THE EFFECT OF CARBON DIOXIDE AND STEAM IN STRENGTH OF MODIFIED TRONOH'S MINING SAND USING QUICKLIME

By

NURUL 'AIN HARUN

FINAL YEAR PROJECT REPORT

Submitted to the Civil Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
Civil Engineering

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CERTIFICATION OF APPROVAL

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Approved:

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UNIVERSITI TEKNOLOGI PETRONAS
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January 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Nurul 'Ain Harun

ABSTRACT

Nowadays, ex-mining locations in Tronoh were being developed and their tailing sand is widely used in industry such as in ceramic and glass manufacturing, in manufacture of calcium silicate bricks and as fill material in highway construction project. The objectives of this project is to determine the optimum lime content at maximum compaction used to modify Tronoh's mining sand and their undrained shear strength by 2two conditions which is further treated by using carbon dioxide at 20 psi and 100°C of steam and without carbon dioxide and steam by curing period. Laboratory experiments that have been carried out in this project are sieve analysis, compaction test, addition of carbon dioxide and steam in mining sand-lime mixes and unconfined compression test. Sieve analysis indicates that sample of Tronoh's mining sand is classified in poorly graded sand. Optimum lime content of 10% at maximum dry density of 2.0178 Mg/m^3 and 8% optimum moisture content was used in every mixes. Then the strength of mining sand-lime mixes was compared with sand-lime-CO_2-steam mixes by curing period. The results indicated that undrained shear strength of sand-lime mixes is increase by curing, 29.5 kPa for 3 days to 275.36 kPa for 28 days. Undrained shear strength between sand-lime mixes with addition of carbon dioxide and steam by curing period were compared. Results indicated that immediate undrained shear strength of sand-lime mixes increase by duration of 1, 2 and 4 hours addition, where 1 hour test give 201.19 kPa, 203.47 kPa for 2 hours test and 232.75 kPa for 4 hours. Besides, increase in curing period of these mixes will increase their undrained shear strength of 2 hours test by 301.42 kPa for 3 days curing to 407.59 kPa for 7 days curing. Strength of 4 hours test give higher strength compared to 2 hours test which increase from 351.46 kPa for 3 days curing to 413.55 kPa for 7 days curing. This data can be used as references when strength is concerned in construction and manufacturing.

ACKNOWLEDGEMENT

The author is grateful to Allah S.W.T for the completion of this Final Year Project. Deepest gratitude goes to project supervisor, Miss Niraku Rosmawati Ahmad for her guidance, commitments and helps in ensuring that the author accomplished the project objectives. Special thanks to co-supervisor, Dr. Nasiman Sapari for his contributions in this project. The author would like to express special gratitude to the Geotechnical Engineering Laboratory assistant, Mr. Zaini and Miss Izhatul Imma for their assistance in helping the author conducting laboratory works.

Sincere thanks goes to other Civil Engineering lecturers who have involved directly or indirectly in this project for the help and support rendered. Appreciate their sharing, support and commitment in guiding the author upon completion of this project.

The author wishes to thank and convey affection to author's family and Syed Qamarul Hidayat for their constant support and encouragement throughout undertaking the project. Their sacrifices and sincerity will always be appreciated.

Last but not least, million thanks to all parties involved who contributed to the completion and success of this project.

Thank You.

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LIST OF ABBREVIATIONS

SiO_2	Silicon dioxide
Al_2O_3	Aluminum oxide
CaO	Calcium oxide
Fe_2O_3	Iron oxide
TiO_2	Titanium dioxide
MgO	Magnesium oxide
Na_2O	Sodium oxide
K_2O	Potassium oxide
Ca (OH_2)	Calcium Hydroxide
$CaCO_3$	Calcium carbonate
H_2O	water
BS	British Standard
USCS	Unified Soil Classification System
ASTM	American Society for Testing and Materials
C_u	Uniformity coefficient, the ratio of the 60% particle size to the 10% particle size
C_z	Coefficient of gradation
D_{10}	Effective size, the particle size for which 10% of particles are finer, and 90% are coarser
D_{30}	Diameter corresponding to 30% finer
D_{60}	Diameter corresponding to 60% finer
F_4	Percent passing 5.00 mm sieve
F_{200}	Percent passing 0.063 mm sieve
R_4	Percent retained on 5.00 mm sieve
R_{200}	Percent retained on 0.063 mm sieve
SP	Poorly graded sand
GW	Well- graded gravel
UC	Unconfined Compression
CBR	California Bearing Ratio

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Tronoh was active in open cast tin mining since 19th century; hence the availability tailing sand is high. Due to abundant source, readily available and cheap, mining sand is widely used in Perak including Tronoh in calcium silicate brick, glass and ceramic manufacturing and also used in construction of highway.

Mining sand in Tronoh area has best potential as highly containing silica. The raw mining sand has average SiO_2 higher than 95% and Al_2O_3 less than 1% and other minor composition of CaO, Fe_2O_3, TiO_2, MgO, Na_2O and K_2O as in Appendix B. Mostly, Tronoh's mining sand has bad particle distribution curve, highest percentage of particle larger than 500μm (Mohd Suhaili, 1995). Thus, mining sand has high permeability that can create significant problems for pavement and construction on ex-mining location exposed to settlement.

Lime is widely used for short-term soil improvements. A wide range of investigations has been performed on soil lime-stabilization in previous years by several authors (N.Litter, 1995). Lime is an excellent choice for short-term modification of soil properties. Lime can treat soil which has beneficial effect on the engineering properties of soil, strength gain, improved workability and enhanced durability (L. Smith, June 2004). Blending and compacting of lime to soil silica and alumina in the presence of water form cementing material where mainly carbonation, cation and base-exchange and flocculation-agglomeration occur, referrer to as pozzolanic reaction. The cementing products are calcium-silicate-hydrates and calcium-aluminates-hydrates (L. Smith, June 2004). From a practical viewpoint, the immediate changes in strength and stiffness of the soil-lime mixture. Compaction energy, moisture content and density, curing time and temperature and lime percentage influenced the strength of soil-lime mixture (K.S Heinick, 2001).

Long-term changes referred for largely improving strength and stiffness which influence by other factors such as addition of carbon dioxide and steam. Calcium oxide will react with CO_2 to form $CaCO_3$. When lime is mixed with water and sand, the result is cementing materials which hardens and secure particles together. At room temperature, the reaction of lime with carbon dioxide is very slow. It is speeded by mixing lime with water. The concept of sand-lime mixing is used in calcium silicate brick's manufacturing, mixture of clean raw materials was compress under high steam pressure (Rock Chemical Industries Malaysia Berhad, 2004).

1.2 Problem Statement

The long term performance of any construction project depends on the soundness of underlying soils. Unstable soil can create significant problems for pavements or structures. A good soil is when it can give and provide long-term strength and stability particularly with respect to the action of water and other environmental influences.

Mining sand is an uncompacted soil that in the end will give problems in any development. Nowadays, the development of Tronoh can be obviously seen; the upgrading of pavement, building, housing and etc. Mining sand or fine-grained soil must be modified first in order to serve or employed as sub grade or sub base in pavement system. Poor sub grade soil conditions can result in inadequate pavement support and reduce pavement life.

Over the time, the environmental influences such as precipitation and underground drainage will affected the physical of soil. Water will penetrate through cracks or weak zones and then will develop channels and voids beneath ground. Water will easily passing through sand particles with large grain size. A mix of both surface water and ground water will contribute to development of sinkhole.

1.3 Objectives and Scope of Study

There are several objectives needed to be achieved in this project which are:

- To determine the optimum lime content in modified Tronoh's mining sand.
- To measure the strength of compacted Tronoh's mining sand and lime mixture by curing period.
- To measure the effect of CO_2 and steam in strength of compacted Tronoh's mining sand and lime mixture by curing period.

CHAPTER 2

LITERATURE REVIEW

2.1 Tronoh's Mining Sand Location

2.1.1 Introduction

Tronoh was active in tin mining a long ago and nowadays many ex-mining locations appeared around 5 km to South of Tronoh's town. This location was connected by main road of Ipoh- Lumut. Mining or tailing sand is widely used in industry, construction and manufacturing because of its cheap cost and readily availability. Most of Tronoh's mining locations had been developed. Tronoh's ex-mining location showed in Figure 2.1, where the area is marked with the red line, around 5 km from Tronoh's town, represent by blue dotted line.

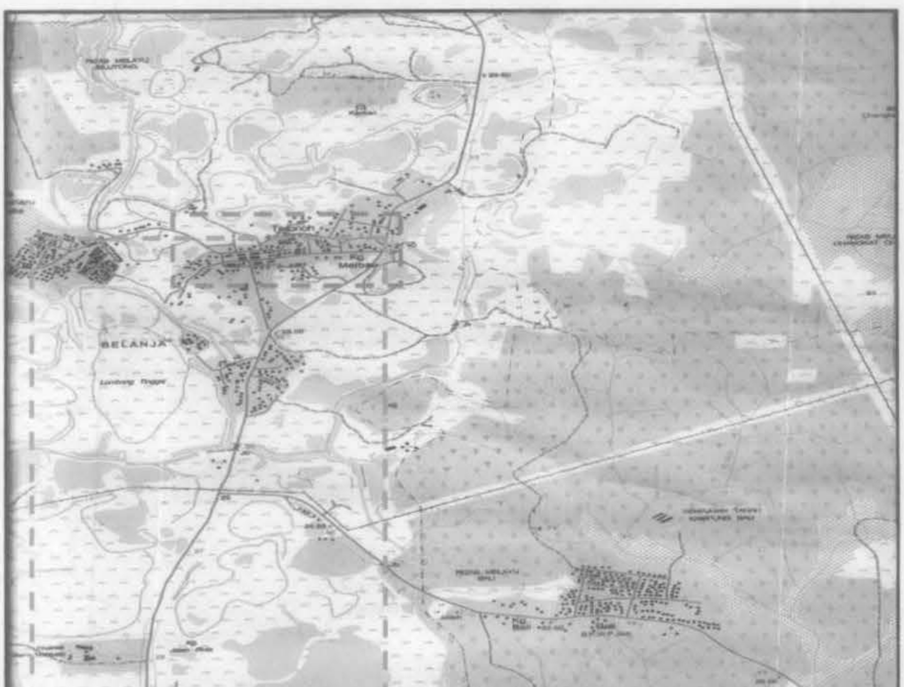

Figure 2.1 : Ex-mining location (Mohd Suhaili, 1995)

2.1.2 Physical Properties

Most of Tronoh's mining sand have a same physical characteristic which is has color of light brown, brown, light grey to dark grey. From observation, this mining sand is dirty. It's also silty and has gravel particle, size range from larger to small particle. In conclusion, mining sand has poor quality in particle size, where more gravel found with increase in depth of sampling (Mohd Suhaili, 1995).

Particle size of mining sand sample difference as depth increase. Mostly, there are two layers which is sand on the upper and gavel or slime on the lower part (Mohd Suhaili, 1995).

2.2 Soil Stabilization and Modification

Soil stabilization and modification is important in upgrading the condition of soil. There are many ways of mixed used to stabilize soil. Soil stabilization and modification using lime is proven can improve the condition of soil beneath the road and similar construction projects. In previous studies, the modification of clayey sand to improve their engineering properties is well described. It is shown that among the various stabilizing agents, the most prominent is lime. Besides, stabilized soil using lime is simple and can save time and money (American Road Builders Association, 2004).

Treating soils involved two steps, which are stabilization and modification. Some laboratory testing were also conducted in stabilized soil samples and factors that were taken into accounts such as the quality of soil, stabilization agents, amount of stabilization agent, size of sample, load during curing time, mixing time, temperature during curing, curing time, and specimen for unconfined compression test (P.Shivananda, 2004).

2.2.1 Lime

Quicklime is produced by the thermal dissociation of limestone. Its principal component is calcium oxide. In rock chemical industry-lime uses limestone aggregates with size ranges from 15mm to 32mm. The limestone is calcined in the kiln with temperature of around 1100°C. Quicklime produced is of high quality with minimum of 90% CaO. Rock chemical industry's quicklime is known for its high quality and continues to be successfully applied in the steel manufacturing, soil stabilization and building industry (Rock Chemical Industries Malaysia Berhad, 2004).

Lime in the form of quicklime or calcium oxide (CaO), hydrated lime or calcium hydroxide ($Ca\ [OH]_2$), or lime slurry can be used to treat soils. The chemical reaction transforming calcium carbonate (limestone – $CaCO_3$) into calcium oxide is reversible. Hydrated lime is created when quicklime chemically reacts with water. It is hydrated lime that reacts with soil particles and permanently transforms them into a strong cementations matrix (V.M. Malhotra, 1996). The reaction to form calcium oxide is shown below:

$CaCO_3 \rightarrow CaO + CO_2$..Equation 2.1

Reversible reaction to form calcium carbonate is when calcium oxide react with carbon dioxide. At room temperature, the reaction of lime with carbon dioxide is very slow. It is speeded by mixing lime with water. When lime is mixed with water, it forms calcium hydroxide. Reaction with carbon dioxide is similar to metamorphism process, where fluid activity (CO_2 and water) take part in the process as its agent. These agents will increase the rate of chemical reactions (S. Monroe, 2001). Reaction of calcium oxide with water and carbon dioxide is expressed as below:

$CaO + H_2O \rightarrow Ca\ (OH_2)$... ....Equation 2.2

$Ca(OH_2) + CO_2 \rightarrow CaCO_3 + H_2O$ ....Equation 2.3

Chemical composition is another factor that determines the quality of lime (G.L Mullins, 2005). This composition will react with soil to form cementing materials. Table 2.1 shows the standard chemical composition of lime used in industry. Properties of commercial quicklime are shown in Table 2.1.

Table 2.1: Properties of commercial quicklime (NLA, 1988).

Constituents	High Calcium Range (%)	Dolomitic Range (%)
CaO	92.25-98.00	55.50-57.50
MgO	0.30-2.50	37.60-40.80
SiO_2	0.20-1.50	0.10-1.50
Fe_2O_3	0.10-0.40	0.05-0.40
Al_2O_3	0.10-0.50	0.05- 0.50
H_2O	0.10-0.90	0.10-0.90
CO_2	0.40-1.50	0.40-1.50
Specific Gravity	3.2-3.4	3.2-3.4
Specific Heat at 38°C	442 J/kg	488 J/kg
Bulk density, pebble lime	880-960 kg/m³	880-960 kg/m³

2.2.2 Soil-Lime Reactions by Percentage of Lime

Lime has high percentage of CaO and thus it is used extensively to change engineering properties of fine-grained soils. The addition of lime to soil silica in the presence of water will initiates three primary reactions which are cation exchange and flocculation- agglomeration, pozzolanic reaction and carbonation. Cation exchange and flocculation normally occur in clay particles. Pozzolanic reaction is where soil silica, water and lime will form cementing materials. The resulting cementing products are calcium-silicate-hydrates and calcium-aluminates-hydrates. Carbonation occur when lime react with carbon dioxide, resulting calcium carbonate without formation of cementing materials (Kelly L. Smith, 2004).

Lime can improve workability and compatibility and reduce swelling and shrinkage potentials by saturating the soil particles with calcium ions. This leads to strength increase by pozzolanic and carbonation cementation processes. Cation exchange and pozzolanic reactions result in strength increase. The level of reactivity and hence strength gained in soil-lime mixtures depends on the level of pozzolanic product created (N. Little, 1996).

Studies concerning the performance of some soils under lime stabilization have been conducted by many researchers [e.g. A.Y.B. Anifowose (1989), K.S Heinick (2001), S.O. Faluyi (2005), Panagiotis Eskioglou (2005) and M. Celal Tonoz (2004)]. These studies have also concentrated on the effect of compaction energy, moisture content and dry density, curing time, lime percentage on the unconfined compressive strength of stabilized soil.

These studies were aimed at improving soils by using lime as stabilizing agent and its performance in powder form. The soil samples used in these studies derived from weathered sandstone, coastal plain sands, alluvial sands and expansive clay. The soil-lime mixture design technique was employed in the laboratory, and the percentages of lime used on the samples varied from 0% to10% by weight were prepared (M. Celal Tonoz, 2004). The changes were as a result of the changes in the chemical properties and the composition of the samples due to chemical reactions with lime additive (S.O. Faluyi, 2005). The peak CBRs were obtained at between 8% and 10% lime (A.Y.B. Anifose, 1989).

2.2.3 Soil-Lime Reactions by Curing Period

After soil-lime mixtures were compacted, the molds were wrapped in moisture proof bags and stored in a humid room to cure before testing. The curing periods adopted were 7, 14, 28 and 180 days for the unconfined compression tests and 0 to 28 days for the drained triaxial compression tests (K.S. Heinick, 2001).

According to previous studies, significant strength gain occurs after a relatively long period, which is the induction time necessary for the chemical pozzolanic reactions between mixtures (K.S. Heinick, 2001). Lime-clay mixture cured for 3, 7, 14 and 28 days were compared. As a result of reactions unaxial compressive strength increased after 28 days. In this study, the results indicated that if the curing period is less than 28 days, the strength of lime-treated samples is higher than those of natural samples (M. Celal Tonoz, 2004).

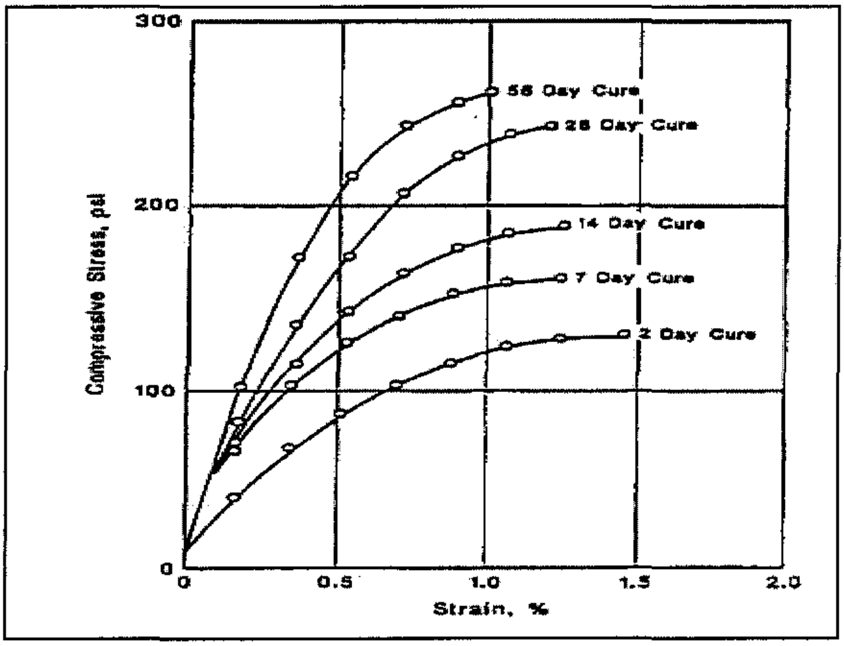

Figure 2.3: Strength of mixture increase with curing time (Sudarth, 1975)

2.3 Soil-Lime Compaction

Generally, specimens were molded at the optimum moisture content and maximum dry unit weight, according to the values obtained from the standard Proctor compaction tests. The addition of lime to the soil caused a reduction in the dry unit weight and an increase in the optimum moisture content (K.S. Heinick, 2001). Soil type has great influence on the maximum dry unit weight and optimum moisture content.

Compaction is a process that resulting in increase in soil density or unit weight, accompanied by a decrease in air volume. In this process, there is usually no change in water content. The degree of compaction is measured by dry unit weight and depends on the water content and compactive effort (weight of hammer, number of impacts, weight of roller and number of passes). For a given compactive effort, the maximum dry unit weight occurs at optimum water content (Davison, May 2000). Compaction is a process of increasing soil density and removing air, usually by mechanical means. The process involved pozzolanic reaction is time and temperature dependant. Therefore, if curing is applied, there is no change in size of the individual soil particles because the void is filled by lime (Kelly L.Smith, 2004).

2.4 Unconfined Compression Strength of Soils

Unconfined compression strength of soil is defined as the maximum unit stress obtained within the first 20% strain (California Transportation Laboratory, March 2000). According to ASTM Standard, unconfined compressive strength, q_u is defined as the compressive stress at which an unconfined cylindrical specimen of soil will fail in a simple compression test. For soils, the undrained shear strength is necessary for the determination of the bearing capacity of foundations, dams, etc. The undrained shear strength of clays is commonly determined from an unconfined compression test. The undrained shear strength of a cohesive soil is equal to one-half the unconfined compressive strength (Prof. Krishna, 2000).

Because the undrained shear strength is independent of the confining pressure as long as the soil is fully saturated and fully undrained, the equation obtained is as below (Das, 2002):

$C_u = q_u /2$..Equation 2.4

2.4.1 Factors Affecting Unconfined Compression Strength of Treated Soil

Lime or cement present can increase the mixture strength for some soils (Jacobson, 2002). Lime will react with silica soil in addition of water to form silicate or cementing material, thus increase the strength of mixture (Kelly L. Smith, June 2004). Figure 2.4 shows particles arrangement after being stabilized by lime. The reaction involved can be expressed as:

$CaO + H_2O \rightarrow Ca(OH_2) + Heat$ .... Equation 2.5

$Ca(OH_2) \rightarrow Ca + 2(OH)$ .... Equation 2.6

$Ca + OH + SiO \rightarrow CSH$ .... Equation 2.7

$Ca + OH + Al_2O_3 \rightarrow CAH$ .... Equation 2.8

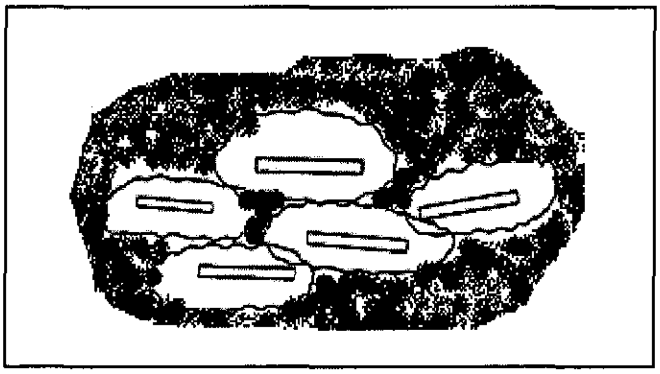

Figure 2.4: Parallel arrangements of soil-calcium-water particles (TTN, 1998)

Pozzolonic reaction is time and temperature dependent. The effect of lime treatment can be classified as immediate and long-term. Immediate modification effects are achieved without curing. Long-term stabilization effects take place during and after curing, and are important from a strength and durability (Kelly L.Smith, 2004). During long-term process, sand will use the moisture and lime to fill the voids and to finish the reaction, further increase the soil's strength (Guney, June 2005).

2.5 Concept of Calcium Silicate Bricks

The process of lime stabilization is simulated in calcium silicate shaped products, generally known as sand lime shaped products, which made from sand, lime and water (e.g., slaked or unslaked lime (quicklime or hydrated lime). They are typically mixed together, molded under mechanical pressure and may be hardened under steam pressure, such as in an autoclave. Process which chemically fuses the raw materials to form calcium silicate will produce the cementing materials of C-S-H and C-A-H (Klein, 2002).

Sand lime shaped products may have several different advantages over other masonry products such as clay or concrete pre-cast products. For example, sand lime shaped products may have accurate dimensions, smooth surface, sharp edges and little or no war-page. The process used to make sand lime shaped products may use siliceous wastes, thereby producing shaped products at less cost. The process may consume less energy than processes to make clay shaped products (Klein, 2002).

Standard mixtures of calcium silicate bricks were made from sand, lime and water. The manufacturing of calcium silicate bricks made of sand-lime mixture molded under mechanical pressure and hardened under steam pressure, of about 1–85 atmospheres at 100-300°C for 2-30 hours or 5–22 atmospheres at 160-220°C for 4-24 hours (Klein,2002).

CHAPTER 3

METHODOLOGY

3.1 Project Identification

In this project, the project methodology is as below:

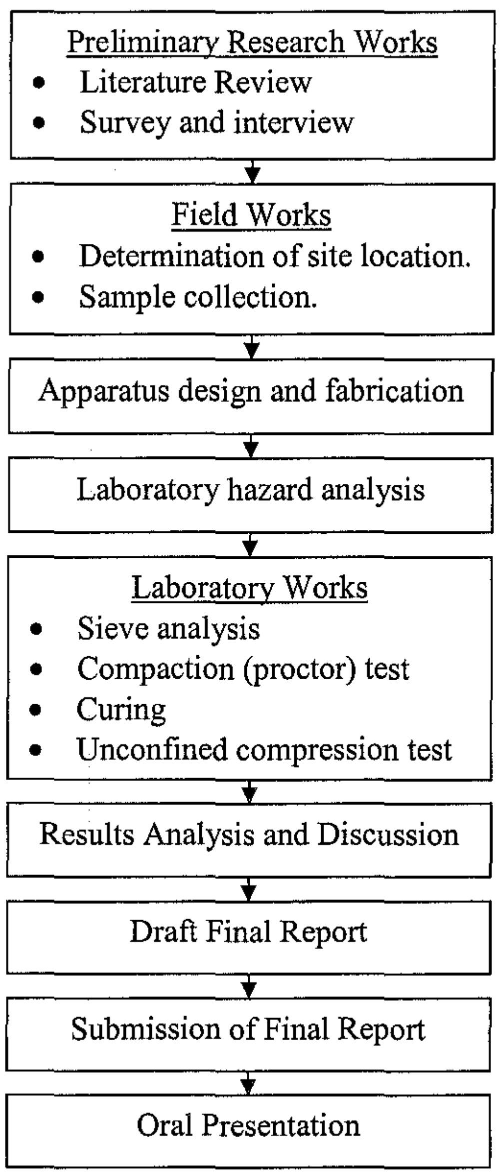

Figure 3.1: Flow Chart of Project

3.2 Site Location

The area covered in this project is the Tronoh's mining area. Based on information, the ex- mining area located about 1 km from Universiti Teknologi Petronas (UTP) and 5 km from Tronoh's town. Samples are collected in this region which the developments were progressively on-going. Figure 3.2 shows Tronoh's mining area where the site location is marked with the line.

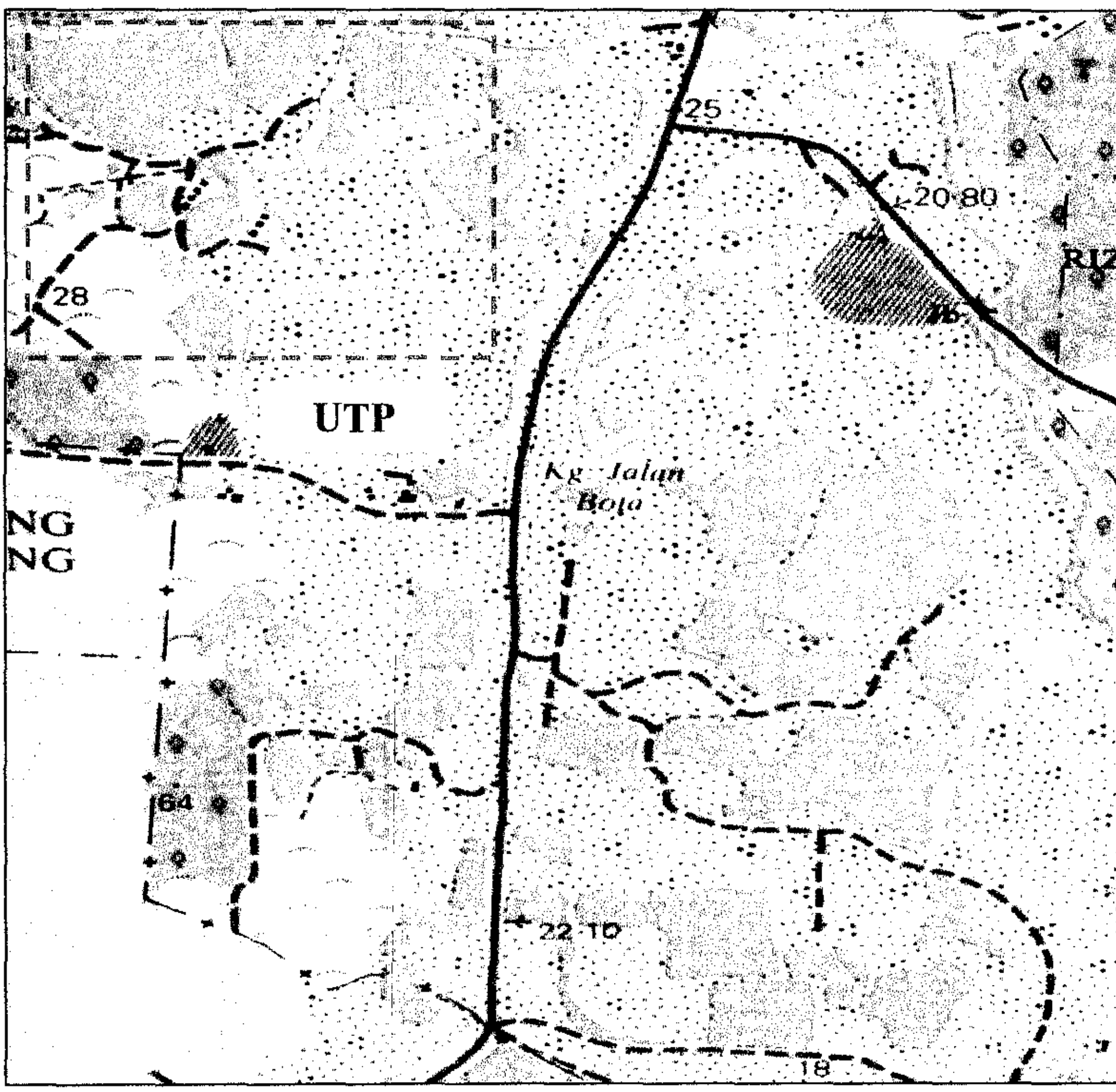

Figure 3.2: Tronoh Mining Area (Not to Scale)

3.3 Field Work

From observation, the site is suitable as the study area for this project because the location has high percentage of developments. Besides, this location is near to UTP. Soil samples are randomly collected around the mine. From field observation, the soil can be classified as sandy soil. The samples are then brought to laboratory for soil testing purposes. Figure 3.3(a) through Figure 3.3(d) shows the pictures captured during samples collection.

Figure 3.3(a): Site View

Figure 3.3(b): Site View

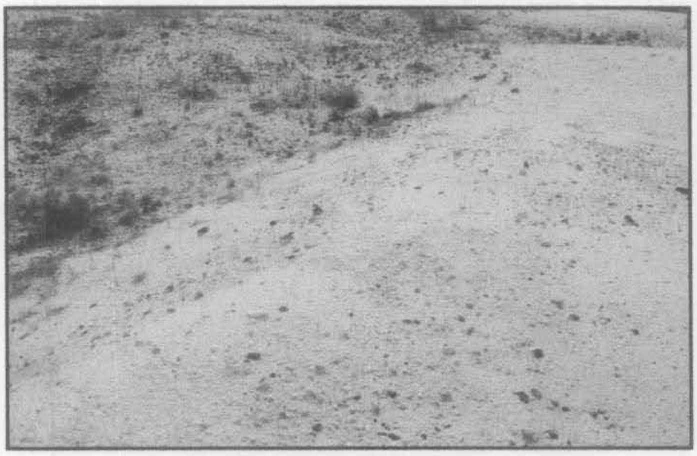

Figure 3.3(c): Sandy Soil

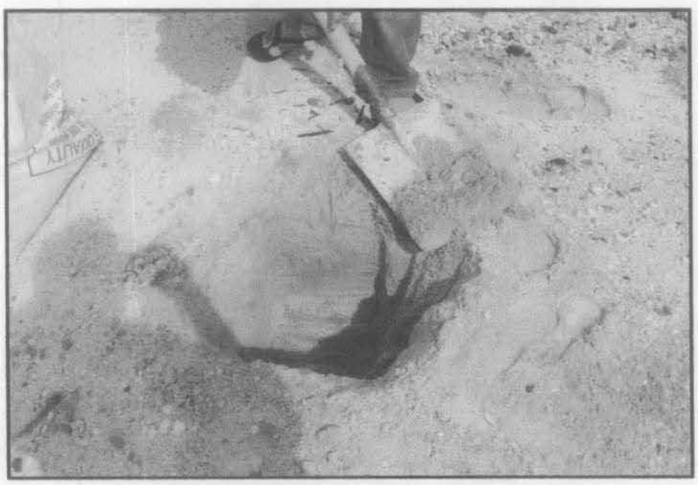

Figure 3.3(d): Sample Collection

3.4 Sample Preparation

3.4.1 Storage

After collection, samples were immediately stored in polythene bags or close container to prevent loss of moisture prior to their use. Deleterious materials such as roots were removed from the samples that were later air-dried (S.O. Faluyi, 2005).

3.4.2 Sieve Analysis

Sieve analysis was conducted to determine the size range of particles present in a soil and its classification (Das, 2002). The samples were sieve by passed through a No. 10 sieve (2 mm opening) to remove large particles (S.O.Faluyi, 2005). Finer particles will influence the denseness of packing which further increase in strength of soil-lime mixture.

One of primary factor that determine lime quality is particle or mesh size. Particle size is measured by standard size sieve mesh as showed in Figure 2.1 and is the main factor influencing the rate of reaction of lime applied to soil; the finer its grind, the more surface area lime has available to react with soil (G.L Mullins, 2005).

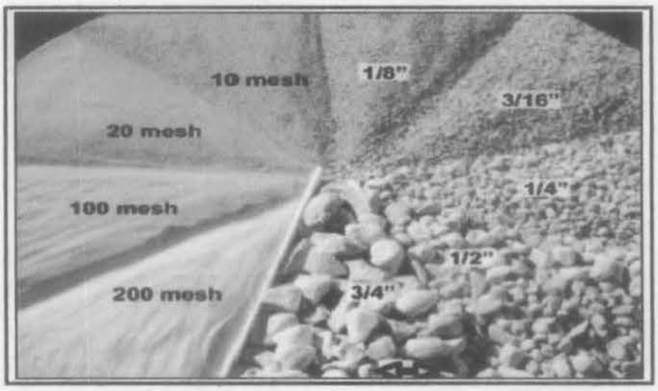

Figure 3.4: Standard particle size of lime (National Stone Association)

3.5 Apparatus for Laboratory Preparation of Stabilized Soil

In order to carry out test on sand-lime-CO_2-steam mixes, an apparatus is designed and fabricated. The apparatus was designed using purely steel in order to stand heat impact. Three channels were designed and fabricated for steam, CO_2 and output reaction which is water. The diameter of tube that is connect the channel with the steam and CO_2 sources is 5 mm. Figure 3.4 and 3.5 show the apparatus and a schematic diagram.

Figure 3.4: Apparatus

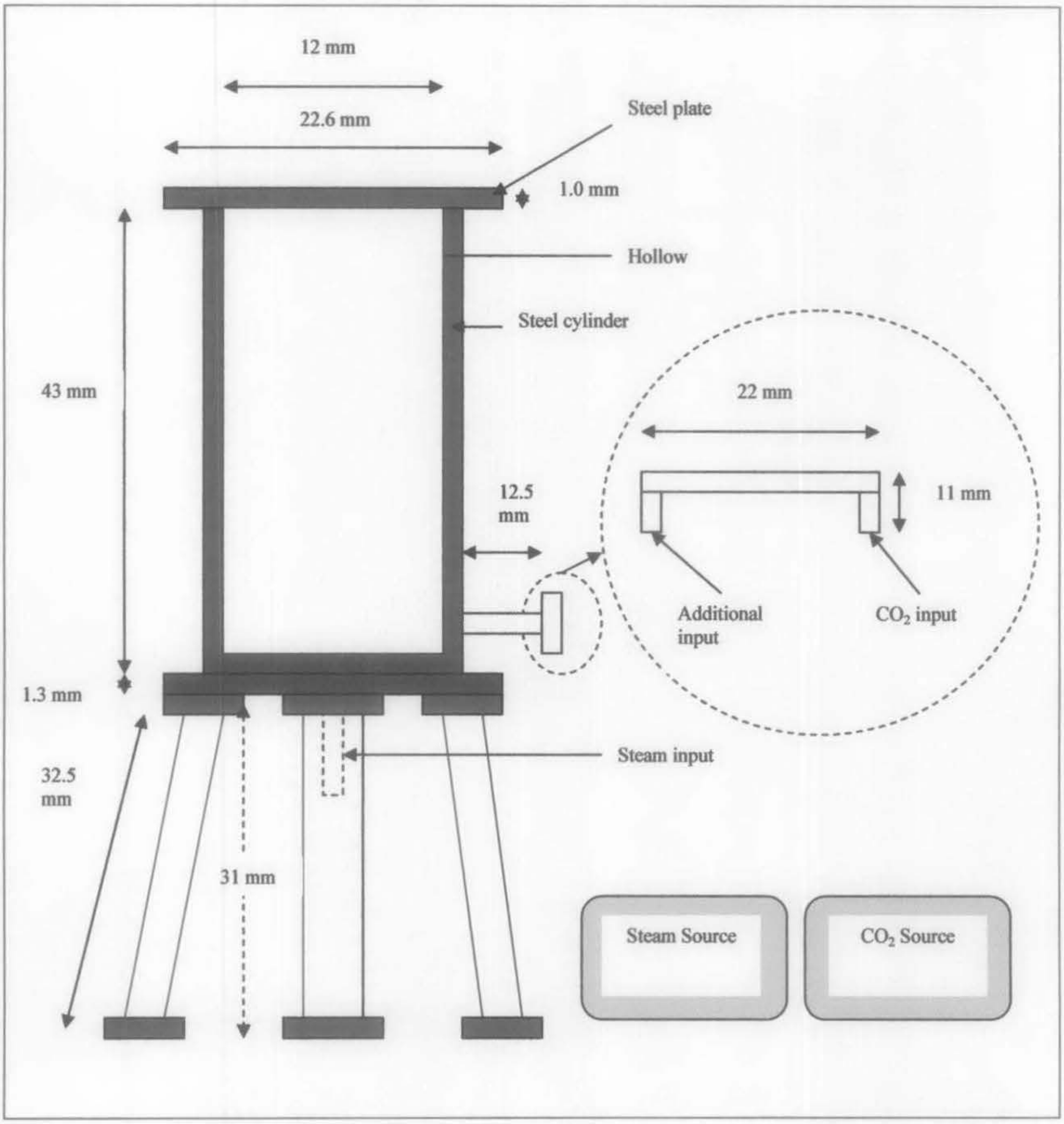

Figure 3.5: Schematic diagram of apparatus used to stabilize sand-lime mixture

3.6 Laboratory Work Hazard Analysis

3.6.1 Compaction (Proctor) Test

Hazard Identification	Safety Precaution
Misuse of this equipment may result in serious injury to personnel.	▪ Do not operate machine with wet hands. ▪ Read equipment's manual. ▪ Pay attention to all danger and caution statements.
This equipment generates moderate levels of audible noise when in use.	▪ Wear ear protection (ex. earplugs).
Hand injuries	▪ Wear gloves. ▪ No attempt should be made to adjust the mould or rammer during compaction. ▪ If any problem arises during compaction, immediately press the stop button.

3.6.2 Handling of Quick Lime (CaO)

Hazard Identification	Safety Precaution
CaO is more caustic and can produce severe burns quickly when in contact with moist skin. Can developed forms of skin irritation (dermatitis) through prolonged contact.	▪ quicklime should be washed off or at least brushed off immediately after contact with skin, since it is caustic ▪ Clothing: long sleeved shirt or sweat shirt. Rolled up sleeves or short sleeved shirts should not be permitted. ▪ Wear gloves.
Eyes are the greatest danger that exposed to lime hazard, where loss of sight may result from lime burns.	▪ Wear safety glasses with side shields, or goggles, at all times while working with lime. ▪ If lime is in the eyes, hold worker's eye open and flush out with water immediately. Too much water cannot be used.
Lime is in fine powder where mouth and nose are exposed to inhalation problem due to dusty environment.	▪ When construction conditions are quite dusty, a light-weight filter mask should be worn, although inhalation of some lime dust is not injurious.

3.6.3 Handling of Carbon Dioxide (CO_2)

Hazard Identification	Safety Precaution
Cold CO_2 gas can cause severe frostbite to the eyes or skin	▪ Protect your eyes with safety goggles or a face shield. ▪ Cover the skin to prevent contact with snow or cold gas, or with cold pipes and equipment. Protective gloves can be quickly and easily removed and long sleeves are recommended for skin protection and precaution.
Do not touch frosted pipes or valves	▪ If accidental exposure occurs, consult a physician at once. If a physician is not readily available, warm the areas affected by frostbite with water that is near body temperature. ▪ Keep work area well ventilated.

3.6.4 Handling of Heat (Steam) Pressure

Hazard Identification	Safety Precaution
The combination of exploding metal and superheated steam can be extremely dangerous.	▪ The area around the boiler should be kept clean of dust and debris, and no flammable materials should be stored near any boiler.
Correct steam pressure and boiler water level should be maintained at all times	▪ Having fire extinguisher equipment at hand should be taken to prevent injury to bystanders and equipment.
Boiler explosion	▪ The boiler and safety valves should be inspected on a regular basis.

3.7 Laboratory Work

The laboratory tests carried out are divided into two major laboratory tests which are compaction proctor test and unconfined compression test. The samples were sieve at a first place before compacted in six mixes of 2 to 12% lime. The optimum lime content at 10% is used for further test. The mix again divided into two main mixes, which are sand-lime mixes and sand-lime mixes with addition of carbon dioxide and steam. The sand-lime mixes were cured for 3, 7, 14 and 28 days at 33 °C. Another sand-lime mixes is added with carbon dioxide and steam for duration of 1, 2, and 4 hours with CO_2 pressure of 20 psi and steam at 100 °C. Unconfined compression test were immediately conducted on three samples of sand-lime-CO_2-steam mixes, while four samples were cured for 3 and 7 days.

3.7.1 Sieve Analysis

A sample of known weight is passed through a set of sieves of known mesh sizes. The sieves are arranged from larger to smaller diameters. The largest sieve size used is 5 mm and smallest is 0.063 mm. The sieves are mechanically vibrated for 15 minutes. The weight of sediment retained on each sieve is measured and converted into a percentage of the total sediment sample.

Samples were sieve by passed through 2 mm opening to remove large particles. In this project, the samples that passing through 600 μm sieve opening are used in sand-lime mixture to produce higher strength of soil-lime mixture. Strength gain by reduces the void between particles. Figure 3.6 shows sample before sieve.

Figure 3.6: Raw mining sand

3.7.2 Compaction (Proctor) Test

Standard proctor compaction test were performed to determine the maximum dry density and optimum water content corresponding to addition of lime in the mixes. In these tests, six samples of sand-lime mixtures were compacted in three equal layers by using light manual compaction test in which a 2.5 kg rammer is used. Each layer was received 27 blows (BS-1377 Part 4, 1990). The sample was test varies in lime and moisture content. Lime content increase by 2% by its weight and 2% for moisture content according to limitation given in British Standard.

Percentage of lime used in this test is varies from 2% to 12%, as shown in Table 3.1.

Table 3.1: Percentage of lime and sand in each sample

Sample	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Lime Content (%)	2	4	6	8	10	12
Percentage of Sand (%)	98	96	94	92	90	88

Data obtained were analyzed and compaction curves were plotted for each mixes to get the optimum lime content. Then, sample with maximum compaction will further tested. This sample was prepared in cylindrical block (specimen) of 38 mm by using sampling tube which has a sharp cutting edge (BS-1377 Part 8, 1990). Specimens then proceeded by addition of carbon dioxide and steam and curing process.

3.7.3 Addition of carbon dioxide and steam

The specimens were introduced to carbon dioxide, varies in duration and pressure. By interpreted calcium silicate brick manufacturing, specimens were tested under 1, 2 and 4 hours carbon dioxide. The pressures of carbon dioxide were varied in the range of 1-85 atmospheres. The pressure of 1.36 atmospheres (20 psi) was tested to specimens by considering the laboratory scale.

On the same time, the specimens made of sand-lime mixture were hardened under steam pressure at 100°C for 1, 2 and 4 hours. In calcium silicate brick manufacturing, mechanical pressure was introduced in producing high-strength sand-lime product, but in this project carbon dioxide was introduced by simulated metamorphism process.

Table 3.2: Addition of carbon dioxide and steam pressure

CO_2/steam (hr) / Curing period (day)	**1**	**2**	**4**
0	x	x	x
3		x	x
7		x	x

3.7.4 Curing

All the specimens were wrapped in moisture proof bags and stored in a humidity oven to cure before testing. Standard humid temperature of 33°C was set. The curing periods adopted in this project were 3, 7, 14 and 28 days for sand-lime specimens. On the other hand, sand-lime-carbon dioxide-steam specimens were cured for 3 and 7 days only due to time constraints.

3.7.5 Unconfined Compression Test

- Sand-lime mixture

The unconfined compression test is conducted to determine unconfined compressive strength of cylindrical specimen of soil. After being cured for days, four specimens were subjected to an axial load which rapidly applied to the specimen to cause failure. Axial compression is applied at constant rate of deformation (BS-1377 Part 8, 1990). Immediate unconfined compression test can't be done due to sand's brittleness.

- Sand-lime-carbon dioxide-steam mixture

Four specimens have been tested after being cured for 3 and 7 days with 2 and 4 hours carbon dioxide. Addition of carbon dioxide and steam induced the chemical reaction between the mixtures. Immediate unconfined compression test was also conducted for three specimens with different duration of carbon dioxide pressure of 1, 2 and 4 hours and 100°C steam pressure. Test conducted on mixtures were shown in Table 3.2.

CHAPTER 4

RESULTS & DISCUSSIONS

4.1 Sieve Analysis

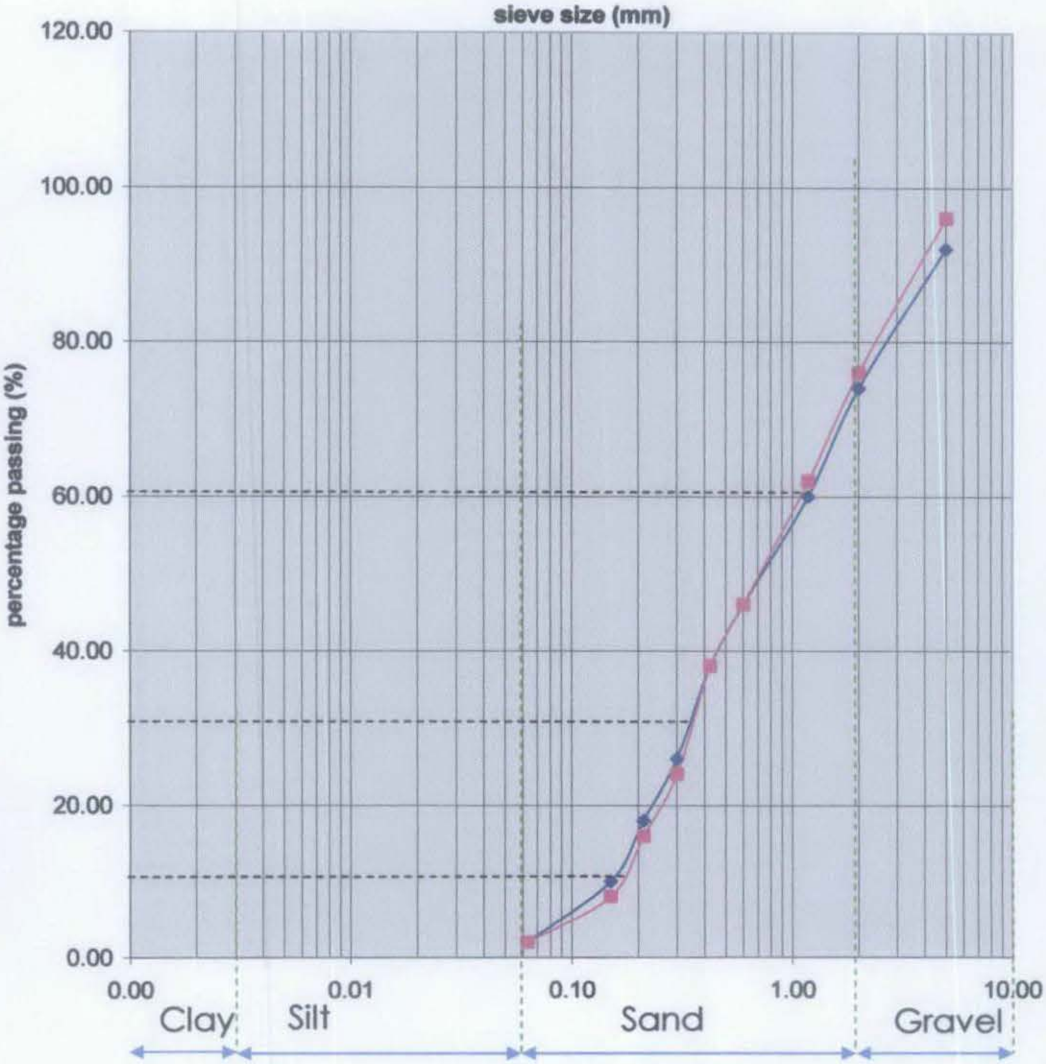

Figure 4.1: Particle Size Distribution Curve of Mining Sand Samples

Table 4.1: Soil Parameter and Classification Based on USCS

Sample	D_{60}	D_{30}	D_{10}	Uniformity Coefficient, C_u $C_u = D_{60}/ D_{10}$	Uniformity Coefficient, C_z $C_z = D_{30}^2/ (D_{60} x D_{10})$	R_4	R_{200}	R_4 / R_{200}	Soil Classification
1	1.2	0.34	0.16	7.5	0.602	8.0	97.02	0.0825	Poorly Graded Sand
2	1.22	0.35	0.18	6.75	0.558	4.0	97.23	0.0411	Poorly Graded Sand

Figure 4.1 shows the particle distribution of two samples of mining sand. From the graph in Figure 4.1, samples are classified as sand and gravel. Table 4.1 shows soil parameter and classification based on USCS system. From Table 4.1, the samples are classified as poorly graded sand (SP). Detailed calculations are attached in Appendix D. Particle size of sand influences the speed at which the material dissolves where finer the particle will give higher strength due to adhesion behavior.

4.2 Effect of Lime on Compaction

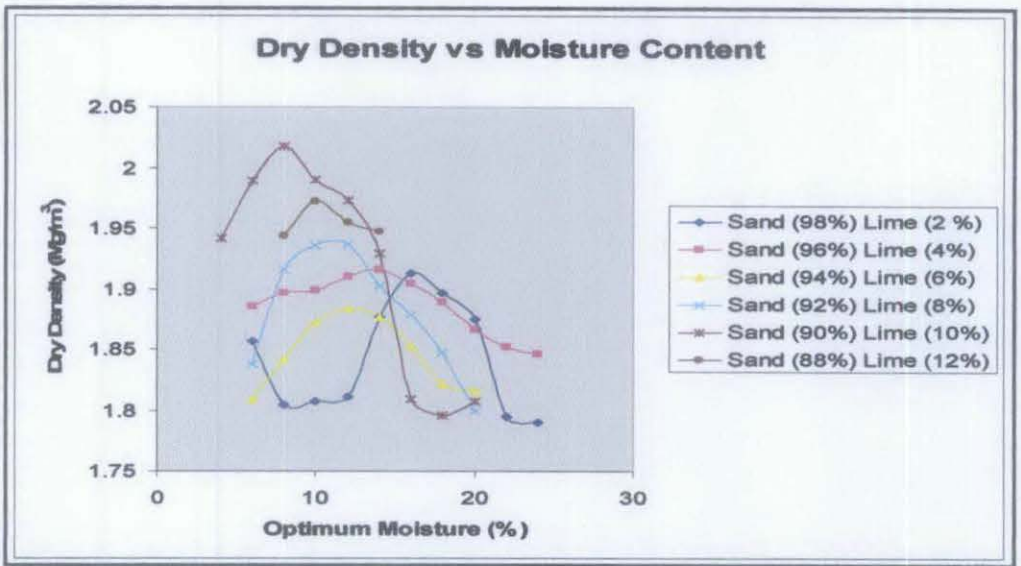

Figure 4.2: Dry density vs. moisture content curves by lime percentage

Table 4.2: Summary of maximum dry density and optimum moisture content

Sample	Lime Content (%)	Percentage of Sand (%)	Maximum Dry Density (Mg/m ^{3})	Optimum Moisture Content (%)
Sample 1	2	98	1.9132	16.0
Sample 2	4	96	1.9156	14.0
Sample 3	6	94	1.8829	12.0
Sample 4	8	92	1.940	11.2
Sample 5	10	90	2.0178	8.0
Sample 6	12	88	1.9719	10.0

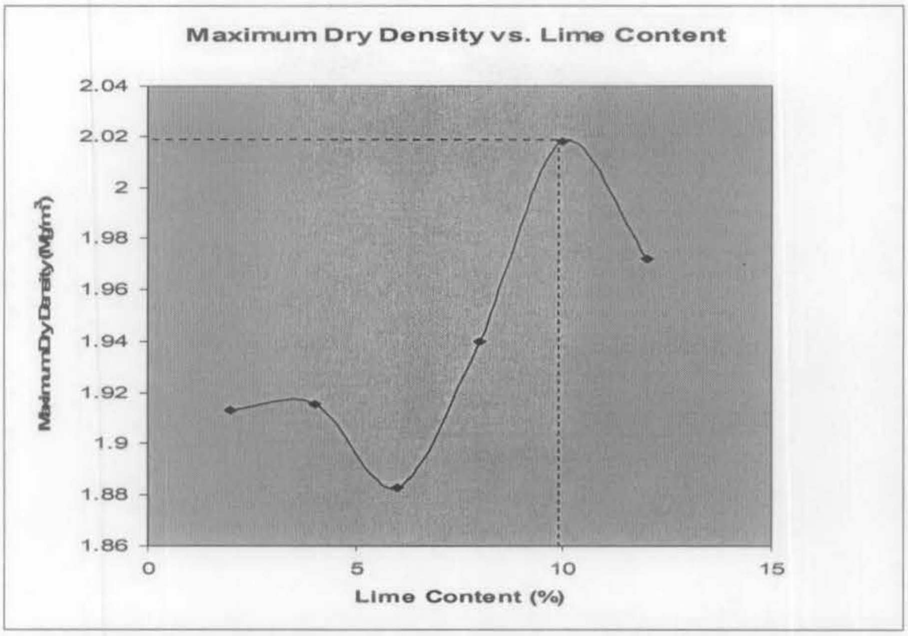

Figure 4.3 (a): Maximum Dry density vs. Lime Content

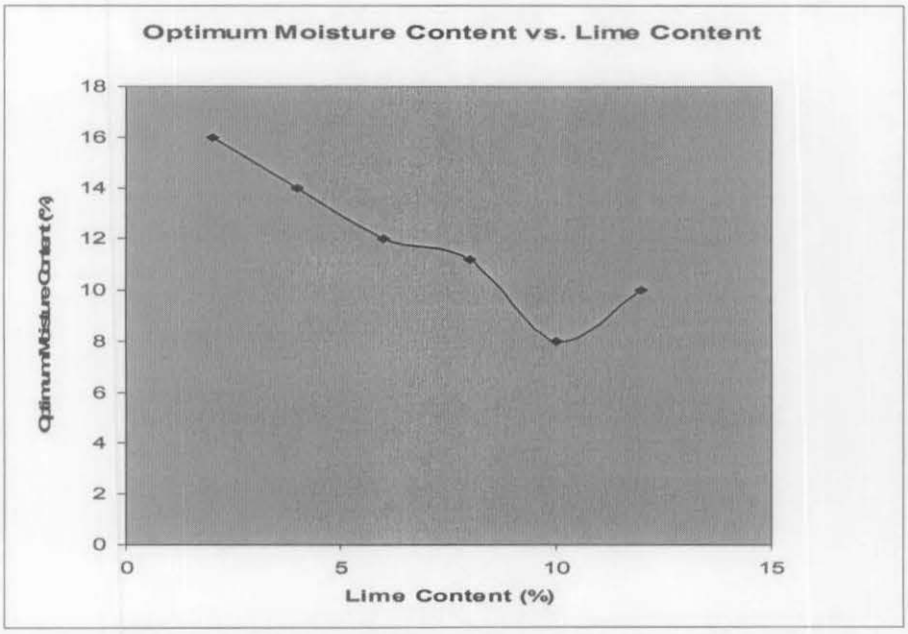

Figure 4.3(b): Optimum Moisture Content vs. Lime Content

Standard proctor compaction tests were performed on the sample taken from the study area to determine the compaction parameters; maximum dry density and optimum moisture content. Dry density-moisture content curves were plotted and shown in Figure 4.2. From the curve, a correlation between optimum moisture content and corresponding maximum dry density can be seen for each sample. The dry density is maximum when optimum moisture content. The detailed calculations are attached in Appendix E.

Maximum dry density and the optimum moisture content of sample vary in lime content are summarized in Table 4.2. Maximum dry density is increased from Sample 1 to Sample 5 and decreased after achieved full compaction. Sample 5 achieved the highest compaction of 2.0178 Mg/m^3. Optimum moisture content used to achieve maximum compaction is 8 %.

Figure 4.3 (a) and (b) show the addition of lime to mining sand caused an increase in the dry density and a reduction in the optimum moisture content. Sand and lime need water to react. The present of moisture in the mixes will provide pozzolanic reaction by chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementing properties. Thus, after obtained optimum lime content, the excessive water doesn't use in reaction anymore.

4.3 Effect of Lime and Curing Period on Shear Strength

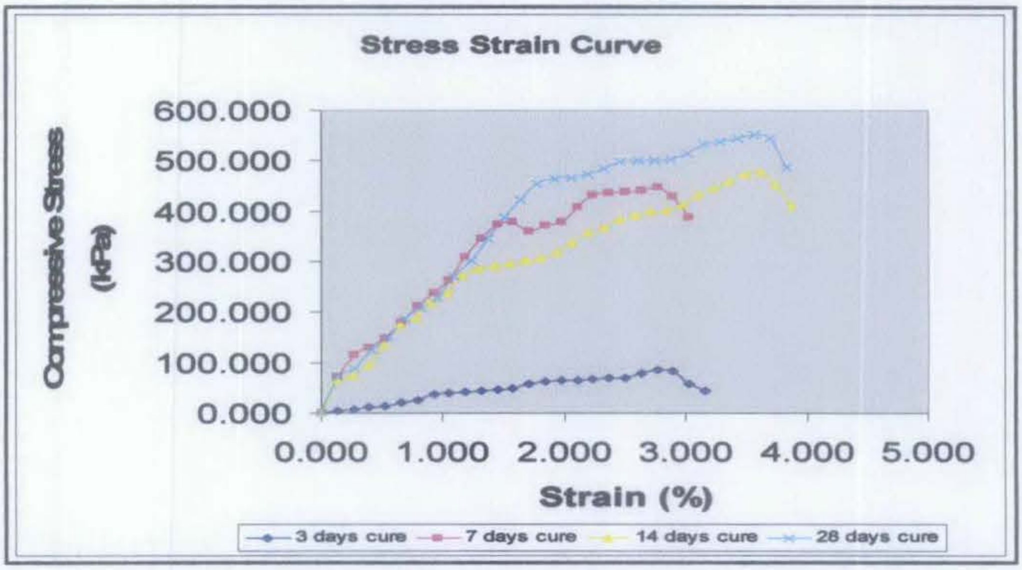

Figure 4.4: Stress- strain curves by curing period

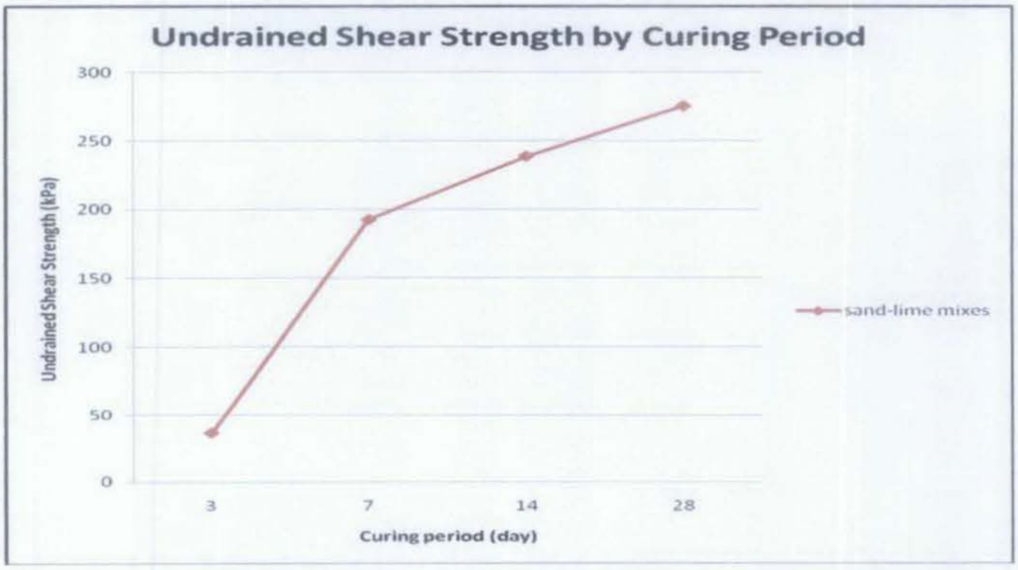

Figure 4.5: Effect of curing period on shear strength

Table 4.3: Summary of unconfined compressive strength of sand-lime mixtures

Sample	Curing period (day)	Undrained Shear Strength	Axial Strength at Failure (%)
Sample 1	3	36.3	2.632
Sample 2	7	192.4	2.763
Sample 3	14	238.47	3.611
Sample 4	28	275.36	3.630

Mining sand samples exhibit improvement in strength after being stabilized with lime. As the strength of soil-lime mixture increases with curing time, the stiffness of the mixture also increases, as measured by a reduction in percent strain during the unconfined compression test. Unconfined compression stress strain curve for each sample were plotted and shown in Figure 4.4. From the curve, the strength of mining sand- lime mixture increase as the curing time increase at 33°C. The detailed calculations are attached in Appendix F.

Unconfined compressive strength of sample with various curing period are summarized in Table 4.3. Undrained shear strength is increase from 36.3 to 275.36 kPa in 28 days. It is about 86% strength increment until 28 days of curing. Figure 4.5 showed the correlation of shear strength of sand-lime mixes by curing period.

4.4 Effect of Lime, CO_2, Steam and Curing Period on Shear Strength

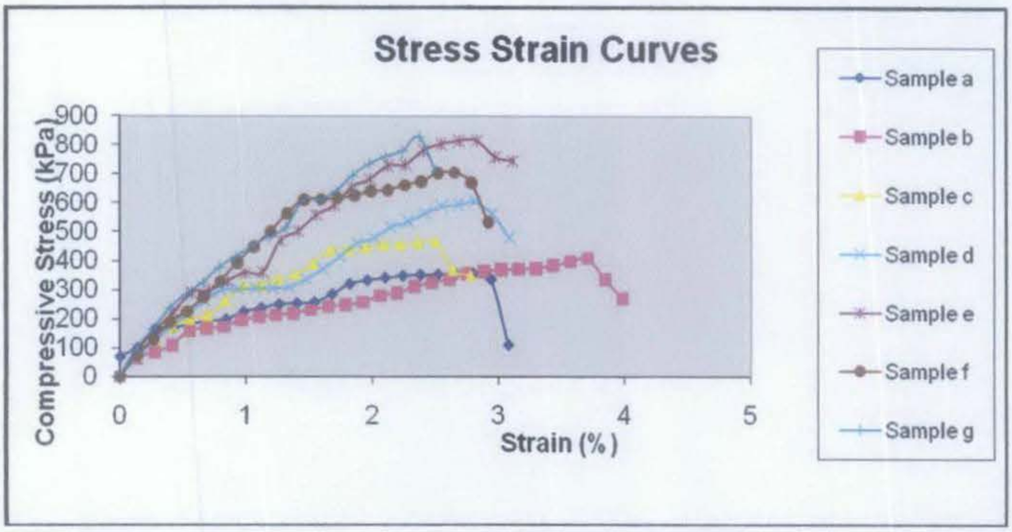

Figure 4.6: Stress- strain curve by curing period and duration of CO_2-steam

Table 4.4: Summary of unconfined compressive strength of sand-lime-CO_2-steam mixes

Sample	Curing Period (day)	CO_2 (hour)	Maximum UC Strength (kPa)
Sample a	-	1	402.37
Sample b	-	2	406.93
Sample c	-	4	465.50
Sample d	3	2	602.83
Sample e	3	4	815.18
Sample f	7	2	702.92
Sample g	7	4	827.10

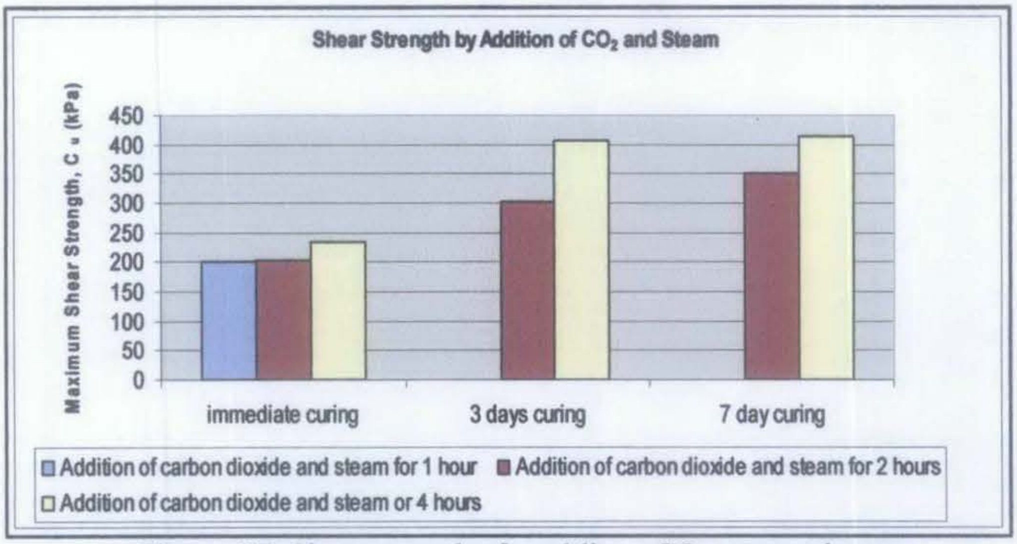

Figure 4.7: Shear strength of sand-lime- CO_2-steam mixture

Unconfined compression test were performed on samples with various duration of carbon dioxide-steam and curing period. This test was carried out to determine their unconfined compression strength with different curing period. Stress strain curves were plotted and shown in Figure 4.6. From this graph, the strength increase with longer curing period and duration of CO_2-steam. The detailed calculations are attached in Appendix G.

Unconfined compressive strength of different details of sample is summarized in Table 4.4. As immediate UCT conducted, the strength showed a linear increment with duration of carbon dioxide-steam addition from 201.19 kPa to 232.75 kPa. The strength further increased by curing period of 3 and 7 days. By 2 hours addition of CO_2-steam, strength increase from 301.42 kPa to 351.46 kPa and 407.95 kPa to 413.55 kPa for 4 hours addition.

Reaction of lime and carbon dioxide is slow at room temperature, as illustrated in Table 4.6 which to compared the UC strength of sand-lime mixes with or without addition of CO_2 and steam by different duration to sand-lime mixes by curing period. Immediate UC strength with addition of CO_2 and steam for 1 hour is higher than 3 and 7 days curing of sand-lime mixes without CO_2 and steam. Immediate UC strength for duration of 2 and 4 hours with addition of CO_2 and steam lower compared to sand-lime mixes for 14 and 28 days curing. This proved that curing duration play a very important role in strengthening the mixture.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

On the basis of the results and discussions presented for current progress, several conclusions can be drawn. Tronoh's mining sand is classified as poorly-graded sand (SP). Sand is already a good engineering material, but in certain conditions, sand give problem in construction and development. So, Tronoh's mining sand need some modification. A well- known solution of lime addition to modified soil is used. Soil compaction is a serious threatening factor, which should be taken into consideration, regarding the strength of mixture. Sand-lime mixtures were compacted and the maximum compaction achieved is 2.0178 Mg/m^3 when 10% lime is added with optimum moisture content of 8 %.

Sample 5 were cured for 3, 7, 14 and 28 days and resulted in increase undrained shear strength, c_u by curing period. The reaction of sand-lime is hardened with ages where the shear strength showed the increment from 36.3 kPa to 275.36 kPa.

Based on results, addition of carbon dioxide and steam to sand-lime mixtures had been proven can increase the shear strength of the mixtures. Although the reaction of carbon dioxide and steam with sand-lime mixtures were slow, the strength can be increased by longer curing period. Carbon dioxide increased the rate of chemical activity of the sand-lime mixtures. This reaction takes a long time to complete, like metamorphism. That is a reason why the mixes experienced a little increment in shear strength. Introducing steam to the mixtures actually can posses high compressive strength. The concept of calcium silicate bricks is applied. Reaction of sand-lime mixtures with carbon dioxide and steam increases the rate of chemical reaction, thus produce more cementing material of calcium hydroxide to stick the particle together.

5.2 Recommendations

The problem encountered until current progress of this project is to extrude the sand- lime mixes from compaction mould for curing process. This is due to brittleness of mining sand. It is recommended to avoid immediate extruding of the sample.

Due to time constraint, this project only focus on unconfined compressive strength of optimum lime content at maximum compaction. It is recommended to further test on different soil-lime percentage with addition of carbon dioxide and steam.

The curing period adopted in this project is only up to 28 days. Processes involved pozzolanic reactions take a long time for strength gain. Hence, it is recommended to increase the curing period.

Besides of curing period, temperature of curing also plays a role in strength gain by the mixture. Delay period is strongly dependent on the temperature of curing, where strength gain after relatively a long period for the chemical pozzolanic reactions between lime, water, and carbon dioxide to form a new cementitious phase. Increase in temperature of curing will accelerates the reaction of mixture. A further study on the effect of temperature of curing is suggested in future.

This project only focuses on carbon dioxide with pressure of 20 psi. Carbon dioxide increase strength of mixture by increase the rate of chemical reaction. Thus, increase in pressure of carbon dioxide will further increase strength of the mixture. It is recommended to test the mixture with carbon dioxide pressure higher than 20 psi. Laboratory experiment involved small scale measure, so the apparatus should be redesign. It is also recommended to perform X-Ray Diffraction of sand-lime-CO_2-steam to see new mineral composed.

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APPENDIX A

PROPOSED GANTT CHART

Project Title : Effect of Carbon Dioxide and Steam in Strength of Modified Tronoh's Mining Sand Using Quicklime

Student Name : Nurul 'Ain Harun

Student ID : 5722

Supervisor : Miss Niraku Rosmawati Ahmad

Co-supervisor : Dr. Nasiman Sapari

NO.	DETAILS / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Study week	After final	within 2 weeks
1	Literature Review	√	√	√															
2	Submission of Progress Report 1			√															
3	Site selection and Soil sampling				√														
4	Design and fabrication of apparatus					√	√												
5	Laboratory work				√	√	√	√	√	√	√	√	√	√	√				
6	Submission of Progress Report 2									√							√		
7	Submission of first draft of Interim Report to Supervisor															√			
8	Submission of Dessertation Final Draft																√		
9	Oral Presentation																	√	
10	Submission of Project Dessertation																		√

APPENDIX B

MINERAL PROPERTIES

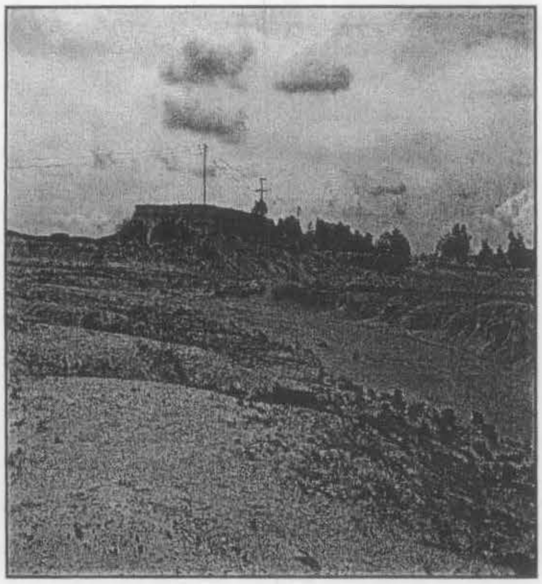
Average mineral composition of Tronoh's raw mining sand

Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	LOI
A	97.9	0.72	0.16	0.24	0.03	0.03	0.02	0.07	0.23
B	98.0	0.63	0.13	0.24	0.03	0.04	0.02	0.10	0.26
C	97.9	0.64	0.14	0.29	0.02	0.02	0.02	0.11	0.31
D	98.1	0.59	0.13	0.26	0.02	0.03	0.02	0.04	0.23
E	98.0	0.67	0.14	0.23	0.04	0.03	0.03	0.05	0.30
F	97.4	0.74	0.24	0.36	0.03	0.02	0.02	0.06	0.36
G	98.2	0.43	0.14	0.29	0.03	0.03	0.01	0.04	0.35
H	97.4	0.74	0.22	0.42	0.04	0.02	0.02	0.10	0.32
J	97.3	0.76	0.20	0.42	0.02	0.02	0.01	0.11	0.31
K	96.5	1.05	0.26	0.56	0.02	0.02	0.02	0.32	0.38
L	97.8	0.64	0.15	0.24	0.03	0.02	0.02	0.09	0.28
N	97.1	0.84	0.20	0.41	0.02	0.02	0.01	0.05	0.42
Q	97.6	0.85	0.17	0.29	0.01	0.02	0.01	0.03	0.39
R	98.4	0.41	0.13	0.24	0.01	0.02	0.02	0.07	0.21

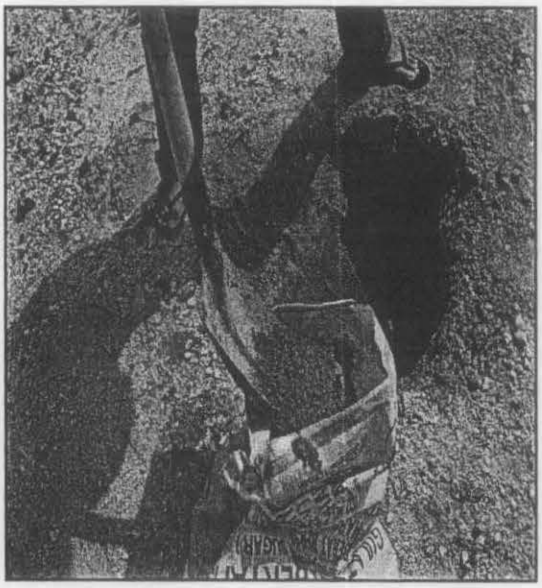
APPENDIX C

SITE VIEWS & SOIL SAMPLING PICTURES

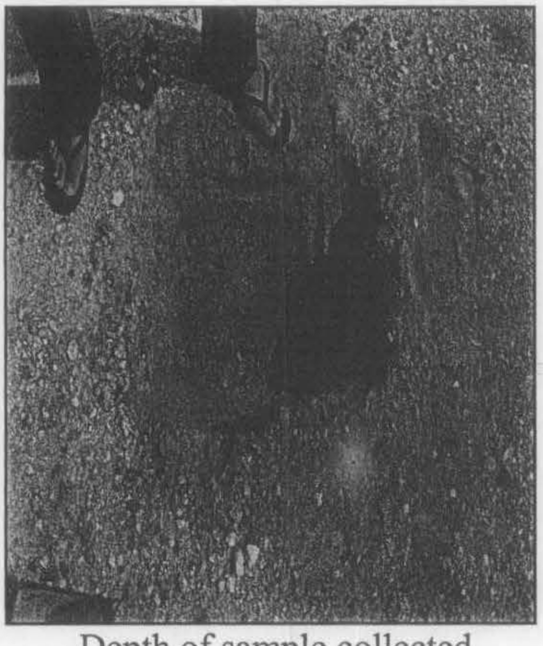
Sample collection and Preparation: Tasik Putra



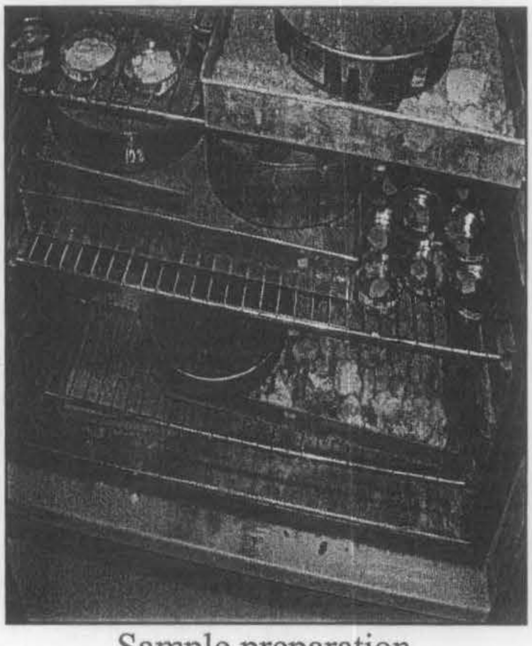
Site location



Sample collection



Depth of sample collected



Sample preparation

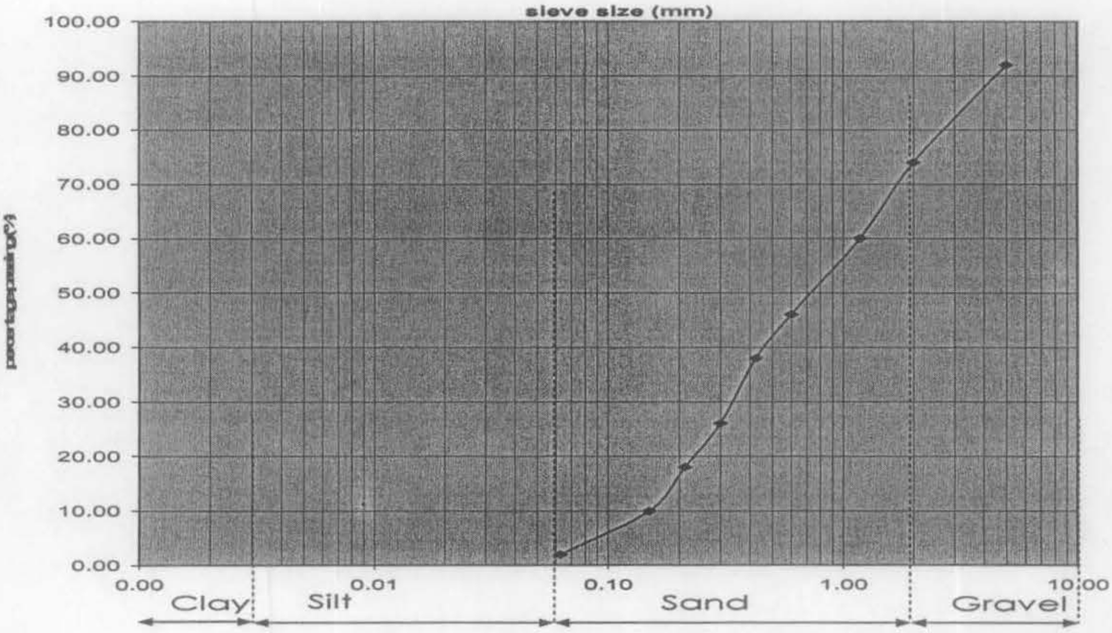
APPENDIX D
SIEVE ANALYSIS CALCULATIONS

RESULT & CALCULATION

Sieve analysis

Calculations (Sample 1)

Sieve Analysis: Sample 1



$D_{60} = 1.20$ mm

$D_{30} = 0.34$ mm

$D_{10} = 0.16$ mm

Uniformity coefficient, $C_u = D_{60} / D_{10}$

$= 1.20 / 0.16 = 7.50$

Coefficient of gradation, $C_z = D^2_{30} / (D_{60} \times D_{10})$

$= (0.34)^2 / (1.20 \times 0.16) = 0.602$

$F_{200} = 2.98 < 5$

$R_{200} = 100 - 2.98 = 97.02$

$F_4 = 96.0$

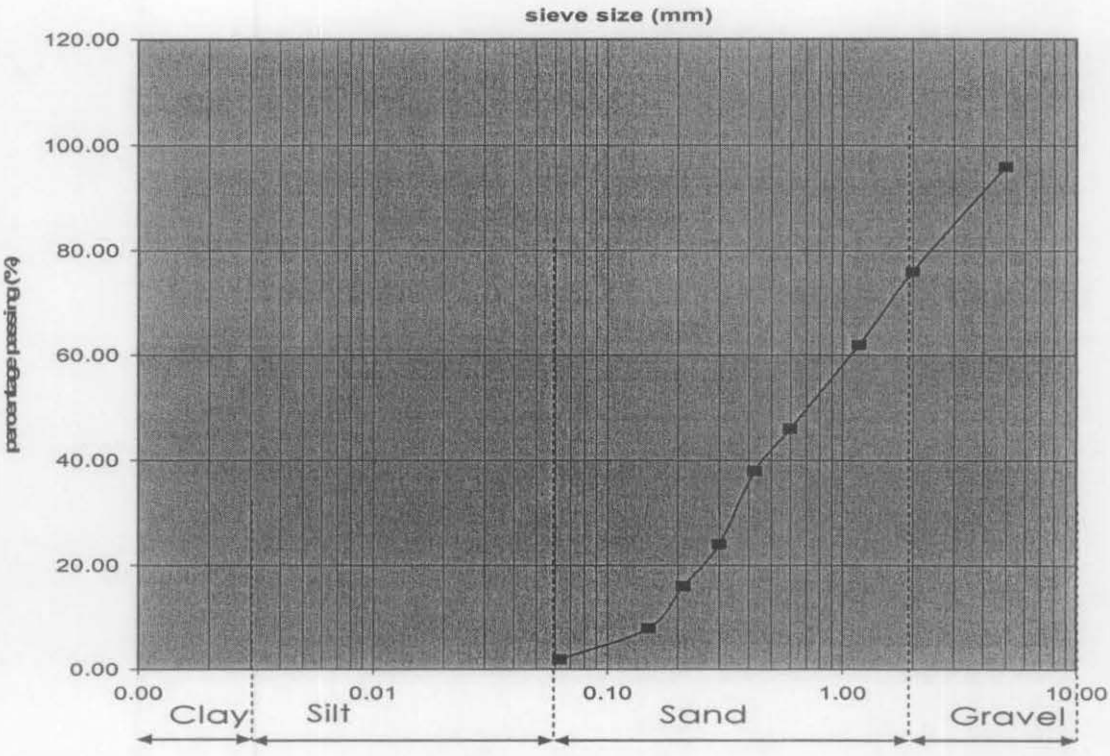
$R_4 \quad = 100 - 92.0 = 8.0\% < 15\%$

$R_4 / R_{200} \quad = 8.0 / 97.02 = 0.0825 < 0.5$

Thus, this soil is sandy. Based on Unified Soil Classification System, the group symbol is **SP.** For this soil, $R_4 = 8\%$, SP <15% gravel, the group name is **poorly graded sand.**

Calculations (Sample 2)

Sieve Analysis: Sample 2



$D_{60} = 1.22$ mm

$D_{30} = 0.35$ mm

$D_{10} = 0.18$ mm

Uniformity coefficient, $C_u = D_{60} / D_{10}$

$= 1.22 / 0.18 = 6.78$

Coefficient of gradation, $C_z = D^2_{30} / (D_{60} \times D_{10})$

$= (0.35)^2 / (1.22 \times 0.18) = 0.558$

F_{200}	$= 2.77 < 5$
R_{200}	$= 100 - 2.77 = 97.23$
F_4	$= 96.0$
R_4	$= 100 - 96.0 = 4.0\% < 15\%$
R_4 / R_{200}	$= 4.0 / 97.23 = 0.0411 < 0.5$

Thus, this soil is sandy. Based on Unified Soil Classification System, the group symbol is **SP.** For this soil, $R_4 = 4\%$, SP <15% gravel, the group name is **poorly graded sand.**

APPENDIX E

COMPACTION (PROCTOR) TEST CALCULATION

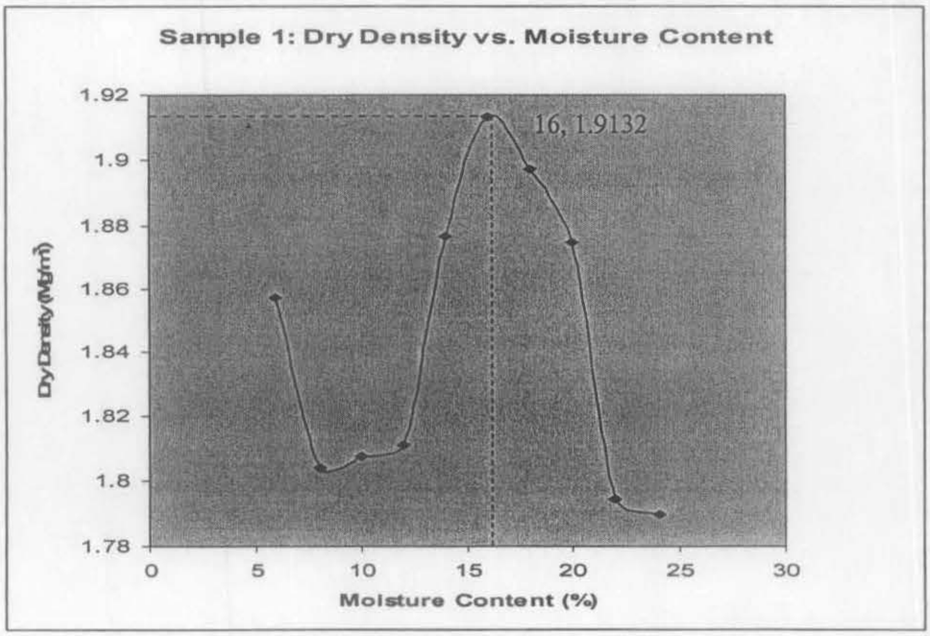
RESULT & CALCULATION

Proctor Test (sand- lime mixes)

Sample 1

Location	: Tronoh	Weight of hammer	: 2.5 kg
Soil Description	: Mining sand	No. of blows	: 27
Volume of mould	: 996.00 cm^3	No. of layers	: 3
Lime content	: 2%	% of sand	: 98%

Test	1	2	3	4	5	6	7	8	9	10
Water content (%)	6	8	10	12	14	16	18	20	22	24
Mass of mould + base (g), m1	6320	6320	6320	6320	6320	6320	6320	6320	6320	6320
Mass of mould + base + soil (g), m2	8280	8260	8300	8340	8450	8530	8550	8560	8500	8530
Mass of compacted soil (g)	1960	2030	1980	2110	2130	2300	2230	2330	2180	2300
Bulk density, ρ (Mg/ m^3)	1.9683	1.9482	1.9884	2.0285	2.139	2.2193	2.2394	2.2495	2.1892	2.2193
Dry unit weight, ρ_d (Mg/ m^3)	1.8569	1.8039	1.8076	1.8112	1.8763	1.9132	1.897	1.8745	1.7944	1.7898



Sample 2

Location : Tronoh

Soil Description : Mining sand

Volume of mould : 996.00 cm^3

Lime content : 4%

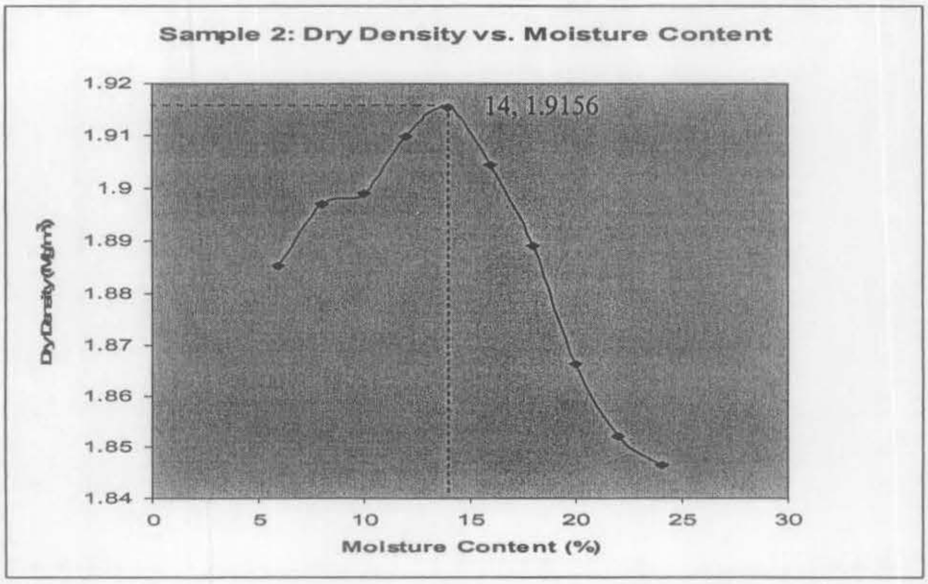
Weight of hammer : 2.5 kg

No. of blows : 27

No. of layers : 3

% of sand : 96%

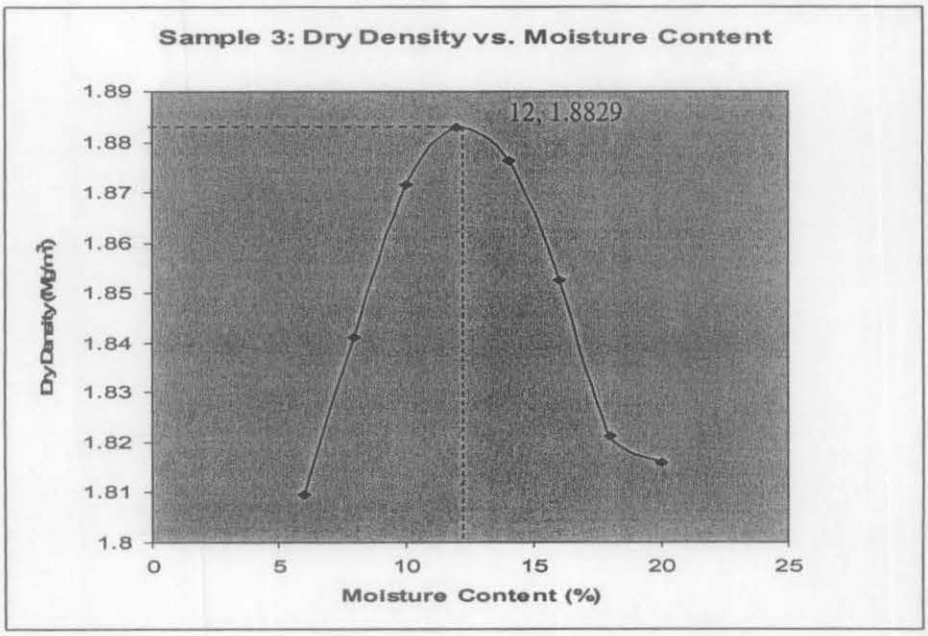
Test	1	2	3	4	5	6	7	8	9	10
Water content (%)	6	8	10	12	14	16	18	20	22	24
Mass of mould + base (g), m1	6320	6320	6320	6320	6320	6320	6320	6320	6320	6320
Mass of mould + base + soil (g), m2	8310	8360	8400	8450	8495	8520	8540	8550	8570	8600
Mass of compacted soil (g)	1990	2040	2080	2130	2170	2200	2220	2230	2250	2280
Bulk density, ρ (Mg/ m^3)	1.9984	2.0486	2.0888	2.139	2.1842	2.2093	2.2294	2.2394	2.2595	1.8465
Dry unit weight, ρ_d (Mg/ m^3)	1.8853	1.897	1.899	1.90983	1.9156	1.9046	1.8893	1.8662	1.8521	1.8465



Sample 3

Location	: Tronoh	Weight of hammer	: 2.5 kg
Soil Description	: Mining sand	No. of blows	: 27
Volume of mould	: 996.00 cm^3	No. of layers	: 3
Lime content	: 6%	% of sand	: 94%

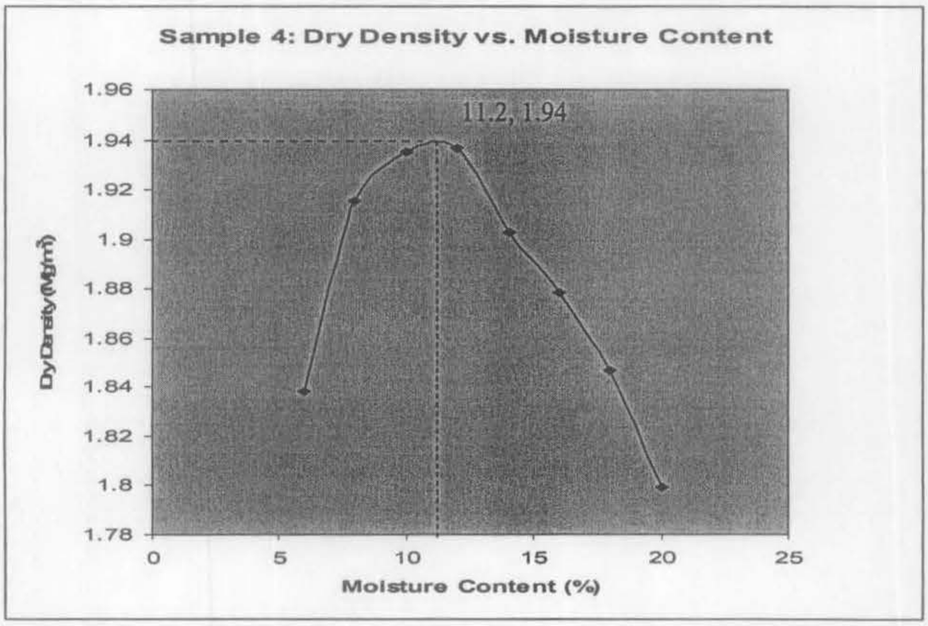
Test	1	2	3	4	5	6	7	8
Water content (%)	6	8	10	12	14	16	18	20
Mass of mould + base (g), m1	6320	6320	6320	6320	6320	6320	6320	6320
Mass of mould + base + soil (g), m2	8230	8300	8370	8420	8450	8460	8460	8490
Mass of compacted soil (g)	1910	1980	2050	2100	2130	2140	2140	2170
Bulk density, ρ (Mg/ m^3)	1.9181	1.9884	2.0587	2.1089	2.139	2.149	2.149	2.1792
Dry unit weight, ρ_d (Mg/ m^3)	1.8095	1.8411	1.8715	1.8829	1.8763	1.8526	1.8212	1.816



Sample 4

Location	: Tronoh	Weight of hammer	: 2.5 kg
Soil Description	: Mining sand	No. of blows	: 27
Volume of mould	: 996.00 cm^3	No. of layers	: 3
Lime content	: 8%	% of sand	: 92%

Test	1	2	3	4	5	6	7	8
Water content (%)	6	8	10	12	14	16	18	20
Mass of mould + base (g), m1	6320	6320	6320	6320	6320	6320	6320	6320
Mass of mould + base + soil (g), m2	8260	8380	8440	8480	8480	8490	8490	8470
Mass of compacted soil (g)	1940	2060	2120	2160	2160	2170	2170	2150
Bulk density, ρ (Mg/ m^3)	1.9482	2.0687	2.129	2.1691	2.1691	2.1792	2.1792	2.1591
Dry unit weight, ρ_d (Mg/ m^3)	1.838	1.9155	1.9354	1.9367	1.9027	1.8786	1.8468	1.7992



Sample 5

Location : Tronoh

Soil Description : Mining sand

Volume of mould : 996.00 cm^3

Lime content : 10%

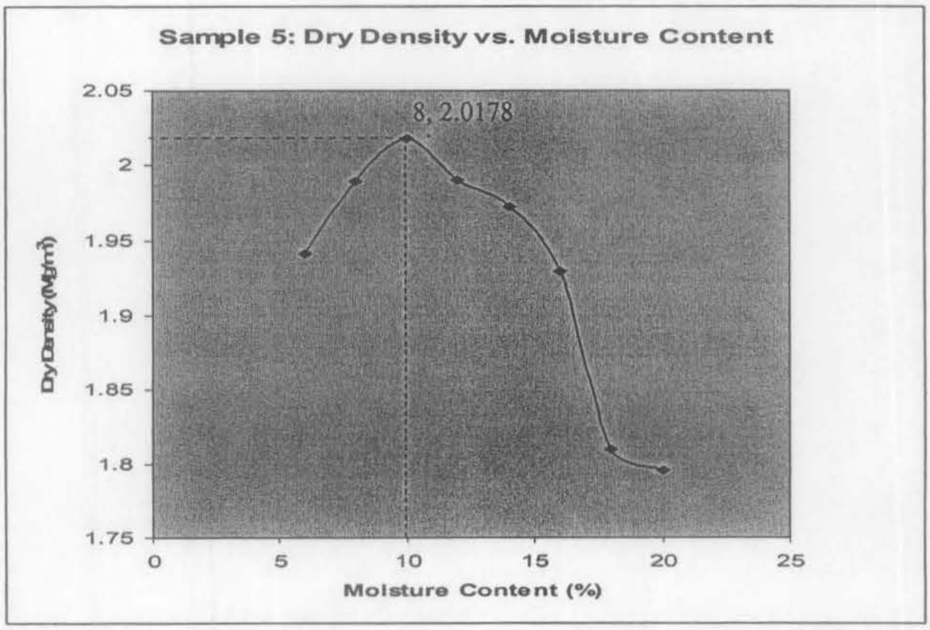
Weight of hammer : 2.5 kg

No. of blows : 27

No. of layers : 3

% of sand : 90%

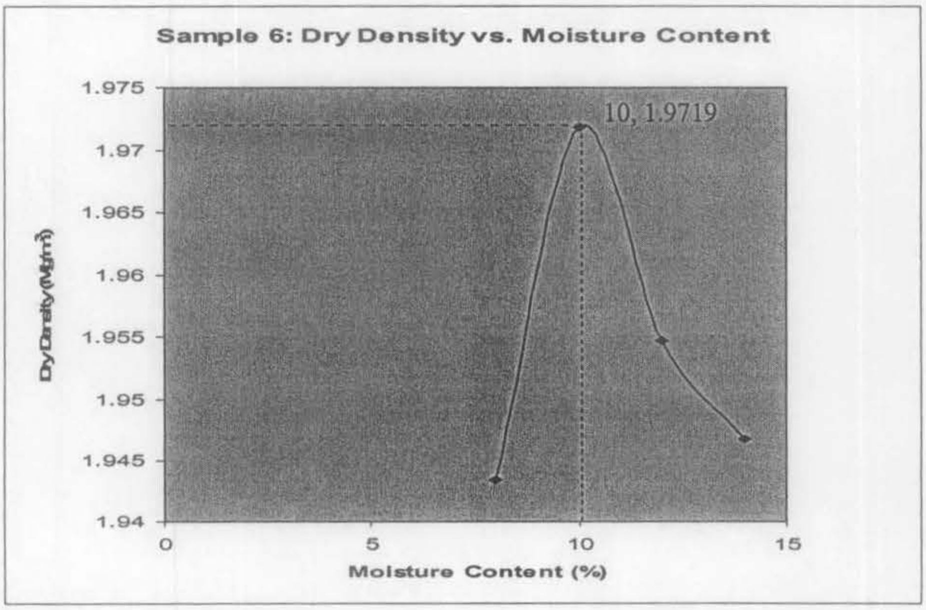
Test	1	2	3	4	5	6	7	8	9
Water content (%)	4	6	8	10	12	14	16	18	20
Mass of mould + base (g), m1	6320	6320	6320	6320	6320	6320	6320	6320	6320
Mass of mould + base + soil (g), m2	8330	8420	8490	8500	8520	8510	8410	8430	8480
Mass of compacted soil (g)	2010	2100	2170	2180	2200	2190	2090	2110	2160
Bulk density, ρ (Mg/m^3)	2.0185	2.1089	2.1792	2.1892	2.2093	2.1993	2.0988	2.1189	2.1691
Dry unit weight, ρ_d (Mg/m^3)	1.941	1.9895	2.0178	1.9902	1.9726	1.9292	1.8095	1.7957	1.8076



Sample 6

Location	: Tronoh	Weight of hammer	: 2.5 kg
Soil Description	: Mining sand	No. of blows	: 27
Volume of mould	: 996.00 cm^3	No. of layers	: 3
Lime content	: 12%	% of sand	: 88%

Test	1	2	3	4
Water content (%)	8	10	12	14
Mass of mould + base (g), m1	6320	6320	6320	6320
Mass of mould + base + soil (g), m2	8410	8480	8500	8530
Mass of compacted soil (g)	2090	2160	2180	2210
Bulk density, ρ (Mg/ m^3)	2.0988	2.1691	2.1892	2.2193
Dry unit weight, ρ_d (Mg/ m^3)	1.9434	1.9719	1.9547	1.9468



RESULT & CALCULATION

Unconfined Compression Test (maximum compaction of sand-lime mix)

Test 1

Lime content : 10% (300 g)

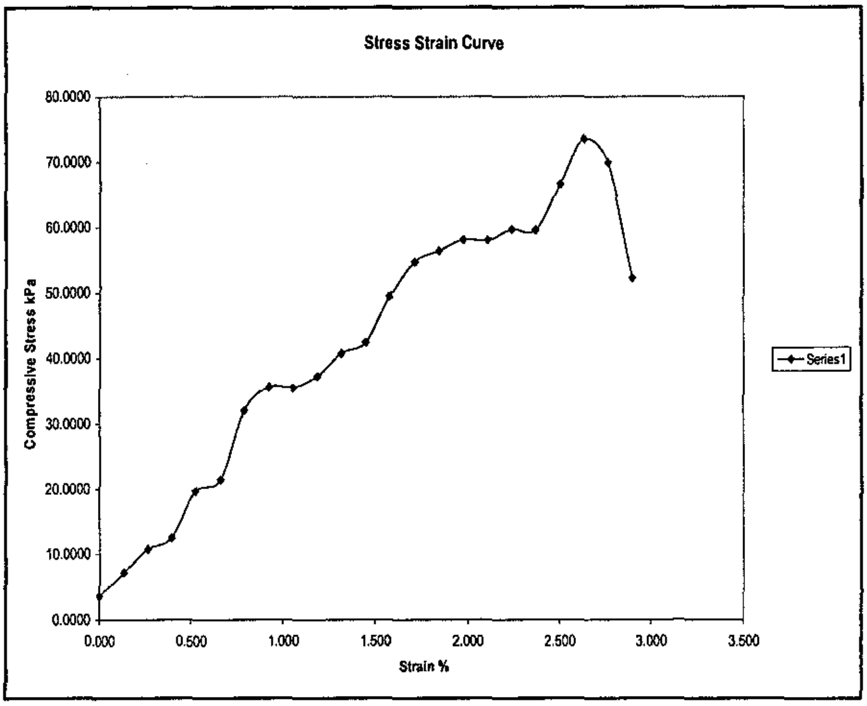
Percentage of sand : 90% (2700 g)

Water content : 8% (240 mL)

Curing period : **3 days**

Specimen details	Initially		After test
Diameter (mm)	38.0	Container (g)	38.7
Area (mm^2)	1134.11	Container+ mass (g)	183.0
Length (mm)	76.0	Container+ mass after 24 hours (g)	180.06
Volume (cm^3)	86.19	Moisture content (%)	2.08

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1134.11	0.0000
10	0.132	2	4.080	1135.60	3.5928
20	0.263	4	8.160	1137.10	7.1761
30	0.395	6	12.240	1138.60	10.7500
40	0.526	7	14.280	1140.11	12.5251
50	0.658	11	22.440	1141.62	19.6563
60	0.789	12	24.480	1143.13	21.4148
70	0.921	18	36.720	1144.65	32.0796
80	1.053	20	40.800	1146.18	35.5967
90	1.184	20	40.800	1147.70	35.5493
100	1.316	21	42.840	1149.23	37.2771
110	1.447	23	46.920	1150.77	40.7728
120	1.579	24	48.960	1152.30	42.4888
130	1.711	28	57.120	1153.85	49.5040
140	1.842	31	63.240	1155.39	54.7346
150	1.974	32	65.280	1156.94	56.4245
160	2.105	33	67.320	1158.50	58.1097
170	2.237	33	67.320	1160.06	58.0315
180	2.368	34	69.360	1161.62	59.7096
190	2.500	34	69.360	1163.19	59.6291
200	2.632	38	77.520	1164.76	66.5544
210	2.763	42	85.680	1166.34	73.4607
220	2.895	40	81.600	1167.92	69.8679
230	3.026	30	61.200	1169.50	52.3299
240	3.158	22	44.880	1171.09	38.3232

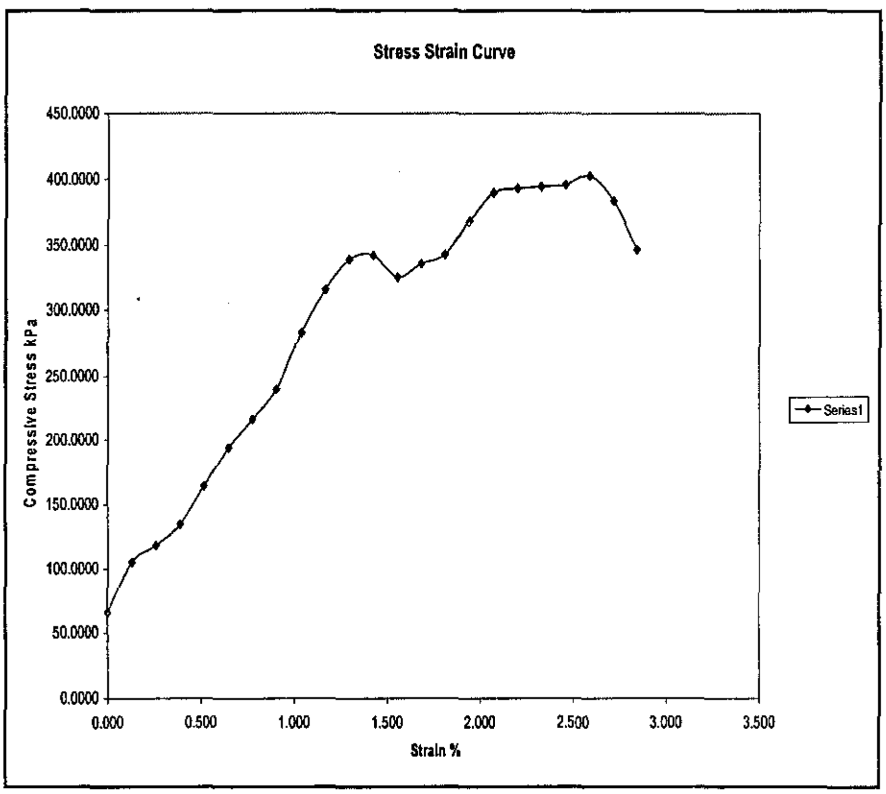


Test 2

Lime content	: 10% (300 g)	Water content	: 8% (240 mL)
Percentage of sand	: 90% (2700 g)	Curing period	**: 7 days**

Specimen details	**Initially**		**After test**
Diameter (mm)	37.17	Container (g)	29.37
Area (mm^2)	1085.11	Container+ mass (g)	177.05
Length (mm)	77.34	Container+ mass after 24 hours (g)	176.26
Volume (cm^3)	83.923	Moisture content (%)	0.54

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1085.11	0.0000
10	0.129	35	71.400	1086.51	65.7147
20	0.259	56	114.240	1087.92	105.0074
30	0.388	63	128.520	1089.34	117.9802
40	0.517	72	146.880	1090.75	134.6595
50	0.646	88	179.520	1092.17	164.3699
60	0.776	104	212.160	1093.59	194.0025
70	0.905	116	236.640	1095.02	216.1054
80	1.034	129	263.160	1096.45	240.0106
90	1.164	152	310.080	1097.89	282.4337
100	1.293	170	346.800	1099.32	315.4665
110	1.422	183	373.320	1100.77	339.1456
120	1.552	185	377.400	1102.21	342.4024
130	1.681	176	359.040	1103.66	325.3172
140	1.810	182	371.280	1105.11	335.9651
150	1.939	186	379.440	1106.57	342.8969
160	2.069	200	408.000	1108.03	368.2201
170	2.198	212	432.480	1109.50	389.7980
180	2.327	214	436.560	1110.97	392.9552
190	2.457	215	438.600	1112.44	394.2688
200	2.586	216	440.640	1113.92	395.5775
210	2.715	220	448.800	1115.40	402.3682
220	2.845	210	428.400	1116.88	383.5683
230	2.974	190	387.600	1118.37	346.5761

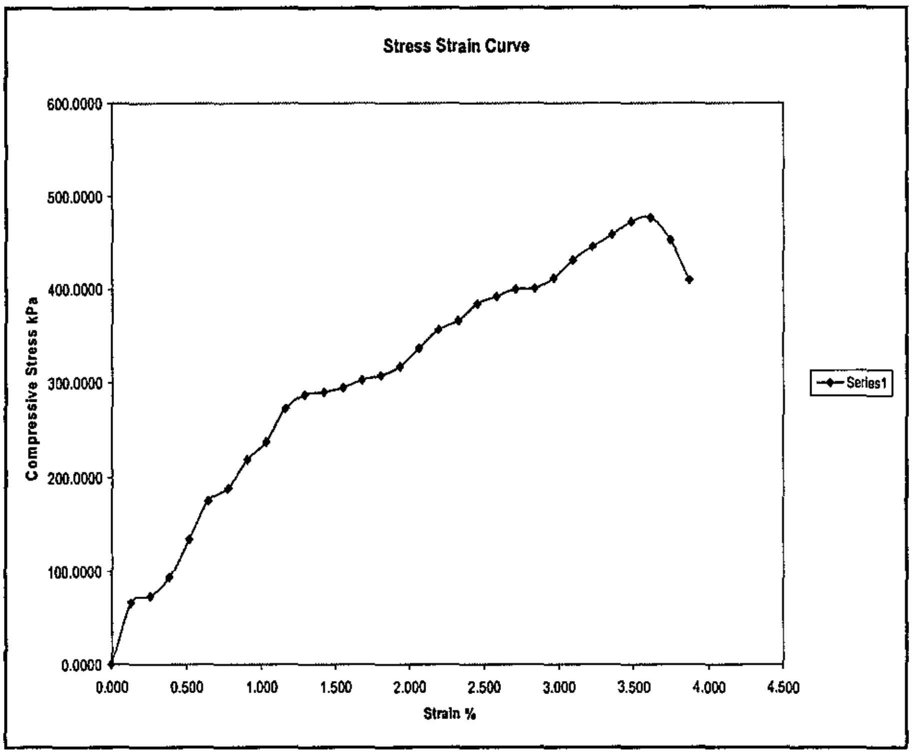


Test 3

Lime content	: 10% (300 g)	Water content	: 8% (240 mL)
Percentage of sand	: 90% (2700 g)	Curing period	: **14 days**

Specimen details		Initially		After test
Diameter	(mm)	38.95	Container (g)	28.90
Area	(mm^2)	1191.53	Container+ mass (g)	171.42
Length	(mm)	77.54	Container+ mass after 24 hours (g)	171.02
Volume	(cm^3)	92.39	Moisture content (%)	0.28

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1191.53	0.0000
10	0.129	39	79.560	1193.07	66.6852
20	0.258	43	87.720	1194.61	73.4297
30	0.387	55	112.200	1196.16	93.8003
40	0.516	79	161.160	1197.71	134.5569
50	0.645	103	210.120	1199.26	175.2076
60	0.774	111	226.440	1200.82	188.5708
70	0.903	129	263.160	1202.38	218.8651
80	1.032	140	285.600	1203.95	237.2189
90	1.161	161	328.440	1205.52	272.4462
100	1.290	170	346.800	1207.10	287.3008
110	1.419	172	350.880	1208.68	290.3010
120	1.548	175	357.000	1210.26	294.9780
130	1.677	180	367.200	1211.85	303.0085
140	1.806	183	373.320	1213.44	307.6546
150	1.934	189	385.560	1215.03	317.3243
160	2.063	201	410.040	1216.63	337.0280
170	2.192	213	434.520	1218.24	356.6788
180	2.321	219	446.760	1219.85	366.2426
190	2.450	230	469.200	1221.46	384.1305
200	2.579	235	479.400	1223.08	391.9622
210	2.708	240	489.600	1224.70	399.7719
220	2.837	241	491.640	1226.32	400.9055
230	2.966	248	505.920	1227.95	412.0025
240	3.095	260	530.400	1229.59	431.3640
250	3.224	269	548.760	1231.23	445.7019
260	3.353	277	565.080	1232.87	458.3454
270	3.482	286	583.440	1234.52	472.6060
280	3.611	289	589.560	1236.17	476.9253
290	3.740	275	561.000	1237.82	453.2144
300	3.869	249	507.960	1239.49	409.8153

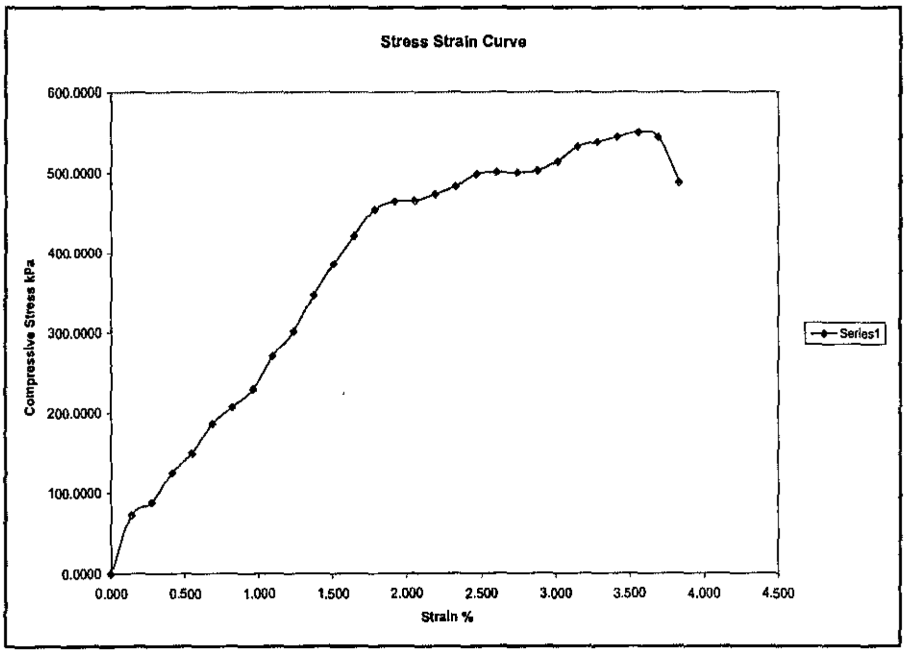


Test 4

Lime content	: 10% (300 g)	Water content	: 8% (240 mL)
Percentage of sand	: 90% (2700 g)	Curing period	: **28 days**

Specimen details	Initially		After test
Diameter (mm)	38.33	Container (g)	38.69
Area (mm^2)	1153.90	Container+ mass (g)	158.56
Length (mm)	73.05	Container+ mass after 24 hours (g)	157.11
Volume (cm^3)	84.29	Moisture content (%)	1.22

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1153.90	0.0000
10	0.137	41	83.640	1155.48	72.3854
20	0.274	50	102.000	1157.07	88.1539
30	0.411	71	144.840	1158.66	125.0067
40	0.548	85	173.400	1160.25	149.4501
50	0.684	106	216.240	1161.85	186.1166
60	0.821	118	240.720	1163.46	206.9008
70	0.958	131	267.240	1165.06	229.3779
80	1.095	155	316.200	1166.68	271.0262
90	1.232	173	352.920	1168.29	302.0816
100	1.369	199	405.960	1169.92	346.9995
110	1.506	222	452.880	1171.54	386.5677
120	1.643	243	495.720	1173.17	422.5468
130	1.780	262	534.480	1174.81	454.9514
140	1.916	268	546.720	1176.45	464.7215
150	2.053	269	548.760	1178.09	465.8045
160	2.190	274	558.960	1179.74	473.7995
170	2.327	280	571.200	1181.39	483.4970
180	2.464	289	589.560	1183.05	498.3386
190	2.601	291	593.640	1184.71	501.0830
200	2.738	291	593.640	1186.38	500.3787
210	2.875	293	597.720	1188.05	503.1087
220	3.012	300	612.000	1189.73	514.4023
230	3.149	311	634.440	1191.41	532.5110
240	3.285	315	642.600	1193.10	538.5977
250	3.422	319	650.760	1194.79	544.6650
260	3.559	323	658.920	1196.49	550.7130
270	3.696	320	652.800	1198.19	544.8235
280	3.833	287	585.480	1199.89	487.9440



IGNEOUS 6% 3 DAYS

L node 76
Area node 1134.11

	delta L	delta L/L node	force gauge	Axial force P	A Corrected area	Axial Stress
0	0.0	0.000	0	0.000	1134.11	0.0000
20	0.2	0.263	14	28.560	1137.10	25.1165
40	0.4	0.526	53	108.120	1140.11	94.8329
60	0.6	0.789	85	173.400	1143.13	151.6882
80	0.8	1.053	126	257.040	1146.18	224.2589
100	1.0	1.316	170	346.800	1149.23	301.7669
120	1.2	1.579	218	444.720	1152.30	385.9397
140	1.4	1.842	263	536.520	1155.39	464.3612
160	1.6	2.105	310	632.400	1158.50	545.8785
180	1.8	2.368	356	726.240	1161.62	625.1947
200	2.0	2.632	400	816.000	1164.76	700.5725
220	2.2	2.895	438	893.520	1167.92	765.0536
240	2.4	3.158	466	950.640	1171.09	811.7553
260	2.6	3.421	492	1003.680	1174.28	854.7174
280	2.8	3.684	508	1036.320	1177.49	880.1084
300	3.0	3.947	518	1056.720	1180.72	894.9814
320	3.2	4.211	500	1020.000	1183.96	861.5149

APPENDIX F

UNCONFINED COMPRESSION TEST CALCULATION

(Maximum compaction of sand-lime mix)

APPENDIX G

UNCONFINED COMPRESSION TEST CALCULATION

(Maximum compaction of sand-lime mix + CO_2 + steam)

RESULT & CALCULATION

Unconfined Compression Test

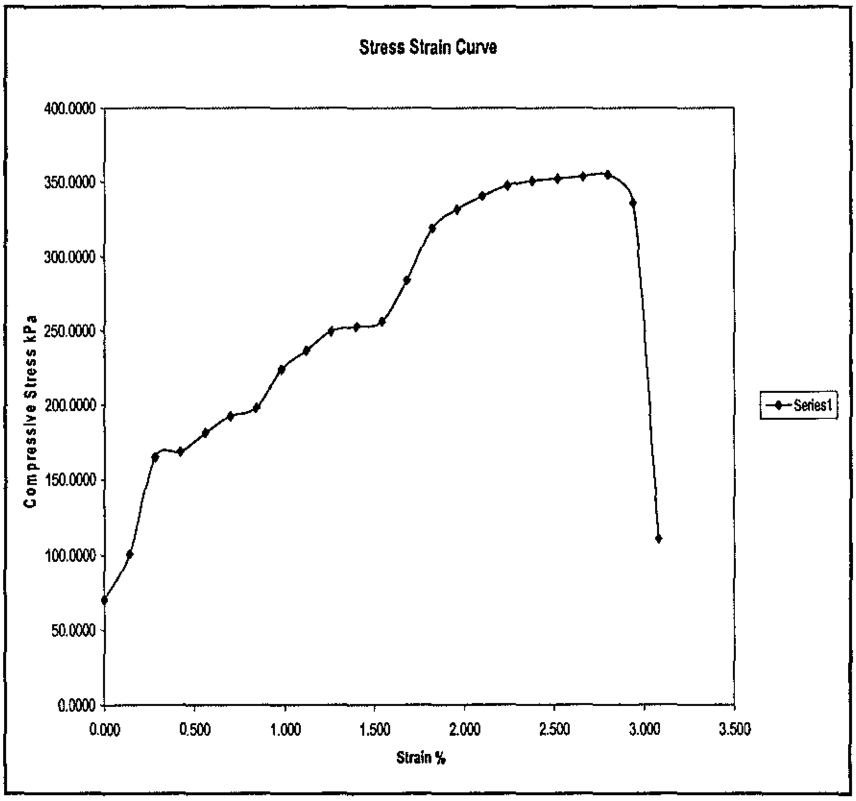
(Maximum compaction of sand-lime mix + CO_2 + steam)

Test 1

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 1 hour
Water content	: 8% (240 mL)	Curing period	: **Immediate**

Specimen details		**Initially**		**After test**
Diameter	(mm)	36.95	Container (g)	18.95
Area	(mm^2)	1072.31	Container+ mass (g)	164.82
Length	(mm)	71.44	Container+ mass after 24 hours (g)	155.63
Volume	(cm^3)	76.61	Moisture content (%)	6.72

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1072.31	0.0000
10	0.140	37	75.480	1073.81	70.2916
20	0.280	53	108.120	1075.32	100.5468
30	0.420	87	177.480	1076.83	164.8168
40	0.560	89	181.560	1078.35	168.3687
50	0.700	96	195.840	1079.87	181.3555
60	0.840	102	208.080	1081.39	192.4186
70	0.980	105	214.200	1082.92	197.7984
80	1.120	119	242.760	1084.45	223.8546
90	1.260	126	257.040	1085.99	236.6870
100	1.400	133	271.320	1087.53	249.4821
110	1.540	135	275.400	1089.08	252.8742
120	1.680	137	279.480	1090.63	256.2556
130	1.820	152	310.080	1092.18	283.9081
140	1.960	171	348.840	1093.74	318.9412
150	2.100	178	363.120	1095.31	331.5233
160	2.240	183	373.320	1096.88	340.3484
170	2.380	187	381.480	1098.45	347.2897
180	2.520	189	385.560	1100.03	350.5007
190	2.660	190	387.600	1101.61	351.8493
200	2.800	191	389.640	1103.19	353.1925
210	2.940	192	391.680	1104.79	354.5304
220	3.080	182	371.280	1106.38	335.5806
230	3.219	60	122.400	1107.98	110.4712

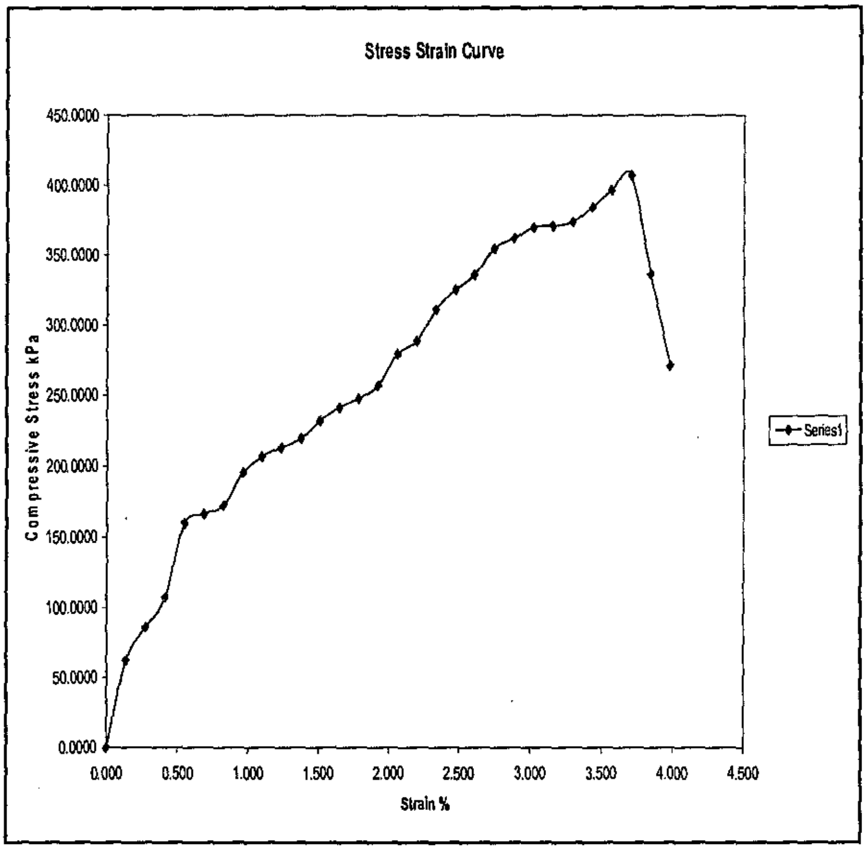


Test 2

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 2 hour
Water content	: 8% (240 mL)	Curing period	: **Immediate**

Specimen details		**Initially**		**After test**
Diameter	(mm)	39.59	Container (g)	18.95
Area	(mm^2)	1231	Container+ mass (g)	157.61
Length	(mm)	72.88	Container+ mass after 24 hours (g)	150.32
Volume	(cm^3)	89.72	Moisture content (%)	5.55

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1231.00	0.0000
10	0.137	38	77.520	1232.69	62.8868
20	0.274	52	106.080	1234.39	85.9374
30	0.412	65	132.600	1236.09	107.2739
40	0.549	97	197.880	1237.79	159.8651
50	0.686	101	206.040	1239.50	166.2278
60	0.823	105	214.200	1241.22	172.5723
70	0.960	119	242.760	1242.94	195.3114
80	1.098	126	257.040	1244.66	206.5138
90	1.235	130	265.200	1246.39	212.7742
100	1.372	134	273.360	1248.13	219.0164
110	1.509	142	289.680	1249.86	231.7691
120	1.647	148	301.920	1251.61	241.2256
130	1.784	152	310.080	1253.36	247.3996
140	1.921	158	322.320	1255.11	256.8061
150	2.058	172	350.880	1256.87	279.1700
160	2.195	178	363.120	1258.63	288.5037
170	2.333	192	391.680	1260.40	310.7585
180	2.470	201	410.040	1262.17	324.8682
190	2.607	208	424.320	1263.95	335.7091
200	2.744	220	448.800	1265.73	354.5767
210	2.881	225	459.000	1267.52	362.1236
220	3.019	230	469.200	1269.32	369.6478
230	3.156	231	471.240	1271.11	370.7297
240	3.293	233	475.320	1272.92	373.4097
250	3.430	240	489.600	1274.73	384.0823
260	3.568	248	505.920	1276.54	396.3211
270	3.705	255	520.200	1278.36	406.9277
280	3.842	211	430.440	1280.18	336.2330
290	3.979	170	346.800	1282.01	270.5120

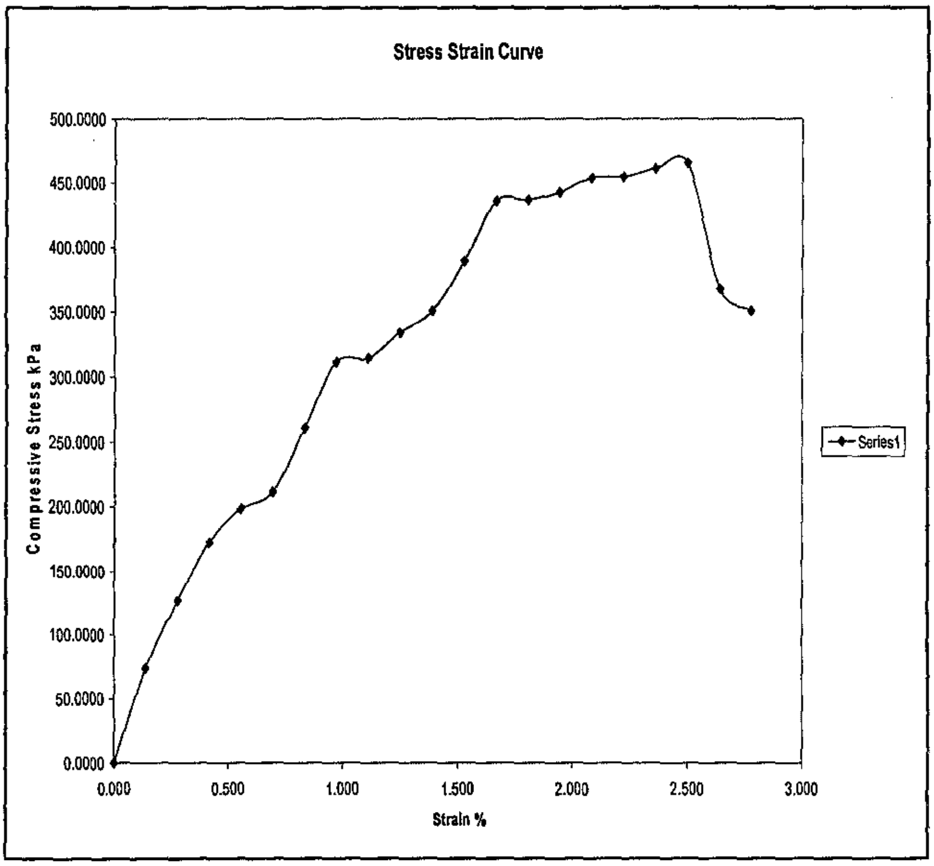


Test 3

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 4 hour
Water content	: 8% (240 mL)	Curing period	: **Immediate**

Specimen details		**Initially**		**After test**
Diameter	(mm)	38.89	Container (g)	18.77
Area	(mm^2)	1187.86	Container+ mass (g)	166.47
Length	(mm)	72.03	Container+ mass after 24 hours (g)	158.88
Volume	(cm^3)	85.56	Moisture content (%)	5.42

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1187.86	0.0000
10	0.139	43	87.720	1189.51	73.7446
20	0.278	74	150.960	1191.17	126.7328
30	0.416	101	206.040	1192.83	172.7324
40	0.555	116	236.640	1194.49	198.1091
50	0.694	124	252.960	1196.16	211.4762
60	0.833	153	312.120	1197.84	260.5695
70	0.972	183	373.320	1199.52	311.2252
80	1.111	185	377.400	1201.20	314.1855
90	1.249	197	401.880	1202.89	334.0954
100	1.388	207	422.280	1204.58	350.5610
110	1.527	230	469.200	1206.28	388.9639
120	1.666	258	526.320	1207.98	435.7009
130	1.805	259	528.360	1209.69	436.7721
140	1.944	263	536.520	1211.41	442.8906
150	2.082	270	550.800	1213.12	454.0348
160	2.221	271	552.840	1214.85	455.0703
170	2.360	275	561.000	1216.57	461.1315
180	2.499	278	567.120	1218.30	465.4992
190	2.638	220	448.800	1220.04	367.8561
200	2.777	210	428.400	1221.78	350.6347

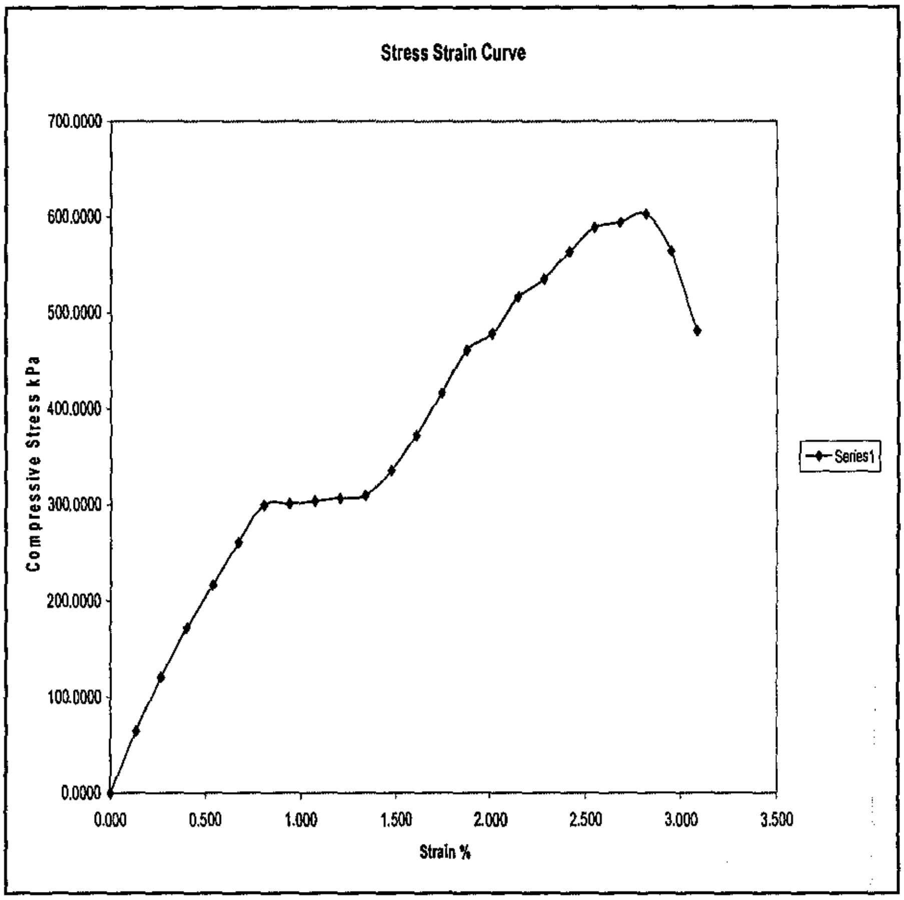


Test 4

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 2 hours
Water content	: 8% (240 mL)	Curing period	: **3 days**

Specimen details		**Initially**		**After test**
Diameter	(mm)	39.58	Container (g)	18.68
Area	(mm^2)	1230.4	Container+ mass (g)	163.83
Length	(mm)	74.59	Container+ mass after 24 hours (g)	162.07
Volume	(cm^3)	91.77	Moisture content (%)	1.22

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1230.00	0.0000
10	0.134	39	79.560	1231.65	64.5962
20	0.268	73	148.920	1233.31	120.7485
30	0.402	104	212.160	1234.97	171.7941
40	0.536	131	267.240	1236.63	216.1032
50	0.670	158	322.320	1238.30	260.2922
60	0.804	182	371.280	1239.97	299.4256
70	0.938	183	373.320	1241.65	300.6638
80	1.073	185	377.400	1243.34	303.5384
90	1.207	187	381.480	1245.02	306.4041
100	1.341	189	385.560	1246.71	309.2609
110	1.475	205	418.200	1248.41	334.9859
120	1.609	228	465.120	1250.11	372.0627
130	1.743	255	520.200	1251.82	415.5558
140	1.877	283	577.320	1253.53	460.5562
150	2.011	294	599.760	1255.24	477.8040
160	2.145	318	648.720	1256.96	516.1013
170	2.279	330	673.200	1258.69	534.8430
180	2.413	348	709.920	1260.42	563.2425
190	2.547	364	742.560	1262.15	588.3293
200	2.681	368	750.720	1263.89	593.9762
210	2.815	374	762.960	1265.63	602.8290
220	2.949	350	714.000	1267.38	563.3666
230	3.084	299	609.960	1269.13	480.6112

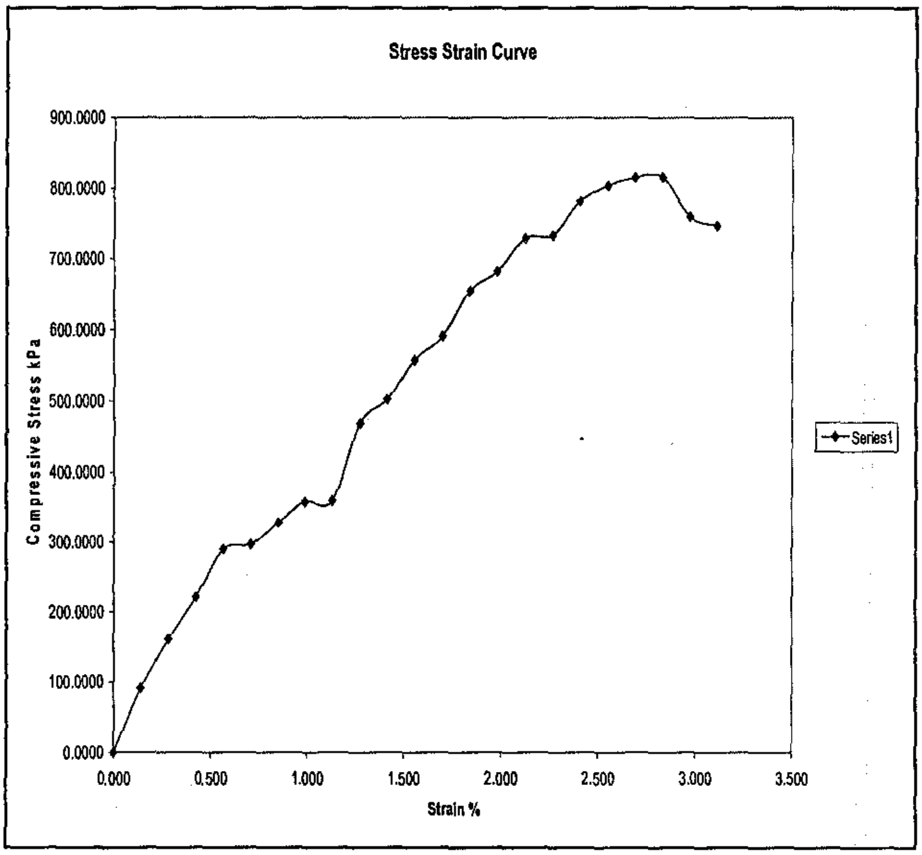


Test 5

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 4 hours
Water content	: 8% (240 mL)	Curing period	: **3 days**

Specimen details		**Initially**		**After test**
Diameter	(mm)	38.89	Container (g)	18.77
Area	(mm^2)	1187.86	Container+ mass (g)	166.47
Length	(mm)	72.03	Container+ mass after 24 hours (g)	
Volume	(cm^3)	85.56	Moisture content (%)	

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1121.02	0.0000
10	0.141	50	102.000	1122.61	90.8598
20	0.283	89	181.560	1124.20	161.5014
30	0.424	122	248.880	1125.80	221.0699
40	0.566	160	326.400	1127.40	289.5159
50	0.707	164	334.560	1129.01	296.3316
60	0.849	182	371.280	1130.62	328.3872
70	0.990	199	405.960	1132.23	358.5485
80	1.132	200	408.000	1133.85	359.8354
90	1.273	261	532.440	1135.48	468.9133
100	1.415	280	571.200	1137.11	502.3279
110	1.556	311	634.440	1138.74	557.1422
120	1.698	330	673.200	1140.38	590.3303
130	1.839	366	746.640	1142.02	653.7878
140	1.980	382	779.280	1143.67	681.3853
150	2.122	409	834.360	1145.32	728.4931
160	2.263	412	840.480	1146.98	732.7760
170	2.405	440	897.600	1148.64	781.4436
180	2.546	453	924.120	1150.31	803.3656
190	2.688	460	938.400	1151.98	814.5954
200	2.829	461	940.440	1153.66	815.1795
210	2.971	430	877.200	1155.34	759.2557
220	3.112	423	862.920	1157.03	745.8068

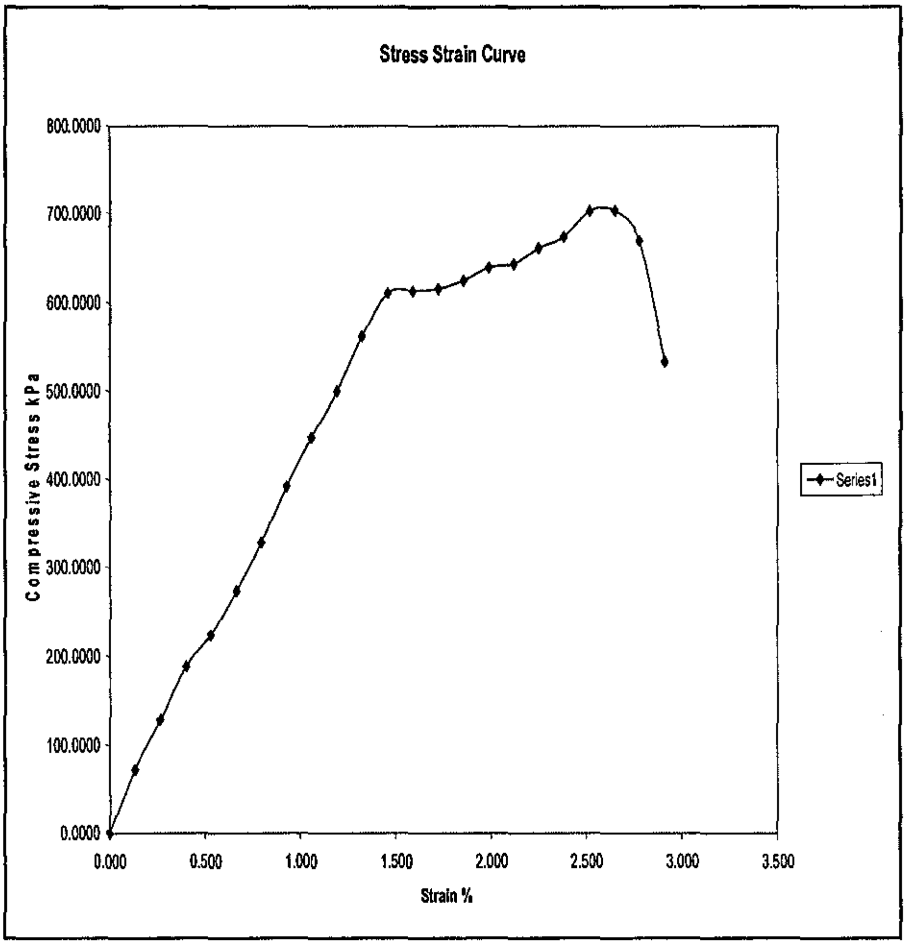


Test 6

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 2 hours
Water content	: 8% (240 mL)	Curing period	: **7 days**

Specimen details		**Initially**		**After test**
Diameter	(mm)	38.87	Container (g)	19.87
Area	(mm^2)	1186.64	Container+ mass (g)	162.23
Length	(mm)	75.53	Container+ mass after 24 hours (g)	161.70
Volume	(cm^3)	89.63	Moisture content (%)	0.37

Deformation gauge reading	**Strain, ϵ**	**Force gauge reading**	**Axial force, P**	**Corrected area, A**	**Axial stress, σ**
0	0.000	0	0.000	1186.64	0.0000
10	0.132	42	85.680	1188.21	72.1083
20	0.265	75	153.000	1189.79	128.5941
30	0.397	110	224.400	1191.37	188.3543
40	0.530	131	267.240	1192.96	224.0146
50	0.662	160	326.400	1194.55	273.2415
60	0.794	192	391.680	1196.14	327.4528
70	0.927	230	469.200	1197.74	391.7376
80	1.059	263	536.520	1199.34	447.3448
90	1.192	294	599.760	1200.95	499.4045
100	1.324	331	675.240	1202.56	561.5014
110	1.456	360	734.400	1204.18	609.8769
120	1.589	362	738.480	1205.80	612.4412
130	1.721	364	742.560	1207.42	614.9964
140	1.854	370	754.800	1209.05	624.2915
150	1.986	379	773.160	1210.68	638.6143
160	2.118	382	779.280	1212.32	642.7999
170	2.251	393	801.720	1213.96	660.4153
180	2.383	401	818.040	1215.61	672.9461
190	2.516	419	854.760	1217.26	702.1995
200	2.648	420	856.800	1218.92	702.9194
210	2.780	400	816.000	1220.58	668.5366
220	2.913	319	650.760	1222.24	532.4319



Test 7

Lime content	: 10% (300 g)	CO_2	: 20 psi
Percentage of sand	: 90% (2700 g)	Duration	: 4 hours
Water content	: 8% (240 mL)	Curing period	: **7 days**

Specimen details		**Initially**		**After test**
Diameter	(mm)	37.84	Container (g)	20.07
Area	(mm^2)	1124.58	Container+ mass (g)	152.97
Length	(mm)	76.07	Container+ mass after 24 hours (g)	152.01
Volume	(cm^3)	85.55	Moisture content (%)	0.73

Deformation gauge reading	Strain, ϵ	Force gauge reading	Axial force, P	Corrected area, A	Axial stress, σ
0	0.000	0	0.000	1124.58	0.0000
10	0.131	53	108.120	1126.06	96.0162
20	0.263	90	183.600	1127.54	162.8317
30	0.394	130	265.200	1129.03	234.8914
40	0.526	158	322.320	1130.52	285.1066
50	0.657	180	367.200	1132.02	324.3757
60	0.789	210	428.400	1133.52	377.9375
70	0.920	230	469.200	1135.02	413.3831
80	1.052	252	514.080	1136.53	452.3232
90	1.183	269	548.760	1138.04	482.1956
100	1.315	287	585.480	1139.56	513.7771
110	1.446	339	691.560	1141.08	606.0572
120	1.577	342	697.680	1142.60	610.6050
130	1.709	358	730.320	1144.13	638.3176
140	1.840	390	795.600	1145.66	694.4439
150	1.972	413	842.520	1147.20	734.4134
160	2.103	428	873.120	1148.74	760.0664
170	2.235	439	895.560	1150.29	778.5539
180	2.366	467	952.680	1151.84	827.0975
190	2.498	402	820.080	1153.39	711.0182
200	2.629	319	650.760	1154.95	563.4552