria, applicable to practice, for each engineering property so as to contextualise the findings and enable the selection of an optimum soil combination for the construction of Rammed Earth walls. The optimal soil combination selected had to give the most advantageous set of physical and mechanical engineering properties. Therefore, specimens manufactured from the optimal soil combination had to comprise of the following:

- A dry & wet compressive strength higher than the minimum acceptable value of 2 MPa for loadbearing applications and 1 MPa for non-loadbearing applications set by Walker *et al.* (2005).
- A drying shrinkage (linear) below the limiting value or typical minimum performance specification set by Walker *et al.* (2005) of 0.5% for loadbearing applications and 1% for non-loadbearing applications.
- Literature states that moisture absorption related to shrinkage and swelling of the material as clay minerals swell and shrink under cyclic weather conditions, can ultimately lead to the failure of a Rammed Earth wall. Therefore, moisture absorption had to be decreased as much as possible.
- The material used was to be workable for production optimisation. Excessive clay content made the material very difficult to work with due to the buildup of lumps

during mixing and sticking to compaction and mixing equipment which hindered production.

- The material must contain sufficient clay content to hold its own shape during manufacture and not deform when formwork is removed.

From the criteria listed above, it was possible to investigate the optimal soil combination for Rammed Earth construction. It was important that compressive strength was not the only factor to consider when designing Rammed Earth walls. The walls were expected to be more vulnerable to adverse conditions than concrete walls and so it was vital that they were also designed for durability. A summary of results (Figures 5.1 – 5.4) is used to select the optimal soil combination, and to discuss and contextualise the findings/conclusions in Chapter 4.

On the basis of literature and the observations, cement stabilised specimens gained strength as a result of chemical & mechanical bonding. The chemical bonding occurred between the cement particles due to a hydration reaction. The products of the hydration bonded mechanically and cemented the particles in the soil increasing the overall strength of the specimens. Lime stabilised specimens gained strength as a result of hydrated lime reacting (pozzolanic reactions) with clay particles transforming them into a matrix.

5.2.1 Construction with unstabilised Rammed Earth

Results (Figure 5.1) showed that the construction of unstabilised Rammed Earth walls was only suitable for non-loadbearing applications. Furthermore, Figure 5.2 showed that unstabilised material could only be employed on interior walls as protection from the environment (water) such as raised footings & eaves overhangs was required. Unstabilised Rammed Earth relied primarily on the bond between clay particles and the gradual loss of moisture (contraction of clay minerals) in terms of compressive strength. This meant that these walls would not be durable when exposed to water due to the detrimental swelling/shrinking properties of clay. As observed in the results (Figure 5.2), all unstabilised specimens including those left to dry for 56 days after manufacture, disintegrated when immersed in moisture for 24 hours and therefore did not record a strength value. When building unstabilised Rammed Earth walls for non-loadbearing applications it was important that a soil combination with the lowest clay content and acceptable (>1 MPa) compressive strength be selected. From results, it was observed that an increase in clay content increased the drying shrinkage (Figure 5.3). This was because a blend containing more clay minerals absorbed more moisture (Figure 5.4) and thus when left to

dry, the increased clay content would cause a wall to shrink more when compared to a wall built from a soil blend of lower plasticity. Therefore, an unstabilised 60DG – 40CF blend would be suitable for interior non-loadbearing applications only. Movement joints will be required to limit drying shrinkage cracking.

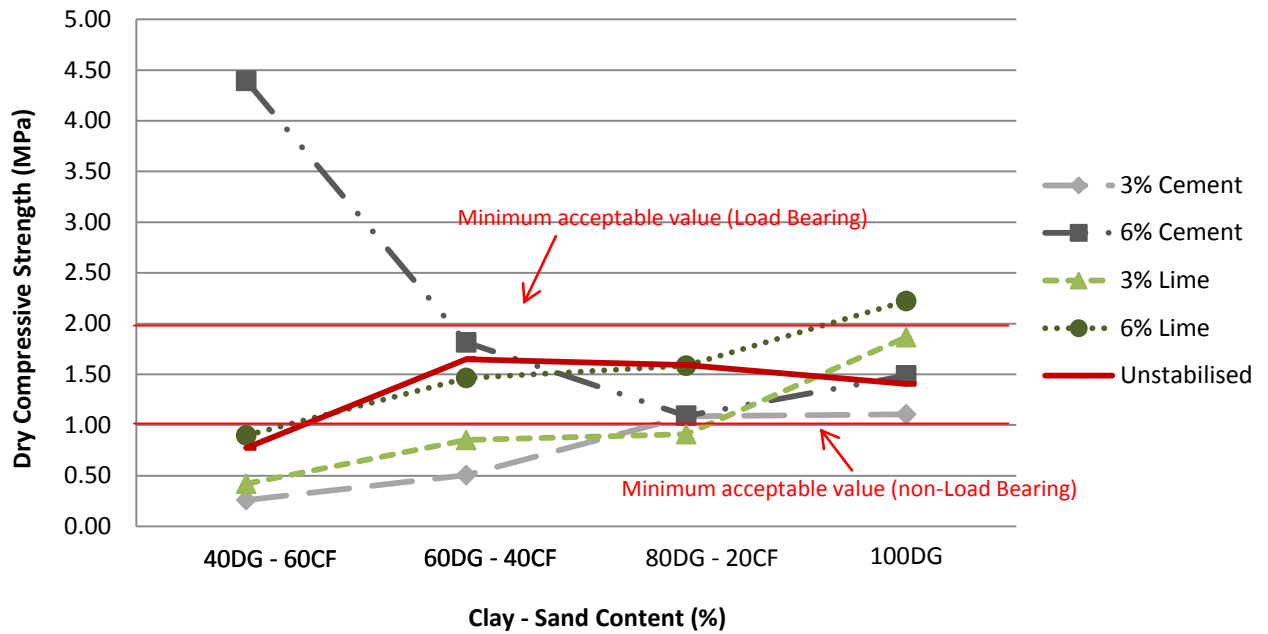


Figure 5.1: Dry Compressive Strength at 56 days after Manufacture for all Soil Combinations

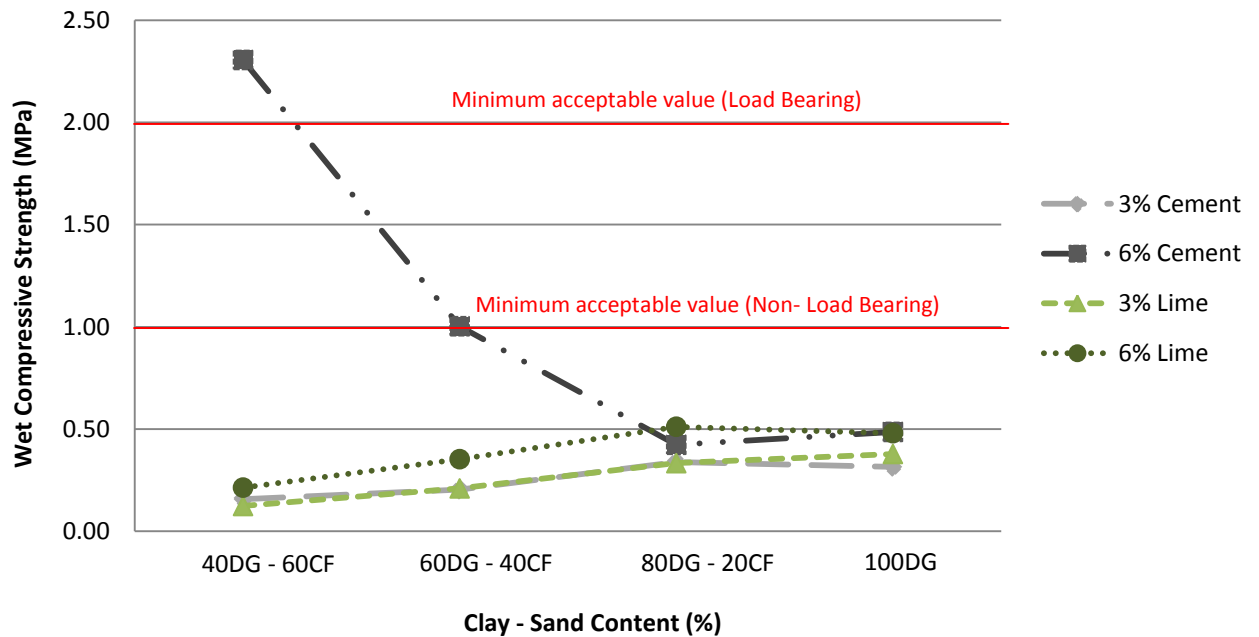


Figure 5.2: Wet Compressive Strengths at 56 days after Manufacture for all Soil Combinations

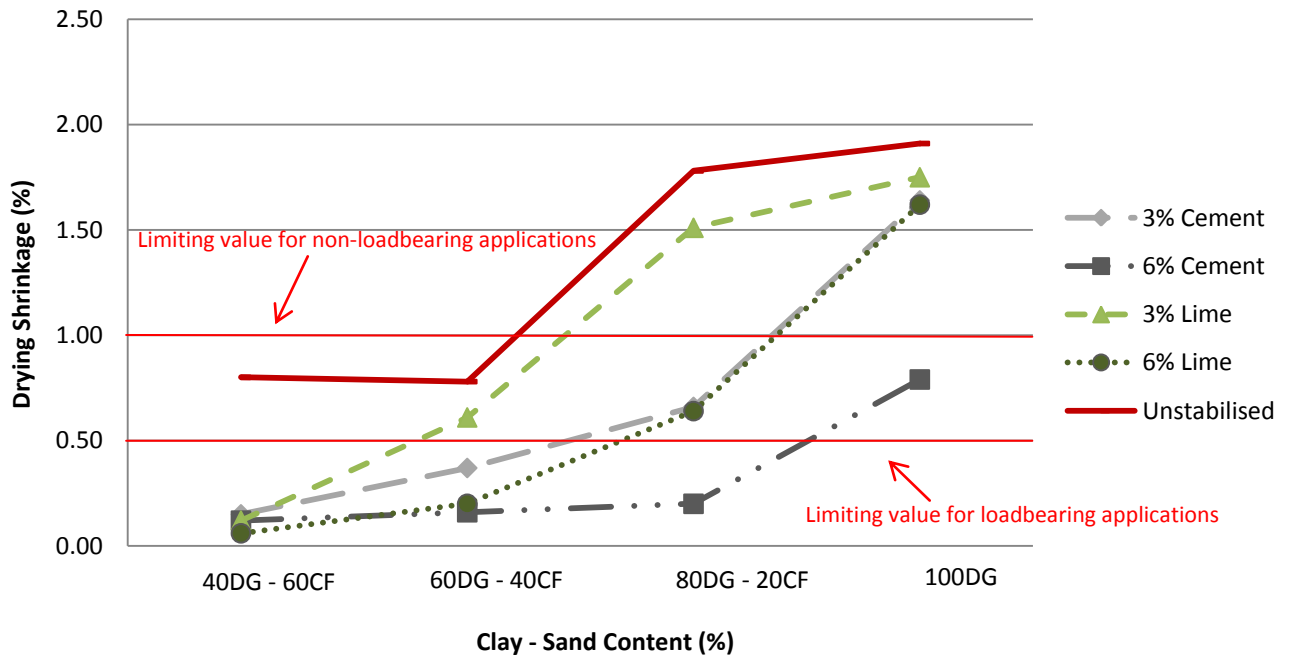


Figure 5.3: Final Drying Shrinkage for all Soil Combinations

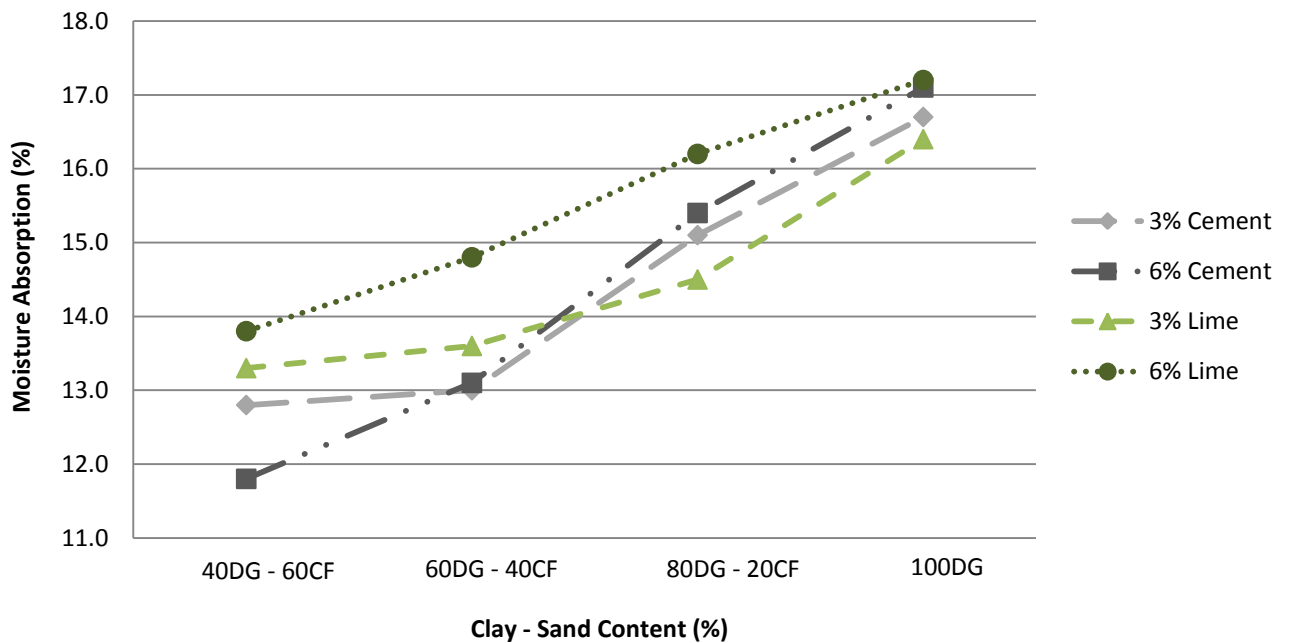


Figure 5.4: Moisture Absorption for all Soil Combinations

5.2.2 Construction with 3% Stabilised Rammed Earth

It was observed from results (Figures 5.1 & 5.2) that 3% stabiliser would be insufficient to have a significant effect on the compressive strength as results suggested that strength remained primarily associated with the bond between clay particles strength and according to results in some cases; it would yield weaker walls than unstabilised walls. This was not fully comprehended but a possible explanation was the combination of 'insufficient' 3% stabiliser content with the swelling/weakening of clay particles during sealed curing over time may have been the cause. Further research is recommended on this effect. However, it was observed that the cement stabilised specimens did not disintegrate during water immersion. All higher plasticity lime stabilised blends aged 7 days after manufacture and 14 days in some cases disintegrated. This demonstrated the difference between the more rapid hydration reactions of cement stabiliser and the less rapid pozzolanic reactions of lime stabiliser.

In the context of Rammed Earth wall construction, it was apparent that only interior non-loadbearing walls may be built using 3% stabiliser, much as was the case with unstabilised walls. The 'wet' compressive strength (Figure 5.2) for all these specimens was below 0.5 MPa which meant that no exterior walls could have been built according to the minimum acceptable value. However, there was an observed advantage of building with 3% stabiliser for its additional durability and longevity of Rammed Earth walls due to the additional water protection and limited drying shrinkage. This 'limited' drying shrinkage depended on the clay content of the blend selected as 3% stabiliser could only limit drying shrinkage to a certain extent with increasing clay content before exceeding the acceptable limit for non-load bearing applications of 1% (Figure 5.3). It was apparent that although lower plasticity blends provided low drying shrinkage, the compressive strength was lower than the acceptable value for non-loadbearing applications. Therefore, a 3% cement stabilised 80DG – 20CF blend was recommended as a suitable material for interior non loadbearing applications.

5.2.3 Construction with 6% Stabilised Rammed Earth

6% stabiliser content in the construction of Rammed Earth walls had a significant effect in terms of compressive strength and durability in the sense that a higher range of soil combinations were suitable for non-load bearing applications. It was noted from results (Figure 5.1) that 6% cement stabiliser content for the various blends was sufficient to result in higher compressive strengths for lower plasticity specimens which suggested that the increase of clay

minerals was retarding hydration reactions in higher plasticity blends. Conversely, 6% lime stabiliser content for the various blends was sufficient to result in higher compressive strengths for higher plasticity blends only which suggested that the increase of clay minerals was promoting pozzolanic reactions within the specimens.

Workability

When selecting a suitable soil combination it was important to take into account the clay content during manufacture as initially, it was the only binder available which would allow the wall to hold its own shape (prevent deformation) when formwork was removed. It was thus recommended that formwork be left to stand for at least 3 days to give the wall time to harden for lower plasticity blends. Furthermore, it was noted that lowered clay content resulted in a lower plasticity index. This meant that on a construction site, there would be a higher probability for the blend to behave as a liquid and deform if the moisture content added to the mixture marginally exceeded OMC. Conversely, if the moisture content was marginally below OMC, there would be a higher probability that the lower plasticity blend crumbled and deformed after manufacture due to minimal activation of the clay minerals. According to literature, the higher the plasticity index, the higher the range of moisture content at which a soil blend exhibited a plastic behaviour. According to Standards Australia (2002), the drop test (A.1.5) was the recommended test to follow to verify OMC during mixing on site. Additionally, too much clay would lead to problems in terms of workability & production. The increase of clay content in the blend caused the fresh specimen to stick to the sides of the mould even when lubricated with oil. Mixing became difficult due to the buildup of clay lumps which was not the case when working with lower plasticity blends.

Non-Loadbearing Construction (6% Stabiliser)

For non-loadbearing applications using 6% stabiliser, the selection process for an optimal soil combination considered workability factors as there was a higher range of suitable blends. The aim in this case was to select an optimal soil combination that would: be workable; pass the minimum acceptable values for compressive strength & drying shrinkage and have relatively low moisture absorption. Figures 5.1 & 5.3 showed that 6% cement stabilised lower plasticity blends offered the highest compressive strengths and lowest drying shrinkage values. Furthermore, these blends recorded the lowest moisture absorptions Figure 5.4. Additionally, it was important that there was sufficient clay content to prevent initial deformation during manufacture and thus a 6% cement stabilised 60DG-40CF was recommended. Interestingly, Figures 5.1 to 5.4 could also be used if a higher content of Decomposed Granite (DG) was

required for a specific project. For example a 6% Lime stabilised 80DG-20CF blend could be selected for a project which required a higher content of DG due to geographical constraints e.g. the economic cost of transporting Cape Flats sand was high and DG was readily available on site. Alternatively, a 6% cement stabilised 100DG blend could have been selected depending on the requirements of the project.

Loadbearing Construction (6% Stabiliser)

It was apparent from results that it was possible to build load-bearing walls but only one soil combination passed the minimum criteria for dry & wet compressive strength and drying shrinkage. The 6% cement 40DG-60CF combination recorded the highest dry & wet compressive strengths of 4.4 MPa and 2.3 MPa (Figures 5.1 & 5.2). The lowest drying shrinkage results were expected for the construction of Rammed Earth walls as the soil combination contained the least clay content and was employing the use of cement as a stabiliser which demonstrated to be more effective (Figure 5.3) at limiting drying shrinkage. Additionally, the combination had the lowest moisture absorption (Figure 5.4) contributed by the relatively impermeable and denser matrix associated with cement stabilisation. However, the lower clay content increased the risk of walls deforming during manufacture. This meant that the 6% cement stabilised 50DG-50CF combination was recommended for the construction of exterior Rammed Earth walls. Testing in the laboratories along with additional testing on full sized walls would be required to demonstrate the structural integrity of these selected soil combinations for Rammed Earth Construction in practice.

6. Conclusions & Recommendations

All the aims of this thesis discussed in Chapter 1 were achieved: 16 soils were selected, classified and underwent 'material selection' tests. Once the suitable materials were selected, specimens were manufactured and tested for compressive strength, drying shrinkage, rate of drying and water absorption. Testing resulted in the following conclusions:

- The optimal soil combination in terms of strength and durability for loadbearing and non-loadbearing applications was a 50% Decomposed Granite - 50% Aeolian Sand blend stabilised with 6% cement.
- Decomposed Granite from Sierra Leone had similar properties to the Decomposed Granite from Cape Town and could be used following successful compliance test results.
- Cement was more effective than lime as a stabiliser in terms of compressive strength and durability.
- In terms of non-loadbearing applications, it was recommended to use cement for blends low in clay content and lime for blends high in clay content. Clay demonstrated to be retarding hydration reactions of cement while promoting pozzolanic reactions of lime.
- Drying shrinkage cracking can be significantly reduced with 6% cement stabiliser for all blends.

In general, it is deemed that Rammed Earth in the Cape Town metropolitan area provided disappointing strength results as most blends recorded compressive strength below the minimum acceptable value of 2 MPa for loadbearing applications according to Walker *et al* (2005). However, more suitable blends become available for non-loadbearing applications as strengths are greater than the minimum acceptable value of 1 MPa. It is also worth noting that, according to Hall & Djerbib (2004), the typical downward thrust of a single storey house is of the order 0.1 MPa. Therefore, suitable blends for non-loadbearing applications could be used for the construction of single storey houses. These blends would need to be stabilised to ensure protection from the environment (water). If double storey houses are required, the selected optimal soil combination could be used to compensate for the required strength.

It is thus possible to build with Rammed Earth in the Cape Town Metropolitan area as Decomposed Granite & Aeolian Cape Flats Sand were widely available in the region.

However, there are no South African building codes for Rammed Earth and contractors & architects will be reluctant to use such materials. Testing on full scale walls is required and would be beneficial to increase user confidence. In terms of the various methods of Rammed Earth construction, testing resulted in the following conclusions:

Construction with unstabilised Rammed Earth

- An unstabilised blend with higher clay content will experience higher drying shrinkage
- Untabilised Rammed Earth walls exposed to the environment (water) will not be durable.
- A 60% Decomposed Granite – 40% Aeolian Cape Flats blend would be suitable for interior non-loadbearing applications only. Movement joints are required to limit drying shrinkage cracking

Construction with 3% Stabilised Rammed Earth

- 3% stabiliser would be insufficient to have a significant effect on the compressive strength as results suggested strength remained primarily associated with the bond between clay particles, similar to the behaviour of unsabilised specimens.
- However, in comparison with unstabilised Rammed Earth walls, 3% stabiliser would provide additional durability & Longevity. Cement stabilised specimens did not disintegrate during water immersion while lime stabilised specimens required a minimum of 14 days for the less rapid pozzolanic reactions to occur and prevent disintegration.
- A 80% Decomposed Granite – 20% Aeolian Cape Flats Sand blend stabilised with 3% cement would be suitable for interior non-loadbearing applications only. Movement joints are required to limit drying shrinkage cracking.

Construction with 6% Stabilised Rammed Earth

- It was recommended to use lime as a stabiliser for Rammed Earth walls high in clay content while cement be used for walls low in clay content.
- Blends low in clay content were more workable during manufacture but have a lower plasticity index i.e. a lower range of moisture content at which a soil will hold its own shape.

- A 60 Decomposed Granite – 40 Aoelian Cape Flats Sand stabilised with 6% cement stabilised blend was the optimal combination for interior & exterior non-loadbearing applications only.
- A 50% Decomposed Granite – 50% Aoelian Cape Flats Sand blend stabilised with 6% cement was suitable for interior & exterior non-loadbearing & loadbearing applications.

6.1. Recommendations

The scope of the thesis was to collect and establish information that will allow for the drawing up of a guideline to building stabilised or unstabilised Rammed Earth housing in the Cape Town metropolitan area. The objectives laid out in Chapter 1 have been met but a few recommendations for further research need mention from analysing results. These are listed below:

- A deeper understanding of
 - a) the unexpected high compressive strength of lower plasticity blends in combination with 6% cement stabiliser.
 - b) the unexpected lower compressive strengths of 3% stabilised specimens in comparison with unstabilised specimens.
 - c) lack of correlation between the dry density and compressive strength of Rammed Earth specimens.
- The effect of bending stresses needs to be explored.
- The performance of blends on full scale walls.
- The performance of Rammed Earth in adverse conditions needs to be explored. This will allow for safety measures that can be used in construction to be established if necessary.

The information that has been collected is a start in the formulation of a guideline. However, extensive research is still needed in this field before such a guideline can be comprehensively drawn up and used.

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Appendix A

Physical Properties of Rammed Earth

A. General

The extent of testing Rammed Earth materials depends on the specified application and the novelty of the material in use. A proven material improves the confidence in its qualities and reduces the level of uncertainty and associated risks. Compliance tests are mostly undertaken on cylinders. In load-bearing applications it is usual to undertake soil classification, moisture-density testing, Unconfined Compressive Strength (UCS) and drying shrinkage assessments. Test conditions for specimens should reflect ambient worst case in-service conditions as much as possible. Resistance to erosion and abrasion, flexural tensile and shear strength tests may also be carried out (Walker *et al.* 2005). Guidance for test procedures are outlined in this appendix.

A.1. Field Test Methods

A.1.1. Sensory Tests

Smell Test - This test determines the presence of organic matter. A sample of soil is smelled. A musty aroma indicates an unacceptable quantity of organic matter. The soil is then rejected. Heating the soil sample enables a more rigorous check (Standards Australia 2002).

Touch Test - Dry and wet soil is rubbed between the fingers. Sands have a rough feel and lack cohesion. Dry silt is less rough than sand and shows some cohesion when wet. Dry clods indicate the presence of clay which becomes very sticky or greasy when wetted (Standards Australia 2002).

A.1.2. Ribbon Test

The ribbon test is used to determine the relative grading of the soil and its suitability for earth construction. Between 50g and 100g of damp soil is mixed and then flattened between thumb and forefingers to produce a ribbon 4 – 6 mm thick. The ribbon is then fed forward out of the hand as shown in Figure A1. The length of ribbon before it breaks is an indication of the sand, silt and clay content. The longer the ribbon, the greater the clay content (Standards Australia 2002);

- < 40 mm: Soil contains insufficient clay but may be suitable for Rammed Earth
- 40 mm to 80 mm: Soil contains low to moderate amount of clay. Suitable for Rammed Earth.
- 60 – 150 mm: Generally unsuitable for earth building.

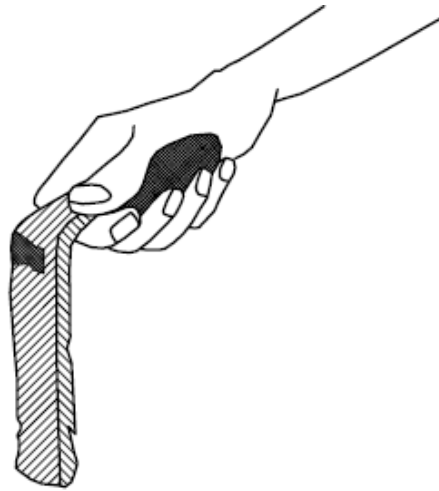


Figure A1 - Ribbon Test (Standards Australia, 2002)

A.1.3. Dry Strength

The dry strength test is used to check the plasticity of a soil and its suitability for earth construction. 50 g to 100 g of soil passing through a 0.425 mm sieve is first collected. The fine soil is then moistened sufficiently to form a ball of approximately 20 mm in diameter. The ball is then dried to remove all free water. Estimation of plasticity relies on the effort required to break and crush the dry ball between thumb and forefingers. Accuracy of this test depends on the experience of the operator (Standards Australia 2002).

- If the soil will not form into a ball or it falls apart on drying, the soil has insufficient fines for earth building. Further testing may prove the soil to be suitable for cement-stabilised Rammed Earth.
- If the ball crushes with little effort, the soil has insufficient fines for unstabilised earth construction, but is generally suitable for cement stabilisation.
- If the ball crushes with moderate difficulty, the soil has sufficient fines for unstabilised and stabilised earth construction.

- If the ball cannot be crushed, or can be crushed only after considerable force, the soil has high clay content and should not be used. However, the soil may be suitable with the addition of sand or lime.

A.1.4. Sedimentation

The sedimentation test is a simple field test to determine approximate fine gravel, sand, silt and clay fractions. A 500 ml transparent watertight jar is used. Particles greater than 6 mm are removed. The jar is filled approximately quarter full with loose soil and then filled to the top with water. The jar is sealed and the water is allowed to completely soak into the soil. The jar is then shaken for 2 minutes, left to stand for 1 hour, shaken for another minute and then placed on a flat surface. Approximately 45 to 60 minutes later, the fine gravel, sand and silt layers should be clearly visible as shown in Figure A2. After a further 24 hours the clay particles should have also settled out of suspension. Without disturbance, the height of each layer should then be measured without disturbance to give relative fine gravel + sand to silt + clay ratios. For some soils it may be difficult to decipher the boundary between clay and silt. This problem is overcome by measuring layers after minute (combined gravel + sand), 45 minutes (sand + silt) and finally 24 hours (sand + silt + clay). If clay has flocculated, then a suitable deflocculant such as sodium bicarbonate, starch, sodium silicate or trisodium phosphate should be added before shaking (Standards Australia 2002).

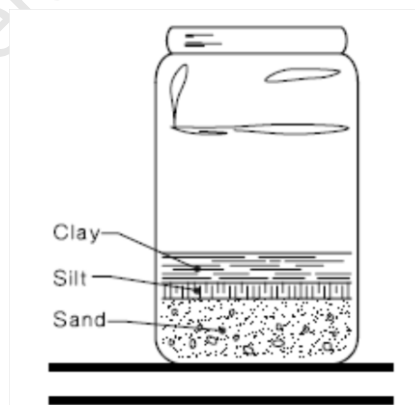


Figure A2 - Sedimentation Test (Standards Australia, 2002)

A.1.5. The drop test

The drop test is used to determine the Optimum Moisture Content of various soils including a stabilised mix. A handful of moist soil is squeezed into a ball which is then dropped from shoulder height onto firm ground. The manner in which the soil breaks on impact will tell

whether the soil mix is at its Optimum Moisture Content. Results are as follows (Standards Australia 2002):

- If the soil breaks into many pieces, the moisture content is less than optimum (Figure (a)).



Figure (a) – Too dry or insufficient clay content (Standards Australia, 2002)

- If the soil remains in one flattened piece, the moisture content is greater than optimum (Figure (b)). However if a stabilised mix gives the same result over a range of moisture contents, it may also mean that the clay content is too high.



Figure (b) – Too wet or excessive clay content (Standards Australia, 2002)

- If the soil breaks into roughly 3 to 6 relatively even pieces, the moisture content is considered to be at optimum (Figure (c)).



Figure (c) – Suitable (Standards Australia, 2002)

A.1.6. Linear Shrinkage

The shrinkage test is used to determine soil suitability and amount of cement required for stabilised Rammed Earth construction. A metal mould with internal dimensions 40 mm × 40 mm × 600 mm is required (Figure A3). The inside of the mould should be lightly coated to prevent adhesion. Particles 6 – 10 mm should be removed from the soil. Firstly, 2 – 2.5 kg of soil is mixed with water close to its Optimum Moisture Content (from drop test). The mould is then filled completely with firm wet soil while tapping the mould to release trapped air. The top surface is then leveled and sundried for 3 to 14 days, until all shrinkage occurs. The total length of dry soil is measured to the nearest millimeter. If the sample cracks into more than one piece it is important to push all the pieces together to get an accurate representation of total linear shrinkage. Linear shrinkage is given by (A.1) as a percentage:

(A.1)

Table A 1 - Suitability and recommended Stabilisation based on Soil Linear Shrinkage (Standards Australia, 2002)

L_s	Comment
<2.5%	Rammed Earth 4% to 6% cement
2.5% - 5.0%	Suitable for stabilised Rammed Earth; 5% to 6% cement
5.0% - 7.5%	Suitable for stabilised Rammed Earth; 6% to 8% cement
7.5% - 10%	Suitable for stabilised Rammed Earth; 8% to 10% cement
>10%	Generally unsuitable for cement stabilised Rammed Earth

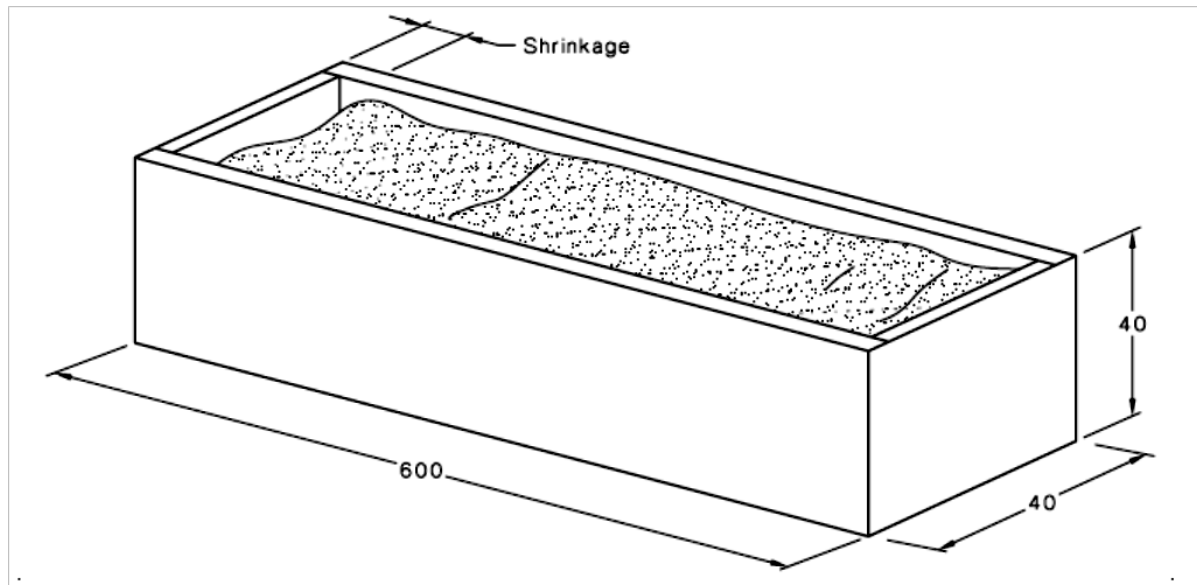


Figure A3 – Shrinkage Test Mould (Standards Australia, 2002)

A.2. Laboratory Testing

A.2.1. Dry Density

The dry density test is used to determine dry density of earth blocks and cylindrical earth specimens. Each specimen firstly oven dried to constant mass, weighed and measured to determine the dry density. Apparatus required include (Standards Australia 2002):

- A well-ventilated drying oven capable of maintaining uniform temperature of C.
- A balance capable of weighing largest specimens and accurate to ± 1 g.
- A desiccator of sufficient size to hold the test specimens.
- A linear scale accurate to ± 0.5 mm.

A

C until constant mass is achieved. The specimen is then allowed to cool to room temperature in the desiccator and then re-weighed to the nearest 1 g. The dry density is determined to the nearest 10 kg/m^3 from:

(A.2)

A.2.2. Shear Strength

The determination of the shear strength may be needed in design to assess racking shear resistance of non-load-bearing Rammed Earth walls. Shear strength may be determined using shear box testing or direct tests on prototype walls (Figure A4). Preparation of materials and specimens should replicate likely site conditions (Walker *et al.* 2005).



Figure A4 - Shear Testing of a Rammed Earth wall (Walker *et al.* 2005)

A.2.3. Moisture - Density

This test is followed in accordance with BS1377-4. A soil sample of known moisture content is compacted in a 1 litre cylindrical mould. Compaction is carried out in five layers of equal thickness by dropping a 4.5 kg weight falling 27 times on each layer from 450 mm. When the cylinder has been compacted to its full height, its weight is recorded to establish its bulk density. The sample of material is then taken for oven drying to establish the soil moisture content. At least five specimens at various moisture contents are prepared the same way and their bulk densities and moisture contents are recorded. After drying, the moisture contents and dry densities are calculated and plotted on a graph as shown in Figure A5. From the resultant curve, it is possible to determine the Optimum Moisture Content for which the soil experiences its maximum dry density for the given compaction.

The compactive energy of the heavy manual compaction test is widely believed to be lower than typical pneumatic works (Walker *et al.* 2005)

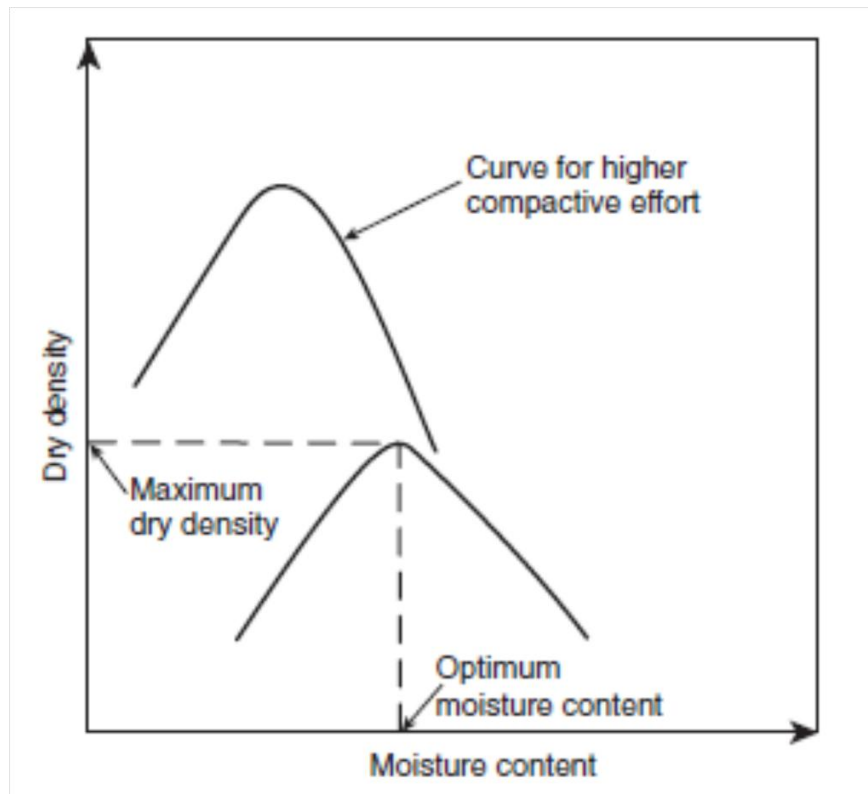


Figure A5 - Relationship between Moisture Content and Dry Density (Standards Australia, 2002)

A.2.4. Flexural Tensile Strength

There is no recognised test procedure for flexural tensile or bending strength of Rammed Earth and in most applications; knowledge of flexural strength is not required. However, when considered necessary, tests should seek to determine flexural strength perpendicular to the horizontal compaction layers. The specimen should be of sufficient size to allow a number of identical compaction layers to be tested under conditions of increasing uniform bending moment. Flexural tensile stress may be applied to test specimens as a four-point load beam test. The influence of self weight should be taken into account when determining flexural tensile strength. The flexural tensile strength of each specimen should be calculated based on gross cross-sectional area (Walker *et al.* 2005)

A.2.5. Drying Shrinkage

The test is a measure of how much Rammed Earth materials shrink linearly on drying following compaction. Drying shrinkage tests are recommended where the shrinkage of

Rammed Earth may have a significant influence on load-bearing walls. S

- C and 40-60% RH.

Linear shrinkage is determined by measuring total or relative changes in length of the cylindrical specimens. Measurements should be made using surface-mounted strain devices such as a DEMEC gauge. Initial measurements should be taken immediately following compaction and demoulding and periodically thereafter during drying. Shrinkage measurements cease when they no longer change with time and when the cylinder mass remains constant. Cylindrical shrinkage is expressed as the ratio of change in length to original datum length (Walker *et al.* 2005).

A.2.6. Water Absorption

The water absorption test is used to determine water absorption of stabilised earth blocks and cylindrical stabilised earth specimens. The increase in mass of oven-dried test specimens, due to immersion in water for 24 hours, is determined and expressed as a percentage of the specimen's initial dry mass. Apparatus required include (Standards Australia 2002):

- A well-ventilated drying oven capable of maintaining uniform temperature of C.
- A balance capable of weighing largest specimens and accurate to ± 1 g.
- A desiccator of sufficient size to hold the test specimens.
- A water tank of sufficient size to hold specimens completely immersed in water.

Before beginning the test, specimens should be properly cured. Large specimens may be cut into smaller representative pieces. Firstly, each specimen is immersed completely in water at ambient temperature for 24 hours. The specimen is then removed from the water and allowed to drain for not more than a minute while t

C until constant mass is achieved. The specimen is then allowed to cool to room temperature and

then re-weighed to the nearest 1 g. The dry mass of each specimen is then recorded. The water absorption of each specimen is determined from:

(A.3)

The order of testing may be varied (oven-drying followed by immersion). This allows experiment to proceed as part of saturated surface dry compression (wet) test.

A.2.7. Accelerated Erosion

The accelerated erosion test is used to determine relative erosion resistance of earth blocks. Specimens are sprayed for 60 minutes by a continuous jet of water. Performance, in terms of erosion rate (mm/hour), is determined by the pitting depth. Apparatus required include (Standards Australia 2002):

- A stand-mounted 50 mm spray nozzle
- A water pump, pipes and valves
- A pressure gauge and a water tank
- A filtration screen to remove particulate matter
- Mounting for the specimen
- A shield and gasket

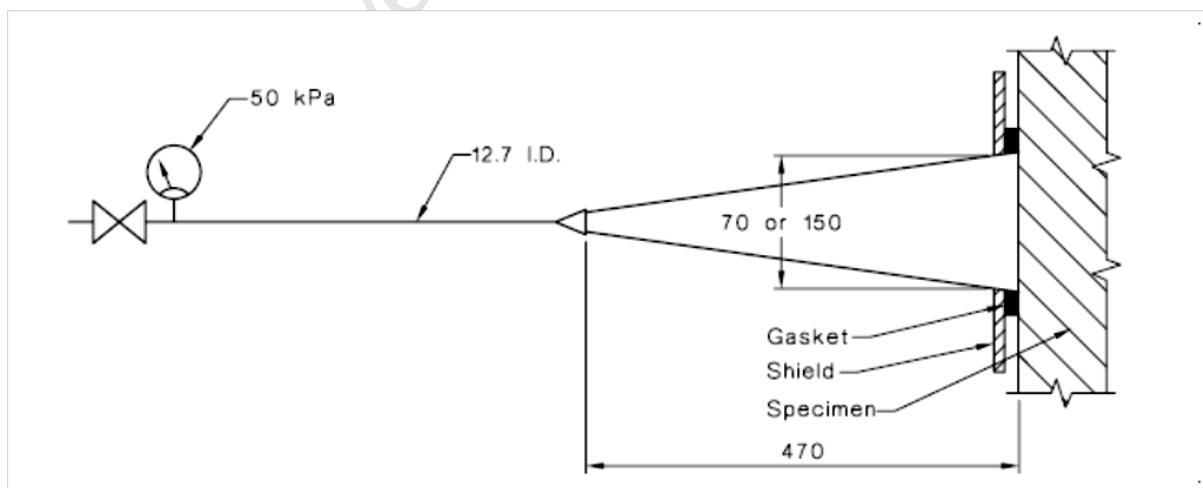


Figure A6 - Accelerated Erosion Test (Standards Australia, 2002)

A representative sample is selected and the specimens test rig is mounted in the same direction as intended in wall construction (Figure A6). The shield should be positioned

such that only a limited area of one face of the specimen is exposed to the spray (Figure A7). Depending on specimen size, the exposed section should be either 150 mm or 70 mm in diameter. A suitably sized insert can be attached over the face of smaller specimens to prevent water loss. Each specimen is then sprayed for 60 minutes. During exposure, the spray is temporarily stopped every 15 minutes to allow progress inspections.

After 60 minutes, the depth of erosion of each pit is measured to the nearest millimeter. The maximum depth is taken as the rate of erosion in mm/hour. In some cases where the spray bores completely through in less than 60 minutes, the test is stopped and the time is recorded to the nearest minute. The erosion rate in such cases is given by the specimen width divided by the time (in hours) to cause full penetration.



Figure A7 - Accelerated Erosion test on Stabilised Pressed Block (Standards Australia, 2002)

A.2.8. Compressive Strength

Compressive strength represents a basic quality control measure for Rammed Earth. This test determines the unconfined compressive strength of earth blocks and cylindrical earth specimens. The specimens are placed in a compression-testing machine and loaded in uniform uniaxial compression until failure.

Compressive strength is obtained from maximum applied loading and nominal cross-sectional area. Unconfined strength is obtained by applying an aspect ratio correction factor

to measured values (Table A2). Samples should be tested at the measured Optimum Moisture Content. Optimum Moisture Content should be determined by oven-drying. Apparatus required include (Standards Australia 2002):

- A compression testing machine capable of applying steady uniform load to failure.
- A linear scale accurate to ± 0.5 mm.

The cylinder or cube is held together while the moistened soil is rammed in 3 equal layers. A heavy rod is used for ramming. Test samples must be cured slowly for an accurate representation of the wall. The sample is carefully extracted from the mould and then wrapped in clear plastic wrap. The samples are then crushed at 7, 14 and 28 days during the curing process so as to evaluate strength gain over time. This relationship between early strength and ultimate strength is very important.

Where specimens are to be tested saturated surface dry, they must be immersed in water for a minimum of 24 hours before testing. Where specimens are to be tested oven-dry, they should be oven-dried to constant mass and allowed to cool to room temperature in a desiccator before testing. Where specimens are tested at some other ambient condition, specimen moisture content should be determined by oven-drying, using representative material collected after failure or using a sample stored under identical conditions. K_a

In strain-controlled devices the moving head should travel at a rate of 1.0 mm/m strain per minute. In load-controlled devices, the load should be applied at a constant rate equivalent to a specimen stress of 0.2 N/mm² per minute. The maximum load (P) and mode of failure is recorded. The unconfined strength (MPa) of each specimen is given by:

(A.4)

The aspect ratio correction factor (K_a) is derived, using linear interpolation from:

Table A2 - Aspect ratio correction factors

Height-to-thickness ratio	0	0.4	1.0	5.0 or more
K_a	0	0.5	0.70	1.0

A.2.9. Atterberg limits

Another significant test the laboratory can help with is to determine the shrinkage characteristics of the soil. The sieve analysis will not differentiate between silt and clay so a

second pair of tests is required. The result of this test yields the Atterberg limits of the soil. The first of the tests measures the Plastic Limit (PL), the amount of water the soil will absorb before changing from a solid state to a plastic state. The second test determines the Liquid Limit (LL), the water content at which the soil changes from plastic to liquid. The numerical difference between the plastic and liquid limits determines the Plasticity Index (PI). The lower the PI, the less a soil will tend to shrink. According to Easton & Wright (2007), a soil with good ramming capabilities should have a PI between 8 and 15. Apparatus required include (University of Texas at Arlington, 2004):

- A linear scale accurate to ± 0.5 mm.
- Casagrande's liquid limit device
- A Grooving tool and a spatula
- Porcelain (evaporating) dish
- Eight moisture cans and a glass plate
- A wash bottle filled with distilled water
- -

C.

A) Liquid Limit

250 g of air-dried soil passing through a 4.25 mm sieve is placed into a porcelain dish. The soil is then mixed thoroughly with a small amount of distilled water until it appears as a smooth uniform past. The dish is then covered with cellophane to prevent moisture from escaping. Four of the empty moisture cans are then weighed with their lids. The liquid limit apparatus is then adjusted by checking the height of drop of the cup. The point on the cup that comes in contact with the base should rise to a height of 10 mm. The block on the end of the grooving tool is 10 mm high and will be used as a gage. The rate to rotate the crank is then adjusted so that the cup drops approximately two times per second (University of Texas at Arlington, 2004).

A portion of the previously mixed soil is placed into the cup of the liquid limit apparatus at the point where the cup rests on the base (Figure (a)).

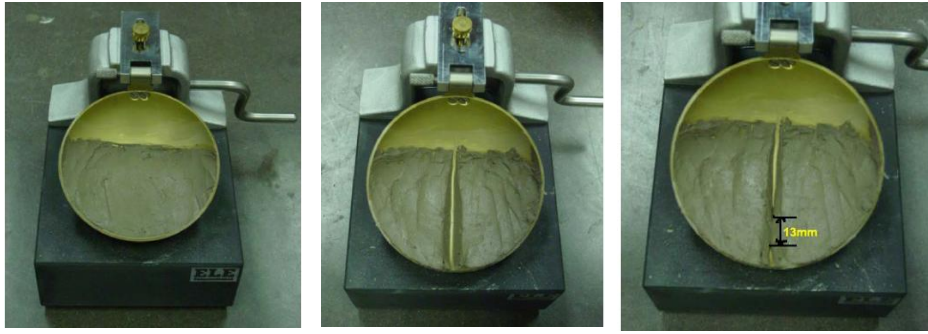


Figure (a)

Figure (b)

Figure (c)

The grooving tool is then used to cut a clean straight groove down the centre of the cup (Figure (b)). The crank of the apparatus is then turned at a rate of approximately two drops per second. The number of drops, N , is counted until the two halves of the soil pat come into contact at the bottom of the groove along a distance of 13 mm (figure (c)). If the number of drops exceeds 50, the soil is remixed and a small amount of water is added and the above step is redone.

A sample is then taken using the spatula from edge to edge of the soil pat and should include the soil on both sides of where the groove came into contact. The soil is placed into a moisture can with its lid on and immediately weighed. The lid is then removed and the can is placed in the oven for at least 16 hours. The remaining soil in the cup is placed into the porcelain dish, remixed and a small amount of water is added.

These steps are repeated for at least two additional trials producing successively lower numbers of drops to close the groove. One of the trials shall be for a closure requiring 25 to 35 drops, one for closure between 20 and 30 drops and one trial for a closure requiring 15 to 25 drops. The water content is determined from each trial. The water content for each of the liquid limit moisture cans is then calculated after they have been dried for 16 hours. The number of drops (N) versus the water content (w) is plotted on the log scale. The liquid limit is determined as the water content at 25 drops.

B) Plastic Limit

The weight of an empty moisture can is determined. Approximately 20 g of dry soil passing through a 4.25 mm sieve is taken and water is added until the soil is at a consistency where it can be rolled without sticking to the hands. The soil is then formed into an ellipsoidal mass (Figure a) and then rolled between the fingers and the glass plate

(Figure b). The thread shall be deformed so that its diameter reaches 3 mm, taking no more than two minutes (University of Texas at Arlington, 2004).



Figure (a)

Figure (b)

Figure (c)

The thread is then broken into several pieces when it reaches the correct diameter. The pieces are then reformed into ellipsoidal masses and re-rolled. This process is continued until the threads can no longer be rolled at 3 mm in diameter (Figure c). The portions of the crumbled thread are gathered together and placed into a moisture can and covered. The cans must contain at least 6 g of soil. The moisture can is then weighed immediately and then placed in the oven for at least 16 hours without its lid. The above steps are then repeated.

The water content for each of the liquid limit moisture cans is then calculated after they have been for 16 hours. The average of the water contents are computed to determine the Plastic limit (PL). The plasticity index is then calculated ($PI = LL - PL$) (University of Texas at Arlington, 2004).

Appendix B

B.Results

B.1. Material Selection

Property	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17*	
Grading (% Passing) (Sieve size in mm)	4.75	100.0	100.0	98.8	99.8	97.7	90.1	81.7	98.9	100.0	98.6	100.0	100.0	100.0	98.7	99.8	91.9	
	2.36	99.4	99.8	99.2	93.9	89.0	85.2	71.1	98.0	99.9	98.3	100.0	100.0	100.0	98.2	99.5	79.3	
	1.18	97.7	92.7	89.1	86.0	86.4	77.6	63.9	93.6	99.8	98.0	100.0	100.0	99.7	97.7	98.9	66.8	
	0.6	78.2	77.6	70.5	75.3	80.9	64.2	46.3	88.5	92.2	96.1	94.5	99.8	87.2	80.3	94.1	58.4	
	0.425	46.0	64.7	62.6	64.4	-	58.7	39.3	37.4	82.3	74.8	89.9	71.2	97.1	78.4	56.7	77.3	54.3
	0.3	23.5	47.1	56.1	48.1	50.1	52.7	26.6	31.8	65.3	47.0	66.5	39.3	44.4	60.0	29.0	45.2	49.9
	0.15	7.8	30.2	47.5	26.6	38.2	44.2	12.9	23.7	33.3	11.0	14.8	8.2	5.1	15.0	10.7	7.4	40.7
	0.075	3.0	22.7	43.6	18.6	32.5	41.7	9.5	20.3	27.5	4.4	9.9	2.6	2.7	3.8	8.4	2.0	35.2
	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Silt (0.02)	-	-	35.8	-	12.4	37.9	-	-	-	4.4	-	-	-	2.6	3.8	8.4	2
Clay (0.005)	-	-	7.8	-	4.9	4.2	-	-	-	0	-	-	-	0	0	0	0	8.6
FM	1.93	1.88	1.38	1.71	1.52	1.75	2.75	2.94	1.22	1.5	1.28	1.58	1.51	1.38	1.58	1.55	2.14	
Atterberg Limits	Liquid Limit (%)	45.6	45.6	45.6	19.5	42.3	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	49.2
	Plastic Limit (%)	29.1	29.1	29.1	No Result	34.9	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	30.7
	Plasticity Index (PI)	16.5	16.5	16.5	No Result	7.3	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	18.5
	Linear Shrinkage (%)	7.2	7.2	7.2	1.6	5	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	Non-Plastic	7.6
Predominant Mineral (XRD)	Quartz	Yes	Yes	Yes	Illite	Kaolinite	Kaolinite, Illite	Smectite	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz	Kaolinite
	Organic Matter	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

B.2. Compliance Testing*Wet & Dry Compressive Strength Results*

Specimens	Treatment	Wet Compression (MPa)				Dry Compression (MPa)			
		7 day	14 day	28 day	56 day	7 day	14 day	28 day	56 day
40DG - 60CF	Unstabilised	-	-	-	-	0.80	1.10	0.82	0.77
60DG - 40Cf	Unstabilised	-	-	-	-	1.47	1.50	1.56	1.65
80DG - 20CF	Unstabilised	-	-	-	-	1.51	1.46	2.07	1.59
100DG	Unstabilised	-	-	-	-	1.82	1.63	1.56	1.40
40DG - 60CF	3% Cement	0.06	0.10	0.07	0.16	0.11	0.10	0.17	0.26
60DG - 40Cf	3% Cement	0.12	0.18	0.13	0.20	0.27	0.40	0.35	0.51
80DG - 20CF	3% Cement	0.12	0.25	0.24	0.34	0.79	0.55	0.49	1.09
100DG	3% Cement	0.20	0.14	0.19	0.32	0.62	0.86	0.79	1.11
40DG - 60CF	6% Cement	0.29	0.82	1.35	2.31	1.08	1.19	3.57	4.39
60DG - 40Cf	6% Cement	0.10	0.13	0.55	1.00	0.70	0.49	1.54	1.81
80DG - 20CF	6% Cement	0.21	0.57	0.42	0.42	0.37	0.57	0.73	1.09
100DG	6% Cement	0.17	0.38	0.44	0.49	0.57	0.98	1.24	1.49
40DG - 60CF	3% Lime	-	0.07	0.04	0.12	0.20	0.32	0.56	0.42
60DG - 40Cf	3% Lime	-	0.22	0.13	0.21	0.76	1.01	0.76	0.85
80DG - 20CF	3% Lime	-	-	0.19	0.33	0.77	1.10	0.97	0.91
100DG	3% Lime	-	-	0.21	0.38	0.98	1.38	1.47	1.87
40DG - 60CF	6% Lime	-	0.14	0.16	0.21	0.48	0.68	0.89	0.90
60DG - 40Cf	6% Lime	-	0.22	0.23	0.35	0.97	0.98	1.20	1.46
80DG - 20CF	6% Lime	-	0.28	0.43	0.51	1.11	1.41	1.45	1.59
100DG	6% Lime	-	0.32	0.31	0.48	1.43	1.49	1.62	2.22

* The hyphens represent the disintegration of specimens

Drying Shrinkage, Rate of Drying & Water Absorption Results

Specimens	Treatment	Drying Shrinkage	Drying	Water Absorption
		(%)	Percentage of original mass (%)	(%)
40DG - 60CF	Unstabilised	0.80	86	-
60DG - 40CF	Unstabilised	0.78	88	-
80DG - 20CF	Unstabilised	1.78	85	-
100DG	Unstabilised	1.91	83	-
40DG - 60CF	3% Cement	0.15	87	12.8
60DG - 40CF	3% Cement	0.37	88	13.0
80DG - 20CF	3% Cement	0.66	87	15.1
100DG	3% Cement	1.64	85	16.7
40DG - 60CF	6% Cement	0.12	91	11.8
60DG - 40CF	6% Cement	0.16	89	13.1
80DG - 20CF	6% Cement	0.20	87	15.4
100DG	6% Cement	0.79	84	17.1
40DG - 60CF	3% Lime	0.12	88	13.3
60DG - 40CF	3% Lime	0.61	87	13.6
80DG - 20CF	3% Lime	1.51	87	14.5
100DG	3% Lime	1.75	87	16.4
40DG - 60CF	6% Lime	0.06	88	13.8
60DG - 40CF	6% Lime	0.20	88	14.8
80DG - 20CF	6% Lime	0.64	86	16.2
100DG	6% Lime	1.62	85	17.2

* The hyphens represent the disintegration of specimens

B.3. Proctor Test*40DG-60CF blend*

Layers	3
Blows per Layer	27
Total blows	81
Volume of Mould (V) cm³	1000

Mass of mould + base + compacted specimen (m2)	7228	7309	7424	7386	7357
Mass of mould + base (m1)	5412	5413	5418	5428	5445
Mass of compacted specimen (m2 - m1)	1816	1896	2006	1958	1912
Bulk density (Mg/m³)	1.82	1.90	2.01	1.96	1.91

Moisture content container No	1	2	3	4	5
Mass wet soil + Container	30.677	41.038	41.987	42.324	47.953
	28.262	39.847	47.084	49.530	51.940
Mass Container	8.174	8.214	8.204	8.218	8.167
	8.130	8.217	8.141	8.189	8.121
Mass dry soil + container	28.572	37.642	37.595	37.372	41.400
	26.370	36.579	42.156	43.387	44.647
Mass dry soil	20.398	29.428	29.391	29.154	33.233
	18.240	28.362	34.015	35.198	36.526
Mass moisture (w)	2.105	3.396	4.392	4.952	6.553
	1.892	3.268	4.928	6.143	7.293
Moisture content	10.320	11.540	14.943	16.986	19.718
	10.373	11.522	14.488	17.453	19.967

Moisture content container number	1	2	3	4	5
Moisture content (%)	10.346	11.531	14.716	17.219	19.842
Dry density (Mg/m³)	1.65	1.70	1.75	1.67	1.60

From Graph (see Figure 4.5):

Maximum dry density (kg/m ³)	1730
Optimum Moisture Content (%)	14.4

60DG-40CF blend

Layers	3
Blows per Layer	27
Total blows	81
Volume of Mould (V) cm³	1000

Mass of mould + base + compacted specimen (m2)	7221	7323	7401	7329	7205
Mass of mould + base (m1)	5412	5417	5422	5447	5452
Mass of compacted specimen (m2 - m1)	1809	1906	1979	1882	1753
Bulk density (Mg/m³)	1.81	1.91	1.98	1.88	1.75

Moisture content container No	1	2	3	4	5
Mass wet soil + Container	35.142	37.721	42.468	44.615	45.865
	29.884	42.225	41.926	41.340	42.115
Mass Container	8.175	8.216	8.222	8.217	8.209
	8.133	8.225	8.148	8.189	8.146
Mass dry soil + container	31.836	34.053	37.893	38.346	39.353
	27.811	38.219	37.389	36.226	36.167
Mass dry soil	23.661	25.837	29.671	30.129	31.144
	19.678	29.994	29.241	28.037	28.021
Mass moisture (w)	3.306	3.668	4.575	6.269	6.512
	2.073	4.006	4.537	5.114	5.948
Moisture content	13.972	14.197	15.419	20.807	20.909
	10.535	13.356	15.516	18.240	21.227

Moisture content container number	1	2	3	4	5
Moisture content (%)	12.253	13.776	15.467	19.524	21.068
Dry density (Mg/m³)	1.61	1.68	1.71	1.57	1.45

From Graph (see Figure 4.5):

Maximum dry density (kg/m ³)	1710
Optimum Moisture Content (%)	15.8

80DG-20CF blend

Layers	3
Blows per Layer	27
Total blows	81
Volume of Mould (V) cm³	1000

Mass of mould + base + compacted specimen (m2)	6142	6211	6368	6347	6327
Mass of mould + base (m1)	4442	4446	4410	4412	4419
Mass of compacted specimen (m2 - m1)	1700	1765	1958	1935	1908
Bulk density (Mg/m³)	1.70	1.77	1.96	1.94	1.91

Moisture content container No	1	2	3	4	5
Mass wet soil + Container	40.231	46.179	46.515	52.045	48.738
	37.403	41.356	43.067	57.818	58.204
Mass Container	9.703	9.588	9.735	9.672	9.772
	9.631	9.656	9.587	9.725	9.612
Mass dry soil + container	37.206	42.120	41.509	45.520	42.154
	34.525	37.862	38.367	50.334	49.944
Mass dry soil	27.503	32.532	31.774	35.848	32.382
	24.894	28.206	28.780	40.609	40.332
Mass moisture (w)	3.025	4.059	5.006	6.525	6.584
	2.878	3.494	4.700	7.484	8.260
Moisture content	10.999	12.477	15.755	18.202	20.332
	11.561	12.387	16.331	18.429	20.480

Moisture content container number	1	2	3	4	5
Moisture content (%)	11.3	12.4	16.0	18.3	20.4
Dry density (Mg/m³)	1.53	1.57	1.69	1.64	1.58

From Graph (see Figure 4.5):

Maximum dry density (kg/m ³)	1670
Optimum Moisture Content (%)	16.2

100DG

Layers	3
Blows per Layer	27
Total blows	81
Volume of Mould (V) cm³	1000

Mass of mould + base + compacted specimen (m2)	6063	6194	6293	6292	6224
Mass of mould + base (m1)	4406	4409	4410	4418	4414
Mass of compacted specimen (m2 - m1)	1657	1785	1883	1874	1810
Bulk density (Mg/m³)	1.66	1.79	1.88	1.87	1.81

Moisture content container No	1	2	3	4	5
Mass wet soil + Container	37.136	47.292	39.900	47.911	52.143
	36.312	40.953	40.506	48.326	50.599
Mass Container	9.720	9.596	9.763	9.728	9.783
	9.650	9.680	9.608	9.740	9.628
Mass dry soil + container	33.947	42.139	35.283	41.360	44.197
	33.273	36.457	35.705	41.843	42.978
Mass dry soil	24.227	32.543	25.520	31.632	34.414
	23.623	26.777	26.097	32.103	33.350
Mass moisture (w)	3.189	5.153	4.617	6.551	7.946
	3.039	4.496	4.801	6.483	7.621
Moisture content	13.163	15.834	18.092	20.710	23.089
	12.865	16.791	18.397	20.194	22.852

Moisture content container number	1	2	3	4	5
Moisture content (%)	13.0	16.3	18.2	20.5	22.9
Dry density (Mg/m³)	1.47	1.53	1.59	1.56	1.47

From Graph (see Figure 4.5):

Maximum dry density (kg/m ³)	1570
Optimum Moisture Content (%)	18.2

B.4. Grading Curves for Blends

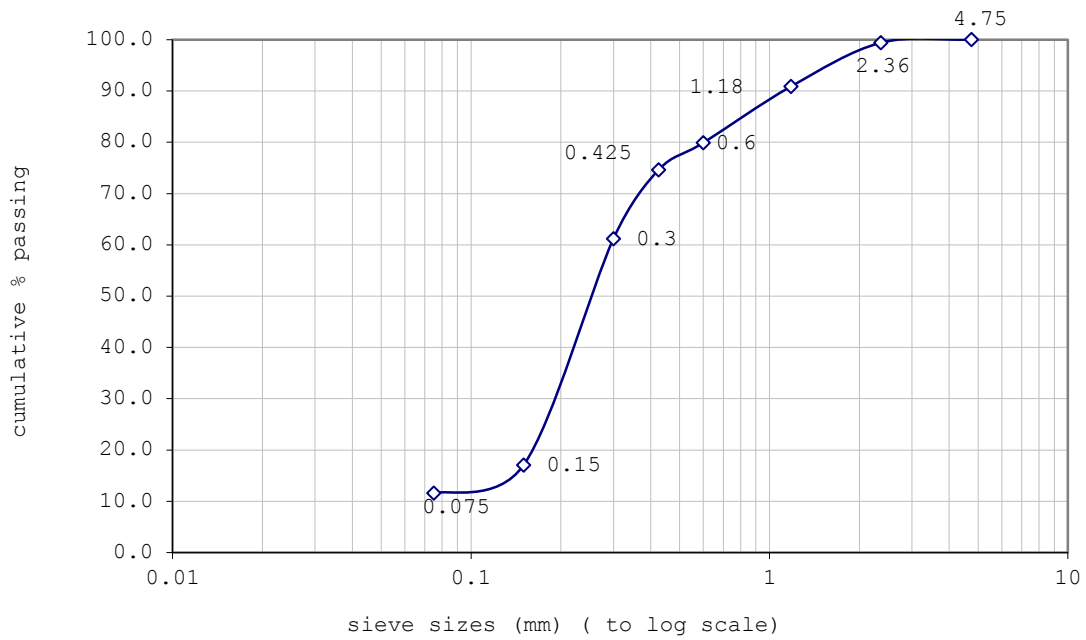


Figure B.1: Grading Analysis of the 40DG – 60CF blend

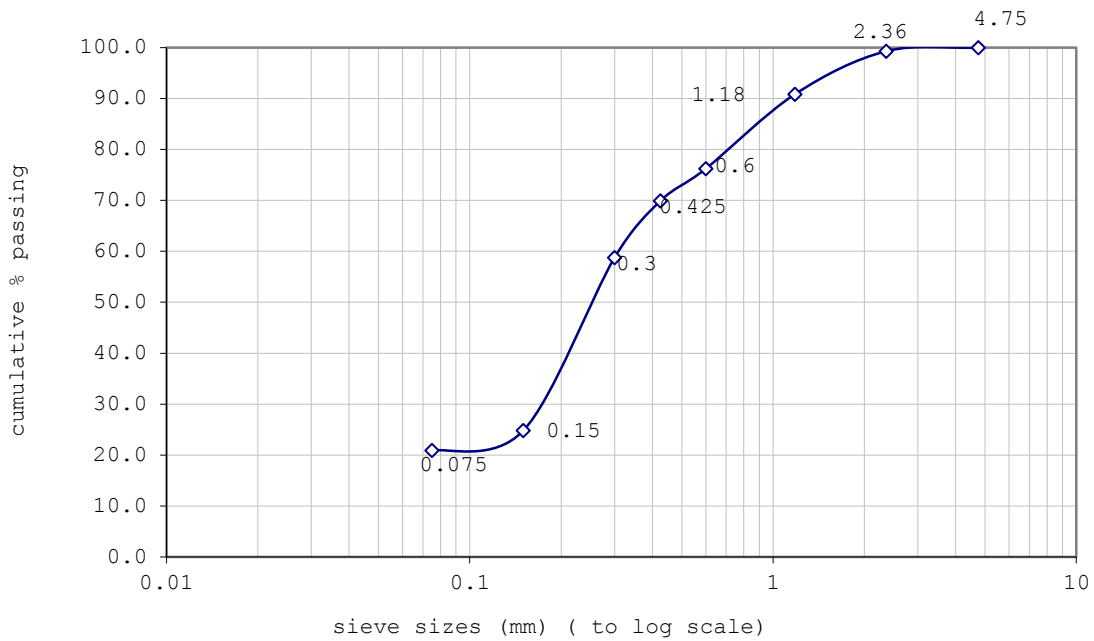


Figure B.2: Grading Analysis of the 60DG – 40CF blend

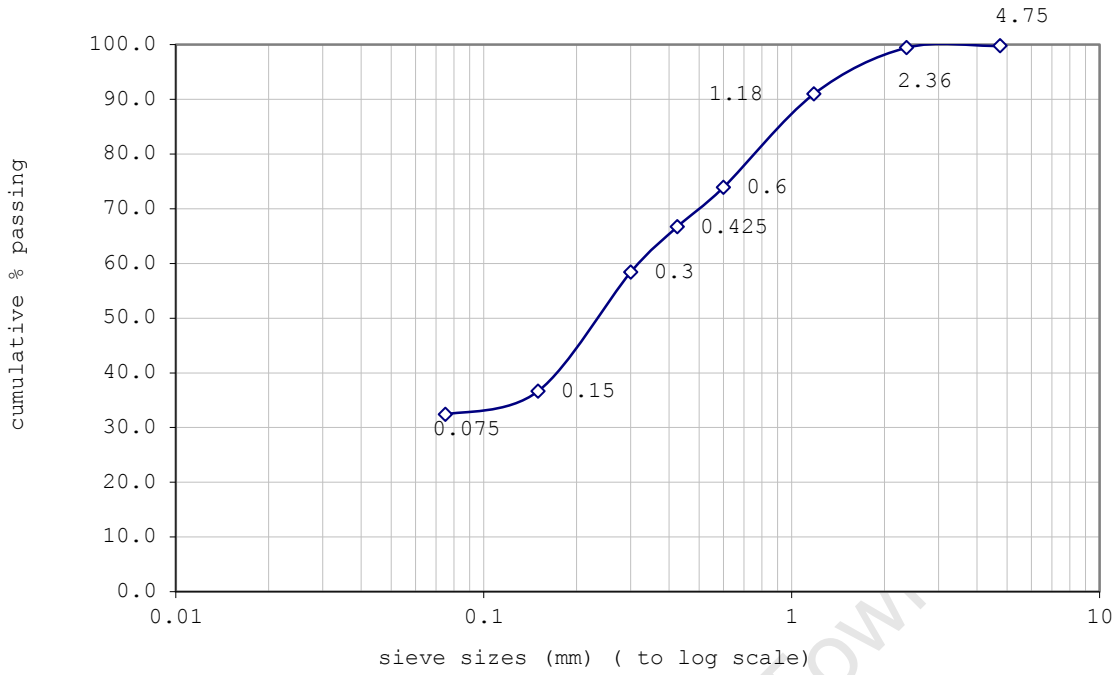


Figure B.3: Grading Analysis of the 80DG – 20CF blend

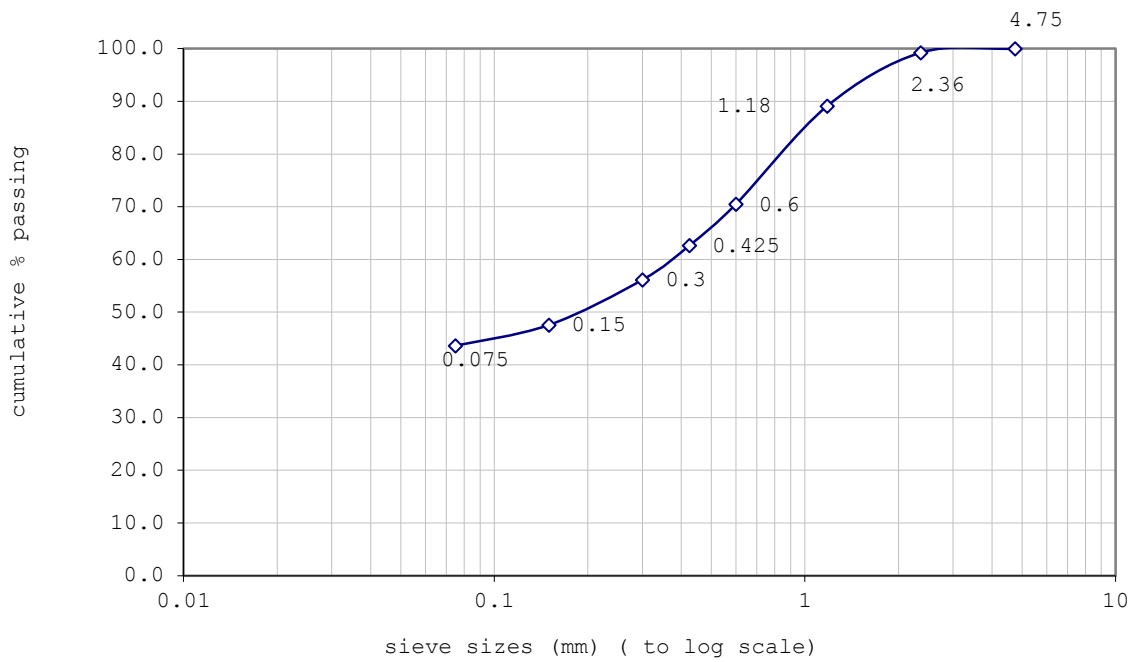


Figure B.4: Grading Analysis of Decomposed Granite (100DG)

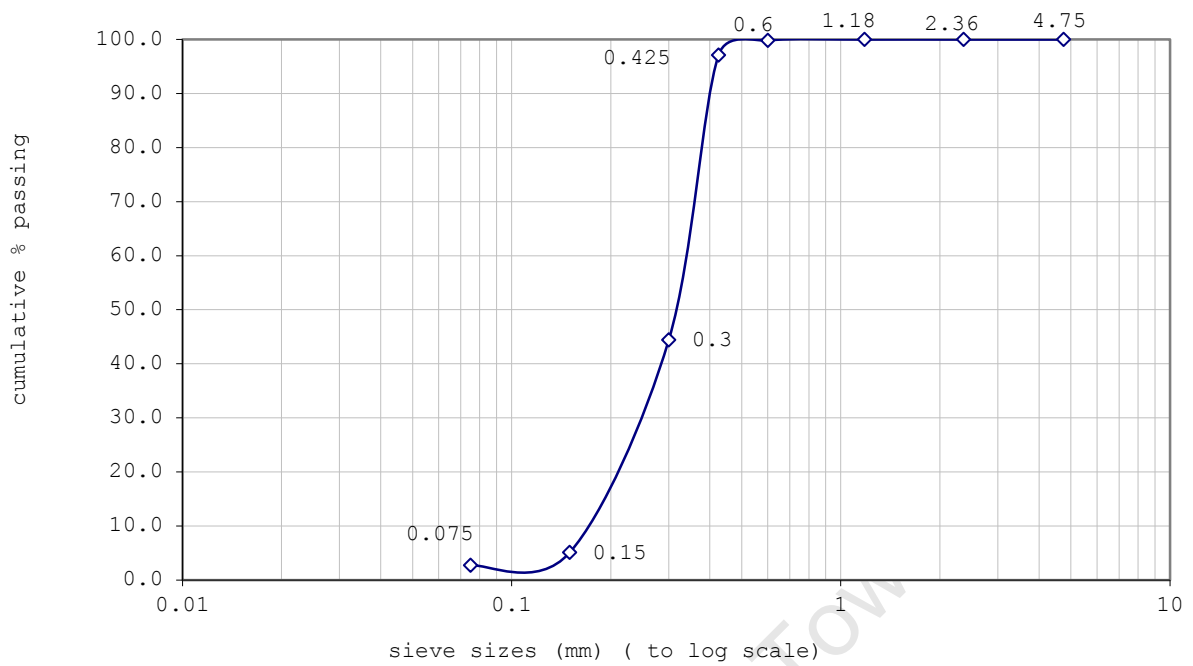


Figure B.5: Grading Analysis of Cape Flats Sand (CF)

University of Cape Town

B.5. Variability of Results*Dry Compressive Strength (MPa)***Standard Deviation and mean of 'dry' specimens**

Days after Manufacture		7		14		28		56	
		σ	x	σ	x	σ	x	σ	x
Specimens	Treatment								
40DG - 60CF	Unstabilised	0.20	0.80	0.18	1.10	0.13	0.82	0.21	0.77
60DG - 40CF	Unstabilised	0.10	1.47	0.15	1.50	0.15	1.56	0.14	1.65
80DG - 20CF	Unstabilised	0.36	1.51	0.13	1.46	0.12	2.07	0.09	1.59
100DG	Unstabilised	0.42	1.82	0.21	1.63	0.37	1.56	0.03	1.40
40DG - 60CF	3% Cement	0.04	0.11	0.05	0.10	0.05	0.17	0.04	0.26
60DG - 40CF	3% Cement	0.06	0.27	0.07	0.40	0.05	0.35	0.03	0.51
80DG - 20CF	3% Cement	0.17	0.79	0.30	0.55	0.11	0.49	0.27	1.09
100DG	3% Cement	0.09	0.62	0.33	0.86	0.18	0.79	0.05	1.11
40DG - 60CF	6% Cement	0.16	1.08	0.29	1.19	0.87	3.57	1.22	4.39
60DG - 40CF	6% Cement	0.21	0.70	0.08	0.49	0.32	1.54	0.09	1.81
80DG - 20CF	6% Cement	0.21	0.37	0.21	0.57	0.08	0.73	0.02	1.09
100DG	6% Cement	0.23	0.57	0.25	0.98	0.73	1.24	0.60	1.49
40DG - 60CF	3% Lime	0.02	0.20	0.17	0.32	0.16	0.56	0.05	0.42
60DG - 40CF	3% Lime	0.33	0.76	0.02	1.01	0.08	0.76	0.11	0.85
80DG - 20CF	3% Lime	0.09	0.77	0.10	1.10	0.22	0.97	0.51	0.91
100DG	3% Lime	0.36	0.98	0.49	1.38	0.16	1.47	0.29	1.87
40DG - 60CF	6% Lime	0.08	0.48	0.03	0.68	0.17	0.89	0.17	0.90
60DG - 40CF	6% Lime	0.28	0.97	0.01	0.98	0.27	1.20	0.11	1.46
80DG - 20CF	6% Lime	0.43	1.11	0.11	1.41	0.41	1.45	0.34	1.59
100DG	6% Lime	0.39	1.48	0.17	1.49	0.41	1.62	0.11	2.22

*Wet Compressive Strength (MPa)***Standard Deviation and mean of 'wet' specimens**

Days after Manufacture		7		14		28		56	
		σ	x	σ	x	σ	x	σ	x
Specimens	Treatment								
40DG - 60CF	Unstabilised	-	-	-	-	-	-	-	-
60DG - 40CF	Unstabilised	-	-	-	-	-	-	-	-
80DG - 20CF	Unstabilised	-	-	-	-	-	-	-	-
100DG	Unstabilised	-	-	-	-	-	-	-	-
40DG - 60CF	3% Cement	0.00	0.06	0.02	0.10	0.01	0.07	0.01	0.16
60DG - 40CF	3% Cement	0.01	0.12	0.01	0.18	0.04	0.13	0.03	0.20
80DG - 20CF	3% Cement	0.09	0.12	0.02	0.25	0.02	0.24	0.17	0.34
100DG	3% Cement	0.07	0.20	0.01	0.14	0.00	0.19	0.07	0.32
40DG - 60CF	6% Cement	0.17	0.29	0.12	0.82	0.34	1.35	0.30	2.31
60DG - 40CF	6% Cement	0.03	0.10	0.02	0.13	0.23	0.55	0.15	1.00
80DG - 20CF	6% Cement	0.05	0.21	0.21	0.57	0.09	0.42	0.00	0.42
100DG	6% Cement	0.09	0.17	0.06	0.38	0.33	0.44	0.12	0.49
40DG - 60CF	3% Lime	-	-	0.05	0.07	0.03	0.04	0.02	0.12
60DG - 40CF	3% Lime	-	-	0.00	0.22	0.06	0.13	0.02	0.21
80DG - 20CF	3% Lime	-	-	-	-	0.01	0.19	0.02	0.33
100DG	3% Lime	-	-	-	-	0.04	0.21	0.07	0.38
40DG - 60CF	6% Lime	-	-	0.06	0.16	0.02	0.16	0.01	0.21
60DG - 40CF	6% Lime	-	-	0.05	0.23	0.00	0.23	0.02	0.35
80DG - 20CF	6% Lime	-	-	0.05	0.43	0.05	0.43	0.06	0.51
100DG	6% Lime	-	-	-	-	0.03	0.31	0.01	0.48

* The hyphens represent the disintegration of specimens

Dry Density (kg/m³)

Standard Deviations and mean of 'dry' & 'wet' Specimens

Specimens	Treatment	'Dry'		'Wet'	
		σ	x	σ	x
40DG - 60CF	Unstabilised	84	1898	-	-
60DG - 40CF	Unstabilised	7	1926	-	-
80DG - 20CF	Unstabilised	58	1866	-	-
100DG	Unstabilised	19	1775	-	-
40DG - 60CF	3% Cement	22	1841	88	1840
60DG - 40CF	3% Cement	21	1895	21	1869
80DG - 20CF	3% Cement	10	1838	39	1821
100DG	3% Cement	6	1778	0	1775
40DG - 60CF	6% Cement	75	1885	0	1856
60DG - 40CF	6% Cement	4	1902	39	1872
80DG - 20CF	6% Cement	20	1839	16	1801
100DG	6% Cement	49	1760	18	1775
40DG - 60CF	3% Lime	10	1790	33	1813
60DG - 40CF	3% Lime	1	1839	66	1873
80DG - 20CF	3% Lime	16	1821	10	1811
100DG	3% Lime	17	1818	33	1769
40DG - 60CF	6% Lime	46	1863	1	1791
60DG - 40CF	6% Lime	6	1848	15	1825
80DG - 20CF	6% Lime	38	1782	5	1767
100DG	6% Lime	41	1688	18	1715

* The hyphens represent the disintegration of specimens

*Drying Shrinkage & Moisture Absorption (%)***Standard Deviations and mean of Drying Shrinkage & Moisture Absorption Specimens**

Specimens	Treatment	Drying Shrinkage		Moisture Absorption	
		σ	x	σ	x
40DG - 60CF	Unstabilised	0.08	0.80	-	-
60DG - 40CF	Unstabilised	0.26	0.78	-	-
80DG - 20CF	Unstabilised	0.22	1.78	-	-
100DG	Unstabilised	0.16	1.91	-	-
40DG - 60CF	3% Cement	0.08	0.15	0.0	12.8
60DG - 40CF	3% Cement	0.02	0.37	0.0	13.0
80DG - 20CF	3% Cement	0.06	0.66	0.2	15.1
100DG	3% Cement	0.09	1.64	0.1	16.7
40DG - 60CF	6% Cement	0.01	0.12	0.2	11.8
60DG - 40CF	6% Cement	0.01	0.16	0.0	13.1
80DG - 20CF	6% Cement	0.01	0.20	0.1	15.4
100DG	6% Cement	0.12	0.79	0.1	17.1
40DG - 60CF	3% Lime	0.01	0.12	0.2	13.3
60DG - 40CF	3% Lime	0.02	0.61	0.4	13.6
80DG - 20CF	3% Lime	0.09	1.51	0.2	14.5
100DG	3% Lime	0.12	1.75	0.2	16.4
40DG - 60CF	6% Lime	0.01	0.06	0.1	13.8
60DG - 40CF	6% Lime	0.01	0.20	0.1	14.8
80DG - 20CF	6% Lime	0.09	0.64	0.2	16.2
100DG	6% Lime	0.31	1.62	0.2	17.2

* The hyphens represent the disintegration of specimens