POSSIBLE USE OF BOTTOM ASH IN EMBANKMENT CONSTRUCTION

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Engineering in Civil Engineering

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DECLARATION

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Prof. S.A.S. Kulathilake

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Abstract

Bottom ash is a solid residue byproduct produced by coal burning for electricity generation. In Sri lanka it has not been developed proper system to dispose of this bottom ash other than using small amount for concrete wall block and paving blocks. Usually 75 tons of bottom ash is produced every day with the operation of three number of power generation units in Lakvijaya Power Station. By product of bottom ash is to be a one of a solution for soil scarcity for filling of embankments. For the testing, it is used 3 set of bottom ash each has different origin. To identify characteristics of bottom ash, several tests were done. Particle size distribution, Specific gravity, plasticity, proctor compaction test and permeability test were done to identify basic characteristics. The test results indicated that granular, permeable, pores structure is available for the bottom ash. Specific gravity and the density are quietly low. The compressibility characteristic of bottom ash was determined by one-dimensional consolidation test by using different loading, unloading and reloading sequences for 3 samples. Low compressibility occurred even at higher loads with higher void ratios. Shear strength parameters were assessed for compacted bottom ash by direct shear test under consolidation drained condition. Cohesion is zero and sufficient friction values are available. Toxicity behaviors were analyzed to identify leach out of toxic materials and radiation risks to the environment. Test results indicated that bottom ash favorably suitable for as an embankment construction.

Keywords: Embankment, Bottom ash, Coal power by-product, compressibility of bottom ash, shear strength of bottom ash

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Jayakody A.C. Chrishanthi

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LIST OF ABBREVIATIONS

Abbreviation	Description
BA	Bottom Ash
CBR	California Bearing Ratio
EPA	Environmental Protection Agency
FA	Fly ash
GCS	Geo Composite Soil
IAEA	International Atomic Energy Agency
ITI	Industrial technology institute
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
PHA	Paddy Husk Ash
SEM	Scanning Electron Microscopy
TCLP	Toxicity Characteristics leaching Procedure
USEPA	United States Environmental Protection Agency
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

1.0 INTRODUCTION

Bottom ash (BA) is a byproduct of coal combustion from coal fired power plant. Finding effective ways of disposal of this byproduct of coal combustion is one major problems faced by engineers in Sri Lanka. Bottom Ash mountains are developing day by day at premises of coal power plant, and it will be very beneficial if this can be utilized in proper manner.

The amount of embankment constructions for roads and highways has increased significantly in recent years in Sri Lanka. Those embankments are sometimes placed on soft soil layers and significant quantities of fill material are required. A shortage of construction filling soil materials exists at present due to environmental constraints imposed by the government in the extract of suitable material. Therefore, the gravel excavation and transport as fill material has become a major problem among contractors and distributers. Thus, there is a scarcity of soils suitable for the construction of embankments. As such, it is important to conduct research to find alternate fill materials. Presence of bottom ash in large quantities may provide a solution to this problem.

Bottom ash is collected at the bottom of the coal burning combustion chamber in a water-filled pond. This material collections increasing daily are stacked at the premises of the power station. This research is directed at investigating the suitability of bottom ash as an embankment construction material.

1.1 Background to the presence of large quantities of bottom Ash

Coal fired power plant is located at Norochcholei in Puttalam provides around 300MW by each unit and with the operation of three units adding 900MW of power to the national Grid. At the present scenario, with running of these three units, around 75tons of bottom-ash are produced every day.

When the conditions in developed countries are considered; The U.S. utility industry generated 16.9 million metric tons of bottom ash in 2006. Just over 45 percent of all bottom ash produced was used, mainly in transportation applications such as structural fill, road base material, and as snow and ice control products. Bottom ash was also used as an aggregate in lightweight concrete masonry units (ASTM C331-05 2005) and raw feed material for the production of Portland cement (Benson and Bradshaw (2011)).The type of bottom ash produced depends on the type of coal-burning furnace (Benson and Bradshaw (2011)).

1.2 Coal burnt by-product of the Bottom Ash need proper waste disposal system

Accumulation of bottom ash in the dumping yard at PowerStation in Sri Lanka is a major problem and economical, an appropriate solution needs to be found. Researches should be conducted to find a solution to the above problems with a proper scientific base.

Coal sources are not available in Sri Lanka. Coal is imported over last few years. Therefore this waste material is new for the country. Coal is mined, cleaned, prepared and transported to site from vessels through the sea. It is fed onto a conveyor belt and pulverized. Pulverized coal is then moved to the boiler mixing with air and blown into the boiler furnace. Bottom ash consists of coarse ash particles that are too heavy to be carried up in the flue gas. Therefore bottom ash becomes molten and then cools into dense granules. The cooled granules are combined with water and pumped to the impoundment. That cannot be used for any further activity in the power generation process.

Figure 1.1: Coal Power Plant & Ash Mountains in Sri Lanka (Lakvijaya Power Station)

1.3 Scientific study of the proper disposal system of coal combustion Bottom Ash produced in Sri Lanka

In many current projects of construction of highways, embankments are to be constructed on land under-laying by soft soils. Placement of embankment load on such compressible ground cause very large settlements. If the load is placed without allowing for some consolidation, shear failures could also take place. If the fill material placed is of lower density it can be beneficial. However, the fill materials need to possess good strength and stiffness characteristics. Permeability is also an important parameter.

During this study attempts will be made to identify desirable qualities of bottom ash to be used as a structural fill material. Basic characteristics such as particle size distribution, plasticity characters, maximum dry density, optimum moisture content and permeability are studied. Other special qualities like compressibility characteristics, shear strength parameters and chemical and microstructural datas are also analyzed.

1.4 Research Objectives

Investigation of Possible Use of Bottom Ash in Construction of Embankments by identifying geotechnical parameters of this material available in Sri Lanka .This would be done by conducting an appropriate laboratory experimental study using bottom ash generated from Lakvijaya Power Station Norochcholei in Puttalam.

The studies done are;

i. Basic properties

ii. Compressibility characteristics

iii. Shear strength parameters

iv. Microstructure

v. Chemical composition and potential to damage the environment.

1.5 Outline of the Thesis

Chapter 2 of the thesis presents a review of literature on the use of bottom ash by previous researches. Chapter 3 presents the basic characteristics of bottom ash by analyzing; particle size distribution, Liquid limit, specific gravity, compaction characteristics, permeability characteristics and CBR value.

Chapter 4 presents, compressibility characteristics of the bottom. Chapter 5 presents the determination of Shear Strength parameters. Chapter 6 discussed about chemical, microstructural, and radioactivity properties of bottom ash. Final discussion and conclusions are presented in Chapter 7.

2.0 LITERATURE REVIEW

In this Chapter the coal combustion bottom ash related experiments and studies on their usage as fill material done in other countries are presented. Soils used for construction of embankment are ranging from granular soils to the finer soils mixed with granular material. Coal combustion Bottom ash is one of the soils that can be used as a material in embankment or construction fill. However, fill material used for construction of embankments; should be well graded, capable of being compacted well, be within a proper range of moisture to optimize compaction, high in shear strength, low in compressibility and be free of unsuitable or deleterious materials, such as tree roots, branches, stumps, sludge, metal.

2.1 Techniques adopted in construction of road embankments in Sri Lanka

Numbers of new roads in Sri Lanka were constructed on terrain consisting of very soft peat, organic soils and clays. Under these ground conditions, various ground improvement methods such as removal and replacement of soils, preloading, preloading with vertical drains, dynamic compaction, deep mixing, piling and vacuum consolidation were applied to enable the construction.

Karunawardena1 and Toki (2015) showed that in southern expressway in Sri Lanka the embankments over a segment of about 4 km in length were constructed by improving the peaty clay by the application of the heavy tamping method.

Studies have been done in Sri Lanka at the laboratory scale to assess the improvements achievable in soft peaty clays by mixing with cement. Research done by Kulathilaka et al (2013) showed that cement weight by the order of 20%-25% by weight will be necessary for achieving an appropriate level of improvement.

Madhusanka and Kulathilaka(2015) studied the possible use of Paddy Husk Ash together with cement to enhance the properties of peaty clay. Paddy Husk Ash is also pozzolonic material and of some cement percentage can be reduced by the use of paddy husk ash making the process more economical. The study reveals that paddy husk ash could be used along with cement but not alone for this purpose.

Scandinavian countries have used industrial by products such as blast furnace slag together with cement to improve peaty soils. One possible use of bottom ash could be in the use of deep mixing together with cement. The other product of coal power plants, the fly ash had been used successfully for deep mixing to improve the strength and stiffness of soft clays.

However, in this research the study is confined to the investigation of the possible use of bottom ash as an embankment construction material.

2.2 Geotechnical properties of Fly and bottom ash mixtures for construction of highway Embankments

Fly ash and bottom ash are the solid residue byproducts produced by coal-burning for electricity generation. Kim et al (2005) evaluated the suitability from two sources of fly ash and bottom ash mixtures with high fly ash contents as construction materials for highway embankments. The ash samples used in this study were extracted from two power plants those were the Wabash River plant and the A. B. Brown plant. Ash Characterization was done by grain size analyzing, microscopic examination and analyzing the specific Gravity. Gradations of the samples were determined using ASTM D422 (1963).

Generally, the fly ash was well graded, ranging from mostly silt to fine sand sizes. The Wabash plant fly ash had more silt size particles than the Brown plant fly ash. Bottom ash gradations from the two ash sources were quite similar. As per the Kim et al (2005) their sizes ranged from sand to small-size gravel. Microscopic Examination was done using a scanning electron microscope (SEM) and a light microscope (LM).

The wide range in specific gravity was attributed to two factors: (1) Chemical composition, and (2) presence of hollow fly ash particles or particles of bottom ash with porous textures. The low specific gravities of Wabash plant fly and bottom ash 2.30 , 2.32 were attributed to their low iron oxide contents and, conversely, the high specific gravities of Brown plant fly and bottom ash are 2.81 , 2.62 and were attributed to their high iron oxide contents.

Jinwoo et al (2014) explained microstructural morphology obtained from SEM analysis. They explained that, compared with the bottom ash, the fly ash particles exhibit irregular and angular morphology and smoother surface texture. Figure 2.1 and Figure 2.2 SEM datas indicated their result images. In addition, they discussed about higher comparable internal porosity in both fly ash and bottom ash which were closely related with the specific gravity and the unit weight. The high porosity provides higher absorption rate. Therefore, the higher porosity may explain the lower specific gravity and lower unit weight.

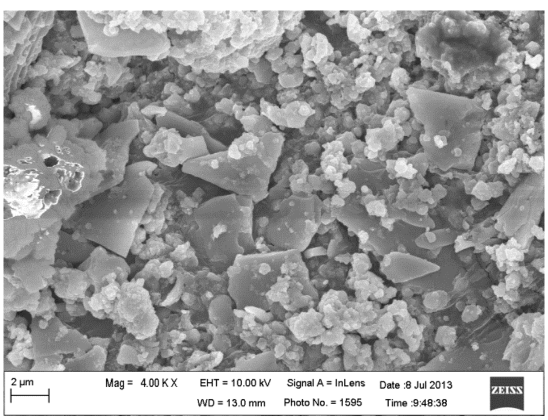


Figure 2.1: SEM images of Fly ash with 4000X magnifications Jinwoo et al (2014)

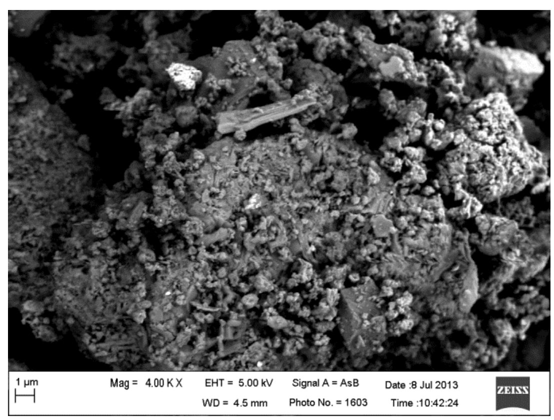


Figure 2.2: SEM images of bottom ash with 4000X magnifications Jinwoo et al (2014)

Kim et al (2005) performed Standard compaction, hydraulic conductivity, one-dimensional compression, and drained triaxial tests on the fly/bottom ash mixtures to obtained Mechanical Properties of Ash Mixtures. Fig. 2.6 shows the compacted dry unit weight versus the water content curves of the ash mixtures.

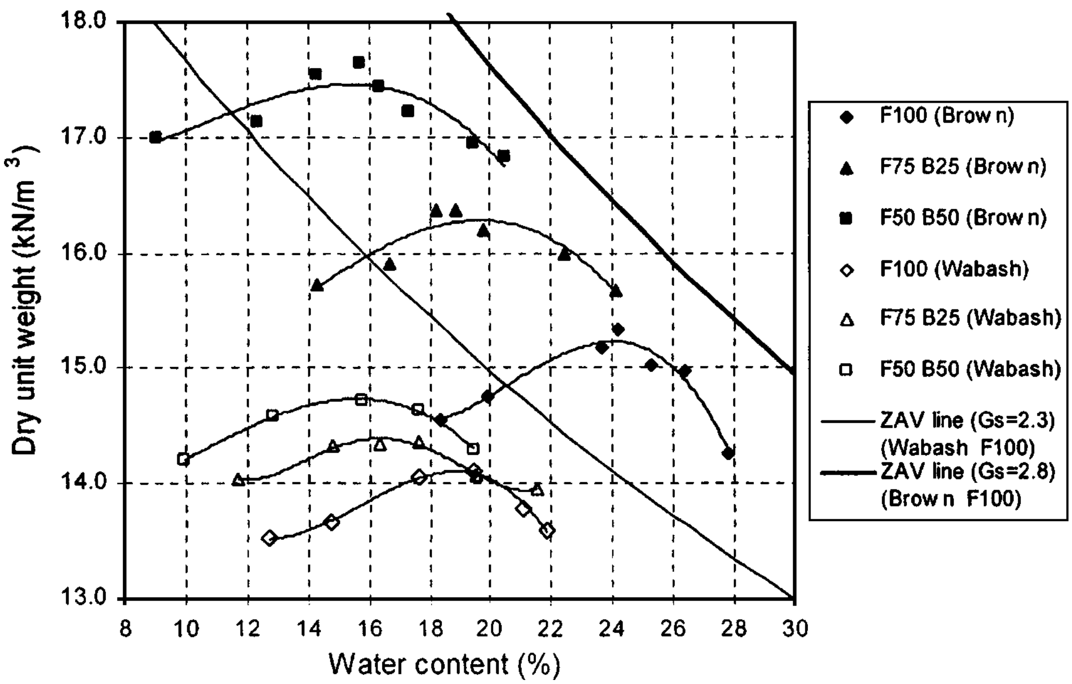


Figure 2.3 : Compaction curves of ash mixtures
Kim et al (2005)

The differences in dry unit weight appeared to be primarily due to the large variations in the specific gravities. Kim et al (2005) expressed that the Brown plant ash mixtures, whose specific gravities were much higher than those of the Wabash plant ash mixtures, had higher maximum dry unit weight (γ_d max) values. It was also often observed, especially in the Brown plant ash mixtures, that some weak large bottom ash particles were broken down into finer particles by compaction. Some bottom ash particle crushing during compaction may have contributed to the increase in the γ_d max of ash mixtures.
The other mechanical property is Hydraulic Conductivity of the ash mixtures was measured by falling head tests. Table 2.1 shows the values of hydraulic conductivity for

compacted ash mixtures. The larger specific surface of fly ash causes more resistance to flow of water through the voids thereby giving lower values of hydraulic conductivity.

Table 2. 1 : Hydraulic Conductivity of Ash Mixtures Kim et al (2005)

Ash source	Mixture composition *(F-Fly Ash & B-Bottom Ash)*	Hydraulic conductivity (m/s)
Wabash River plant	*F100* *F75 B25* *F50 B50*	3×10^{-8} 6×10^{-8} 1×10^{-7}
A. B. Brown plant	*F100* *F75 B25* *F50 B50*	6×10^{-8} 9×10^{-8} 1×10^{-7}

Compressibility of the Brown plant ash mixture samples was greater than the Wabash plant ash mixture samples. The difference in the compressibility appears to be mainly due to different compressibility of the fly ash rather than the bottom ash, because the increasing rate in the compressibility with increasing bottom ash was similar between the two ash sources.

According to the studies of Kim et al (2005), it appears that high volume fly ash mixtures are suitable for use in highway embankments, if proper design and construction procedures are followed. Prior to use, the materials must pass the appropriate environmental requirements set by state regulatory agencies. If the environmental requirements are satisfied, the fly/bottom ash mixtures can provide fill materials of comparable strength and compressibility to most soils typically used as fill materials, while having the advantage of smaller dry unit weights.

Dilip Kumar et al (2014) expressed that in India bottom ash particles that were much coarser than the fly ash were tested in different proportion. They said that the maximum dry density of fly ash and bottom ash mixture decreases with increasing bottom ash content while optimum moisture content increases. Bottom ash exhibited lower density as compared to fly ash but strength characteristics was better than fly ash under as compacted.

In respective proportion the permeability of compacted ash mixtures was found to decrease slightly with increasing fly ash content. Permeabilities of fly ash and bottom ash were 5.580 x 10^{-4}cm/sec and 9.613 x 10^{-4} cm/sec respectively. As such, fly ash could be used as a filling material in core of dyke and mixtures of fly ash and bottom ash in different proportions could be used in highway embankment Dilip Kumar et al (2014).

Shear strength parameters of fly ash and bottom ash showed a variation in cohesion from 0.01 to 0.03 kg/cm^2 and angle of internal friction from 23^o to 34^0. In wet condition it could be safely used in construction of embankment and also body of dyke for water disposal. The CBR value of fly ash and bottom ash in soaked condition was 8.68 % and 26.9%. While in 80%BA+20%FA, 60%BA+40%FA, 40%BA+60%FA, 20%BA+80%FA proportions CBR was 25.68%, 23.4%, 19.3% and 13.86% respectively. As the required value of CBR for sub-base is 7%-20 %. Dilip Kumar et al (2014) expressed that Fly ash and bottom ash mixtures could be used as sub-base of road construction.

2.3 Bottom ash and subgrade soil mixtures

Abdus et al (2014) assessed through the laboratory investigation whether the use of the coal bottom ash was technically feasible as mechanical stabilizer for that particular subgrade soil and to determine the optimum mixture proportion of coal bottom ash to subgrade soil that had yielded the highest CBR value and lowest swelling potential. Abdus et al (2014) investigated three mixtures of subgrade soil and Coal Bottom Ash in the laboratory, each containing varying percentages of coal bottom ash by weight (15%, 30%, and 40%). The laboratory research indicated that the mechanical properties of the subgrade soil were improved with the addition of bottom ash. Both soaked and unsoaked CBR value reached maximum with the adding of 30% coal bottom ash by weight. Abdus et al (2014) demonstrated that coal bottom ash (CBA) might effectively be used as a mechanical stabilizer for the subgrade soil that 30% by weight of coal bottom ash (CBA) added to the subgrade soil yielded the highest unsoaked and soaked CBR values of 140% and 95%, respectively.

In addition, Abdus et al (2014) expected, a decrease in Maximum Dry density (MDD) upon addition of coal bottom ash to the soil was registered due to a lower specific gravity of the coal bottom ash. The swelling potential decreased from 0.17% to 0.04% due to a decrease in the fine portion of the soil by the addition of well-graded coarse sandy gravel coal bottom ash particles. Moreover, at a coal bottom ash content of 30%, the soil was of intermediate plasticity which was more desirable than the subgrade soil which was highly plastic. Therefore Abdus et al (2014) recommended to use a mixture of coal bottom ash to subgrade soil of 30% : 70% for the work.

2.4 General bottom ash Properties of respective sources

Recycled Materials Resource Center of University of Wisconsin-Madison, Benson and Bradshaw (2011) had given user guide lines based on their sources. They have done environmental consideration too. Leachates were analyzed for concentrations of cadmium (Cd) and other heavy metals. Peak Cd and Se concentrations in the leachate from the field exceeded their groundwater standard.

However, Benson and Bradshaw (2011) assume that with application of dilution factors to account for the reduction in concentration expected between the bottom of the pavement structure and the groundwater table, concentrations would not exceed the groundwater quality standards. However bottom ash were used for the back fills with the

Maximum dry density as 11.79kN/m^3 -15.75kN/m^3, Optimum moisture content as 12% - 24% , Internal Friction angle (drained) as 32^0-45^{0}and Hydraulic conductivity as 1-10^{-3}.

Dilip Kumar et al (2014) discussed about physical characteristics of bottom in India of thermal Power Project. Fly ash (FA) and bottom ash (BA) were mixed for testings. Their different proportion was 100%BA, 80%BA+20%FA, 60%BA+40%FA, 40%BA+60%FA, 20%BA+80%FA, 100% FA. Different test such as; grain size analysis, specific gravity, standard proctor test, permeability test, direct shear test, California Bearing Ratio test were done on above different proportions. Maximum dry density (MDD) of fly ash and bottom ash mixture decreases with increasing bottom ash content while optimum moisture content increases. Permeability decreases as fly ash content increases. CBR value decreases for both soaked and unsoaked condition as fly ash content increases. Optimum moisture content of bottom ash is higher than all mixtures of Fly Ash and bottom ash. Dilip Kumar et al (2014) results for the testing by using of 100% bottom ash only were indicated in the Table 2.2.

Table 2. 2 : Some Characteristics of Anpara at India Bottom ash Dilip Kumar et al (2014)

Sp. Gravity	2.27
Clay size particle % (< 0.002mm)	0.0%
Silt size particle % (0.002-0.075 mm)	27.5%
Sand size particle % (0.075-4.75 mm)	72.5%
Optimum Moisture Content (OMC)	32%
Maximum Dry density (MDD) (g/cc)	1.080
Angle of shearing resistant (wet)	34^0
Cohesion (Kg/cm^2) (wet)	0.02
CBR Value (Unsoaked Condition) %	29.6%
CBR Value (Soaked Condition) %	26.9%

Benson and Bradshaw (2011) explained that the bottom ash have angular particles with very porous surface textures. The ash particles range in size from a fine gravel to a fine sand with very low percentages of silt-clay sized particles. Bottom ash is usually a well graded material although variations in particle size distribution may be encountered in ash from the same power plant. They found that the specific gravity of the dry bottom ash is a function of chemical composition, the higher carbon content resulting in lower specific gravity which is indicated in the Table 2.3.

Table 2. 3: Typical physical and mechanical properties of bottom ash

Benson and Bradshaw (2011)

Typical Physical Properties	Value
Specific Gravity	2.1 -2.7
Dry Unit Weight	7.07 - 15.72 kN/m^3
Plasticity	None
Typical Mechanical Properties	Value
Maximum Dry Density kN/m^3	11.79 - 15.72
Optimum Moisture Content, %	12 – 24 range
California Bearing Ratio (CBR) %	21 – 110

2.5 Use of Bottom ash in Improving strength of soils

Sivakumar et al (2015) mainly focused on enhancement of various properties of the cohesive soil in Mugalivakkam, Porur, and Chennai area using the different proportions (0, 20, 30, 35, 40, and 50%) of bottom ash. The cohesive soil used in the project was collected from an open excavation at 1m depth below the natural ground surface from

Mugalivalkam, Porur, Chennai, Tamil Nadu, and India. The soil is tested as per the provisions contained in IS 2720-1983. The bottom ash was collected from Energy Resource Power Plant, Electricity Board, Ennore, Chennai, Tamil Nadu.

As per the Sivakumar et al (2015) the bottom ash was collected from Energy Resource Power Plant, Electricity Board, Ennore, Chennai, Tamil Nadu, bottom ash generally contained more than 20% lime (CaO). Sivakumar et al (2015) expressed that the bottom ash combination of 0%,20%, 30%, 35%, 40%, 50% with cohesive soil were represented variable increase in unconfined compression strength. The optimum value of percentage of bottom ash was taken by considering optimum value of unconfined compression strength. The optimum increase of unconfined compression strength was obtained 35% of bottom ash with cohesive soil mixes.

As per their summarizing bottom ash reduced the liquid limits while the plastic limits were increased, Plasticity indices were reduced by adding bottom ash and bottom ash admixture showed better results when compared to cohesive soil without admixtures.

2.6 Particle size effect on shear properties of Bottom ash added-Geocomposite soil

Hai and Tho (2011) outlined that the marine dredged soil deposit, which are obviously very low in strength and very high in compressibility, are widespread in costal and low-land regions in Korea. During construction of large-scale ports and harbors such as Busan New Port, a large amount of soft soil has been dredged from construction sites. Most of the dredged material is clayey soil with high water content which is usually too soft to be reused for backfilling material without proper treatment.

In practice, such dredged soil has been dumped in waste disposal sites in the sea. As that practice was not environmentally friendly studies were done by them to find proper solution. Hai and Tho (2011) did a study for geocomposite soil (GCS) that contains; dredged soil, bottom ash, cement which can improve the mechanical characteristics of natural dredged soils. Three different particle sizes of bottom ash passing No. 4 sieve, No. 40 sieve, and No. 140 sieve were added into soil mixtures to form geo-composite soil as GCS 4, GCS 40, and GCS 140, respectively.

In this study, Bottom ash with removal of particle larger than No. 4 sieve was chosen as original bottom ash (BA#4). The two generated bottom ash named as BA#40 and BA#140 are crushed from the original bottom ash. The testing program was prepared at different percentages of bottom ash content while water content and cement content are fixed. The finer the particle size of bottom ash provided higher specific gravity to mixture and also the finer particle of bottom ash has the higher unit weight than the coarser.

According to Hai and Tho (2011) the water content of GCS 4 has a higher value than those of GCS 40 and GCS 140. The reason that the water content decreases with increasing bottom ash content is the increased water consumption due to the increasing amount of cementing products resulting from the pozzolanic reaction. For all the results, initial void ratio of mixture also slightly decreases with a decrease in particle sizes because the more cementing production is formed as the smaller particle size of bottom ash is added. Finally it was shown that the unconfined compression strength(q_u), increased with increasing bottom ash content.

2.7 Subgrade stabilization using Lime, Portland cement, Fly ash and bottom Ash

Fauzi et al (2011) proposed an assessment of the utilization of lime, Portland cement (PC), fly ash and bottom ash as stabilizer of soft sub grades material in highway construction. The research was conducted with various contents of lime, PC, fly ash and bottom ash to different types of clay soils from various sites in Kuantan . The engineering properties tested result shown that almost all of samples were high plasticity material, classified as A-7-6 by AASHTO Classification System. That material cannot be used as embankment material for highway construction.

In this study the engineering properties were improved by adding Portland cement, fly ash and bottom ash as stabilizer in soil stabilization. Soil stabilization mixtures were prepared at different lime, Portland cement, fly ash and bottom ash contents: 4%, 8%, 12% by total weigh with the specimens compacted at the optimum water content and CBR tests were then performed on these mixtures.

As observed by Fauzi et al (2011) Portland cement, fly ash and bottom ash stabilization increased the CBR values substantially for the mixtures tested and have the potential to offer an alternative for clay soil sub grades improvement of highway construction and this will reduce the construction cost and solve disposal problems. But, the addition of lime will contribute towards the improvement of soil workability but not to increase in CBR value.

3.0 STUDY OF BASIC CHARACTERISTICS OF BOTTOM ASH

3.1 Introduction

This chapter presents the basic characteristic of the bottom ash samples tested. After studying findings of previous researchers carefully, it was decided to carry on several tests to determine the basic characteristics; particle size distribution, Specific gravity, Plasticity, Proctor compaction test, and permeability test, initially. The strength and stiffness characteristics would be investigated thereafter.

3.1.1 Sample preparation

The coal power plant in Sri Lanka is purchasing bituminous coal from various countries such as Indonesia, Russia, and South Africa. Presently coal is purchased from South Africa. The fuel Gross Calorific Value is around 6300kCal/kg.
Testing has been conducted for three types of bottom ash samples derived from;

1. Coal received in year 2015 from Indonesia - Sample S1
2. Coal received in year 2016 from Russia - Sample S2
3. Coal received in year 2017 from South Africa - Sample S3

Sample S1 Sample S2 Sample S3

Figure 3.1: General images of bottom ash

Bottom ash samples were collected from coal power plant and transported to the place that the research is conducted. Then the sample was unloaded at the site where the sample is exposed directly to the sunlight and the rain. Before all tests, the samples were dried directly under the sun for several days to remove excess moisture.

Before conducting the proctor compaction test, it was made sure that natural air dried samples were taken for the test and later a specified amount of water was added for each sample of trays and kept for 24 hours to reach moisture equilibrium. Other test such as direct shear test and the consolidation test were conducted on the samples extracted from the proctor mould that was prepared under modified Proctor compaction efforts.

3.2 Particle size distribution

Particle size distribution is determined to classify the soil and place it in a standard group. The unified classification system is used for classification.
Sample S3 was collected from coal power plant recently and the source of origin of the coal of the bottom ash is South Africa. Sample S1 and Sample S2 have been collected sometimes ago. Almost similar qualities of surface texture can be identified visually of these bottom ash samples.
The results of particle size distribution tests done for 3 samples of bottom ash Sample S1, sample S2 and sample S3 are presented in Tables at appendices.

3.2.1 Partical size distribution for Bottom ash sample S1, S2, and S3

Particle size distribution curves for the three soils are indicated in Figure 3.2. Percentages of different groups of samples are indicated on Table 3.1. Particle size percentages for Gravel, Sand and Fines were obtained from the particle size distribution curve illustrated at Table 3.1. Average Sand percentage of sample S1, S2 and S3 are higher than seven times the Gravel percentage, and that of Fines is very less than Gravel percentage.

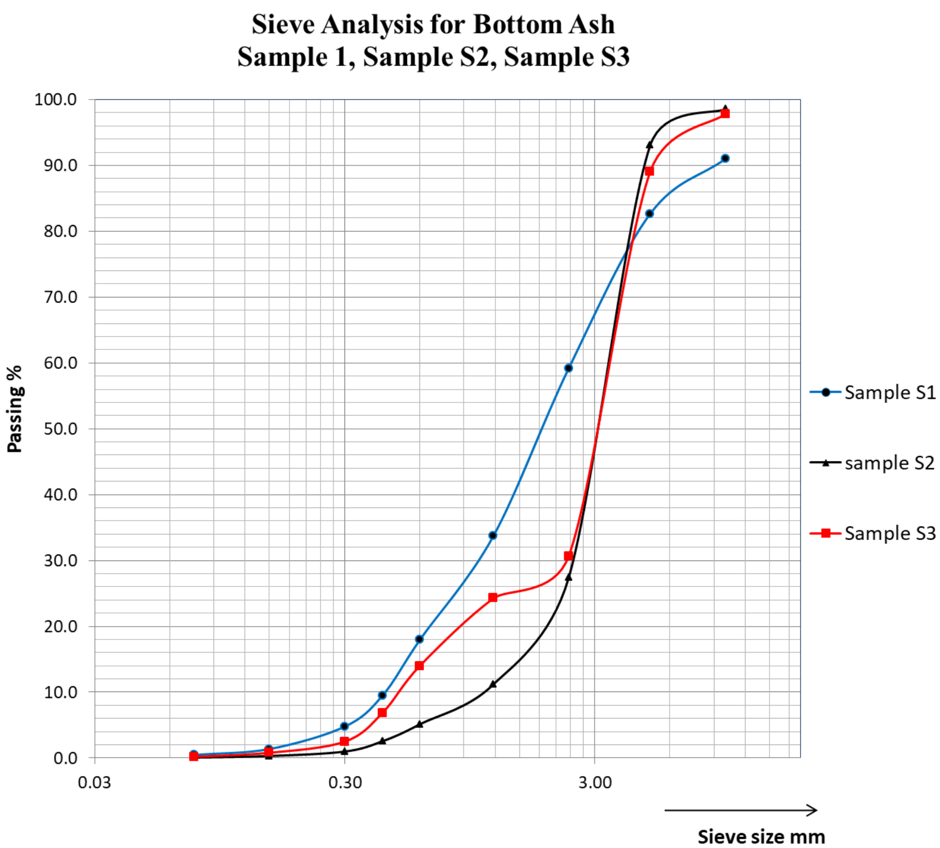


Figure 3.2: Particle size distributions of bottom ash for Samples S1,S2,S3

Table 3.1: Percentage of bottom ash particles in different groups for sample S1,S2 & S3

Group name	Percentage (%)		
	Sample S1	Sample S2	Sample S3
Gravel	17.34%	6.94%	10.94%
Sand	81.28%	92.75%	88.26%
Fines	0.47%	0.07%	0.18%

3.2.4 Classification by grading curves

Particle sizes ranged from sand to small-size gravel. That shapes of the gradation curves indicated that the partical size distributions are well graded and sample S1 & Sample S3 can be classified as well graded sand. Sample S2 is classified as poorly graded sand. The ash materials in research were classified by Unified Soil Classification system.

Table 3.2 : Basic Grain Size Indices and Unified Soil Classification System

Bottom Ash Sample	D_{10} mm	D_{30} mm	D_{60} mm	Cu (Coefficient of uniformity)	Cc (Coefficient of curvature)	Group name
Sample S1	0.402	1.01	2.2	5.47 > 4	1<Cc=1.15 < 3	SW
Sample S2	1.03	2.3	3.2	3.11 < 4	1< Cc=1.6 < 3	SP
Sample S3	0.5	2.1	3.3	6.6 > 4	1< Cc=2.67 < 3	SW

3.3 Liquid Limit Characteristics

The cone penetration test method was used to determine the liquid limit of the samples. As indicated in BS 1377: Part 2, the penetration is plotted with the moisture content in the Figure 3.3. The best fit straight line is drawn through the experimental points and the liquid limit is taken as the moisture content corresponding to a penetration of 20mm. Test was performed on Sample S3.

These test values shows non plastic nature and plastic limit could not be conducted. Hence the test is not conducted for the sample S1 and S2.

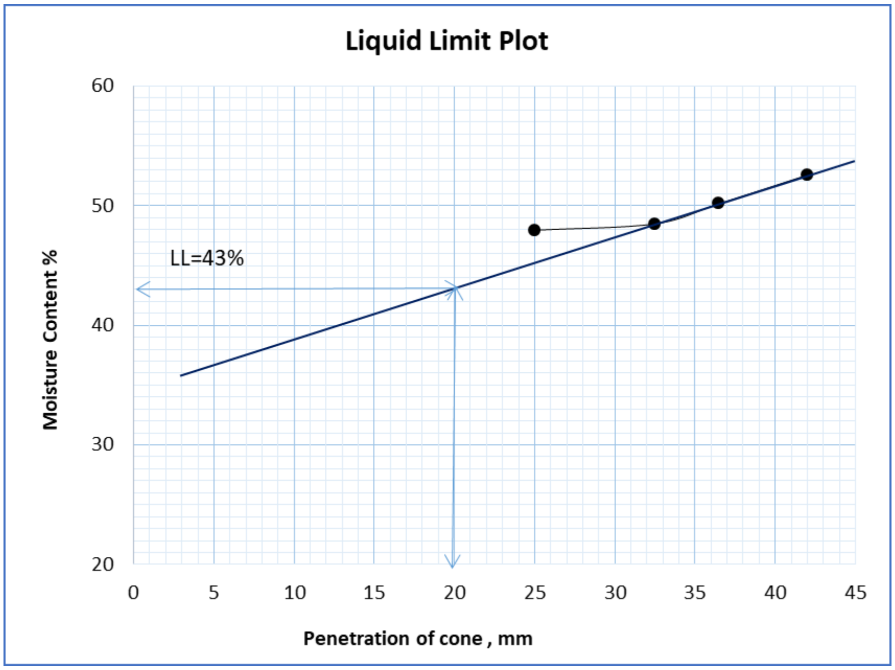


Figure 3.3: Penetration Vs Moisture content

3.4 Specific Gravity

The values of specific gravity obtained for different samples of bottom ash are summarized in Table 3.3. BS1377: 1975 specifies method was used to obtain the partical specific gravity. The specific gravity indicated at the table 3.3 is the ratio of the weight of a volume of the bottom ash to the weight of an equal volume of water as specifying in the standards.

Table 3.3: Specific Gravity of Bottom Ash

Sample Name	Specific Gravity
S1	2.19
S2	1.80
S3	1.91

3.5 Compaction characteristics

The compaction characteristics (optimum moisture content and maximum dry density) of a soil fill material are two of the most important parameters that affect embankment performance. Most specifications for embankment construction require the compacted fill material to have an in-place density that is within a certain percentage (usually 95 percent or greater) of the maximum dry density at a moisture content that is within a certain percentage of optimum. The optimum moisture and maximum dry density of Bottom ash was determined in the laboratory using the modified proctor compaction tests.

The test was performed in accordance with BS 1377:4:1975. Testing was done for all three samples S1, S2 and S3.

When the samples were prepared, corresponding amounts of water is added to the sample and was kept for the 24 hours before the testing. A separate sample was used for each moisture contents without reusing any of the already used samples.

3.5.1 Dry Density and optimum Moisture content for BA Sample S1

Detailed results of the Proctor compaction test are presented in appendices and graphically presented in Figure 3.4. Air void lines for 0%,5% and 10% air voids are also presented in Figure 3.4.

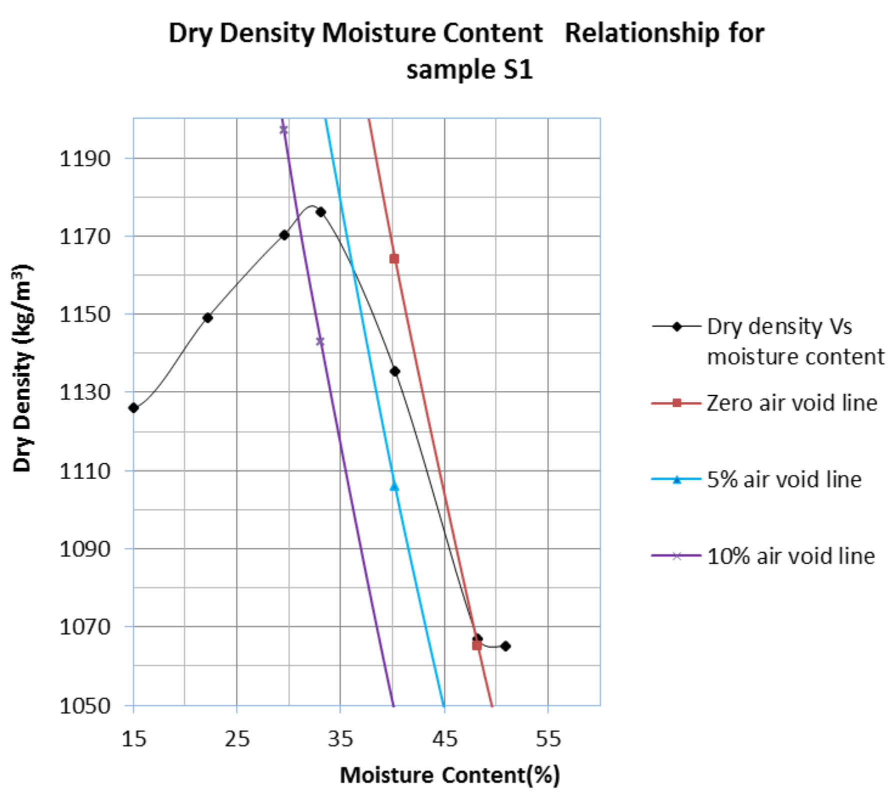


Figure 3.4: Dry densities & Moisture content relationship for Sample S1

3.5.2 Dry Density and optimum Moisture content for BA Sample S2

Similar sample preparation and the test method were adopted for the bottom ash sample S2. Detailed results are tabulated in appendices. The results are graphically presented together with 0%, 5% and 10% air void lines in Figure 3.5.

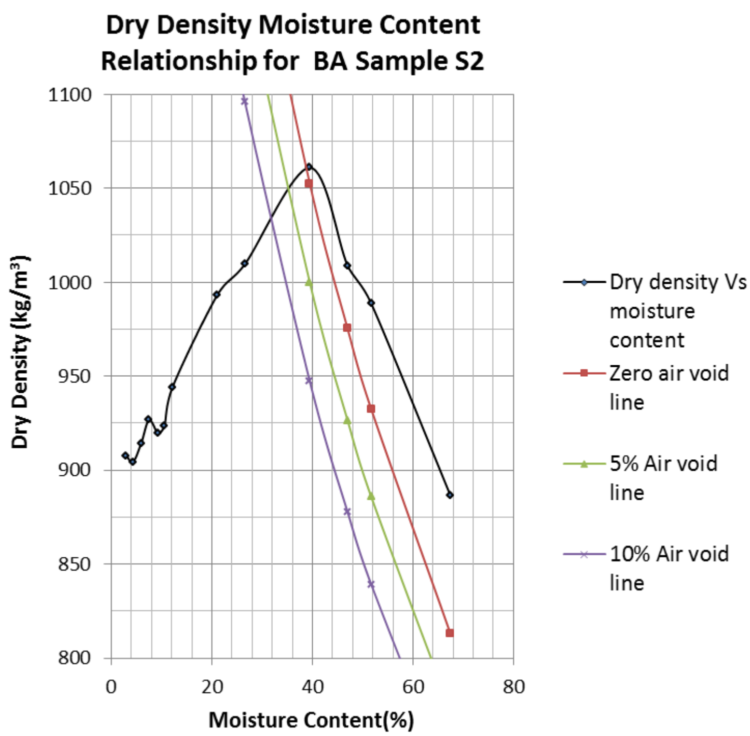


Figure 3.5: Dry densities & Moisture content relationship for Sample S2

For the sample S2, optimum moisture content is quite high and maximum dry density low just around that of water. Zero air void line did not lie above the compaction curve as in a normal soil. As suggested by Jinwoo (2013) this may be due to some microstructural change. Possibly, the structure could be pores absorbing significant amount of water to the pores.

3.5.3 Dry Density and optimum Moisture content for BA Sample S3

The bottom ash sample S3 was also subjected to the same proctor compaction testing. The results of the compaction test and air void ratio lines are tabulated in appendices and presented graphically in Figure 3.6. The maximum dry density of the sample S3 is obtained as 1201 kg/m^3 and optimum moisture content is 27.9%.

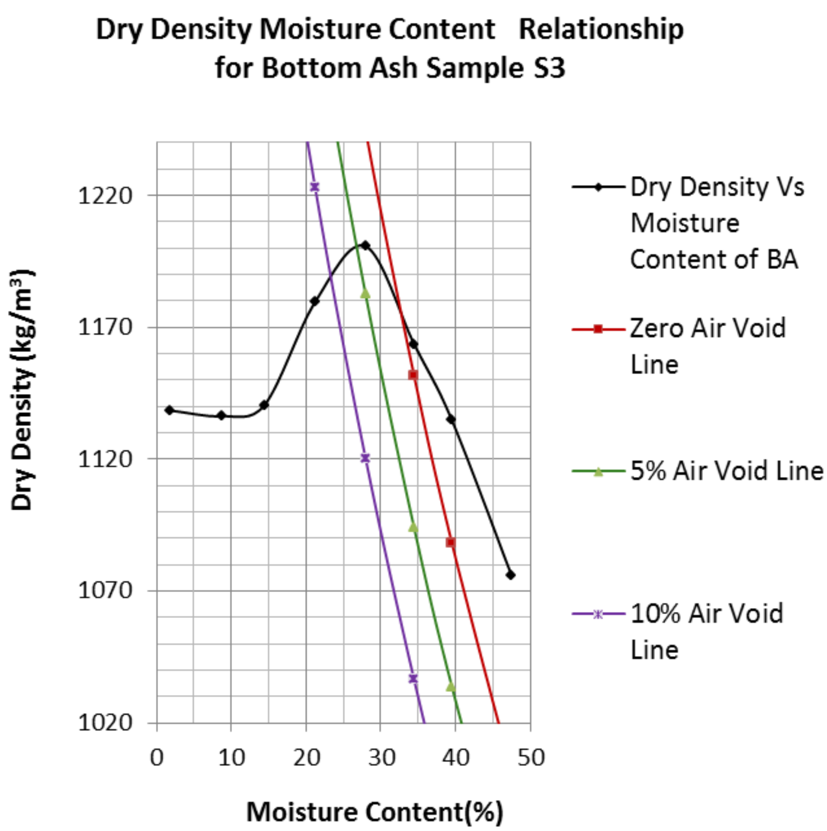


Figure 3.6: Dry density, moisture content relationship for Sample S3

3.5.4 Comparison of compaction test data for samples S1,S2 & S3

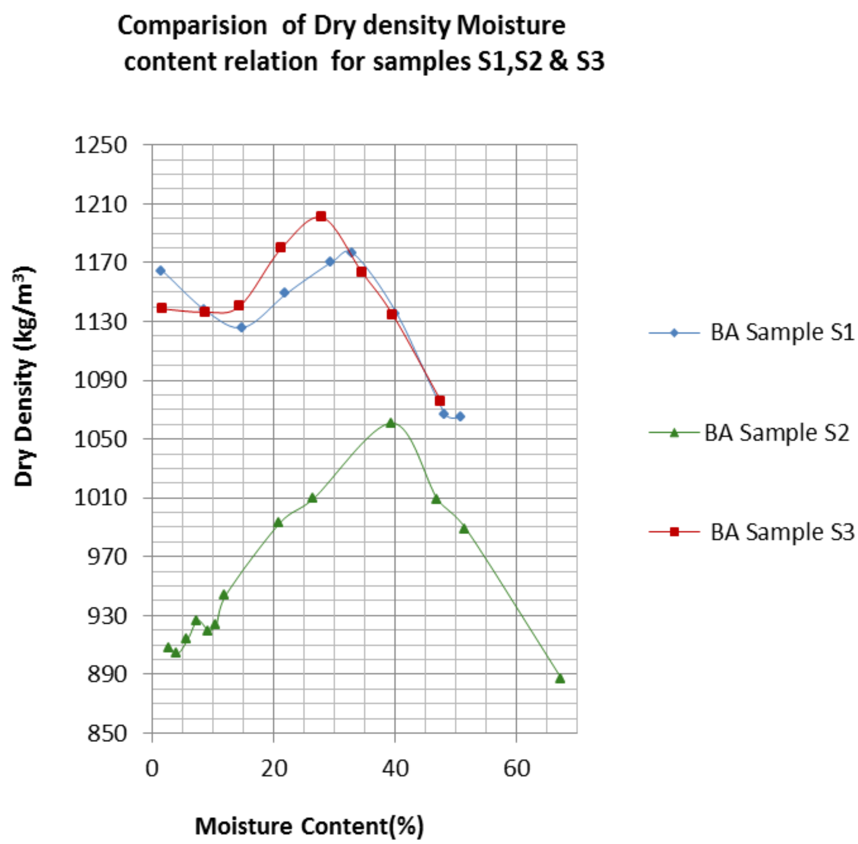


Figure 3.7: Dry density, moisture content relationship for Sample S1, S2,S3

Table 3.4 : Maximum Dry density and Optimum moisture content for all samples

Sample Name	Maximum dry density kg/m^3	Optimum moisture content(OMC) %	Specific gravity
S1	1177	32.0	2.19
S2	1060	39.5	1.80
S3	1201	27.9	1.91

The specific gravity, optimum moisture content and maximum dry density values of the three samples of bottom ash are summarized in Table 3.4. It could be noted that in all three samples the specific gravity is much lower than that of a normal inorganic mineral soil. The dry density is lower and the optimum water content quite high as for a highly plastic material but the material is non-plastic. It was also seen that 0% air voids lines below the compaction curve. Sample S3 had a greater density compared to sample S2. All these features confirm that the bottom ash particles are having porous structures. These pores are getting filled easily by the water added for the compaction, thus requiring more water for the process of compaction. The density of the compacted material is also low. The presence of high amount of water has not caused any problem in workability of the material.

Hence it is suitable as a fill material. Even with the higher optimum moisture content the bulk density is in the order of 1500 kg/m3 and can still be considered as a fill material of lighter weight.

3.6 Coefficient of Permeability (k) of the Bottom Ash

The coefficient of permeability was determined for the sample S3 after compacting under modified proctor effort and saturation of the sample. As the fines content was negligible, it was decided to use the constant head method to find the coefficient of permeability. Eight number of trial set were done and experimental datas are tabulated and illustrated at appendices. Results are graphically presented in rate of flow and head difference graphs in Figure 3.8 and Figure 3.9.

The compacted sample is with smaller porous and velocity through the soil become so small and the flow can be considered as laminar. Then Darcy’s law was applied for head difference in the constant head apparatus. The coefficient of Permeability values computed is presented in Table 3.5.

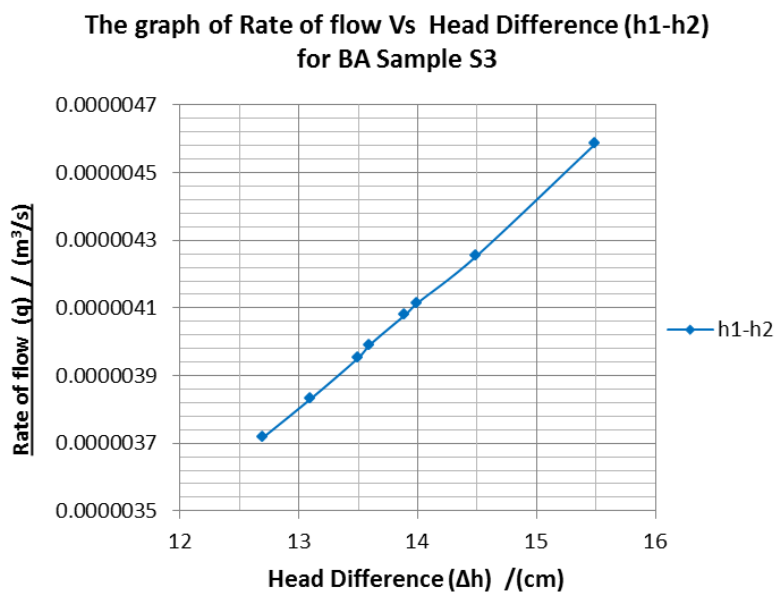


Figure 3.8: Rate of flow vs (h_1-h_2) Head difference for set 1

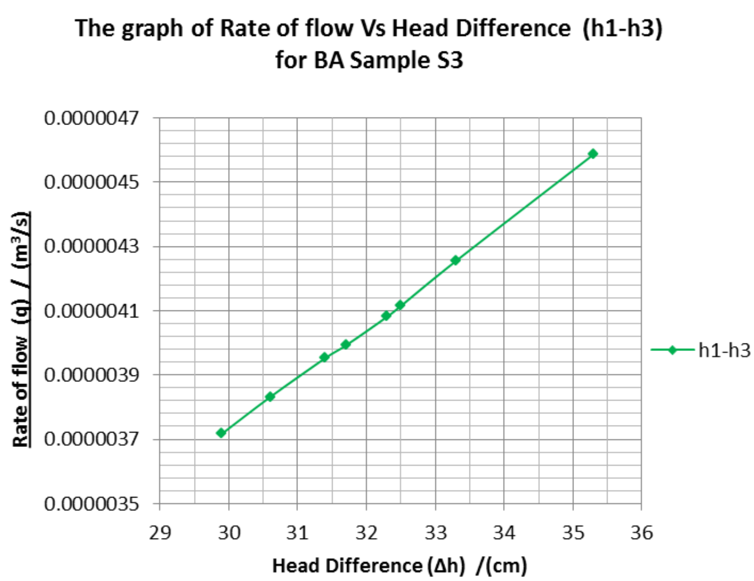


Figure 3.9: Rate of flow vs (h_1-h_3) Head difference for set 2

Table 3.5 : Coefficient of Permeability for Sample S3

Head difference Set	Coefficient of Permeability k (m/s)
1	3.70×10^{-4}
2	3.81×10^{-4}

Table 3.6 : Typical values of Coefficient of permeability in type of soils

k (m/s)

1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11}

<table>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Clean Gravels</td><td colspan="3">Clean gravels, Clean sand and Gravel</td><td colspan="4">Very fine sands, organic and inorganic sits , mixture of sand , silt and clay</td><td colspan="2">Clays</td></tr>
<tr><td colspan="6">Well drain soils</td><td colspan="2">Poorly drained soils</td><td colspan="3">Practically impervious</td></tr>
</table>

Table 3.6 expressed that typical value of coefficient of permeability. Therefore the Experiment values show that the bottom ash fall within the range of sandy soil. Thus bottom ash can be considered to be a well-drained material.

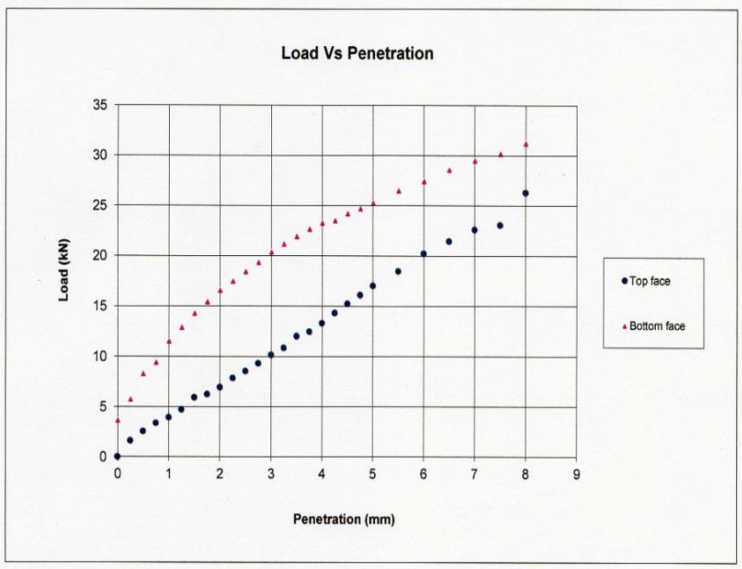
3.7 CBR value of Bottom Ash

CBR is widely used in the determination of suitability of subgrade or subbase material in road constructions. Therefore the test was performed on Bottom Ash sample S3 to evaluate the suitability in embankment construction.

As per the ICTAD guide line SCA/5 regarding requirement of embankment material, the minimum four day soaked CBR at 95% Maximum Dry Density (modified) should not be less than 7% for Type I and 5% for Type II. Bottom ash test values showed that unsoaked CBR value is 129% and soaked CBR value is 74%. Respective results are presented in Figure 3.10 and Figure 3.11.

Hence it satisfied the requirements very well.

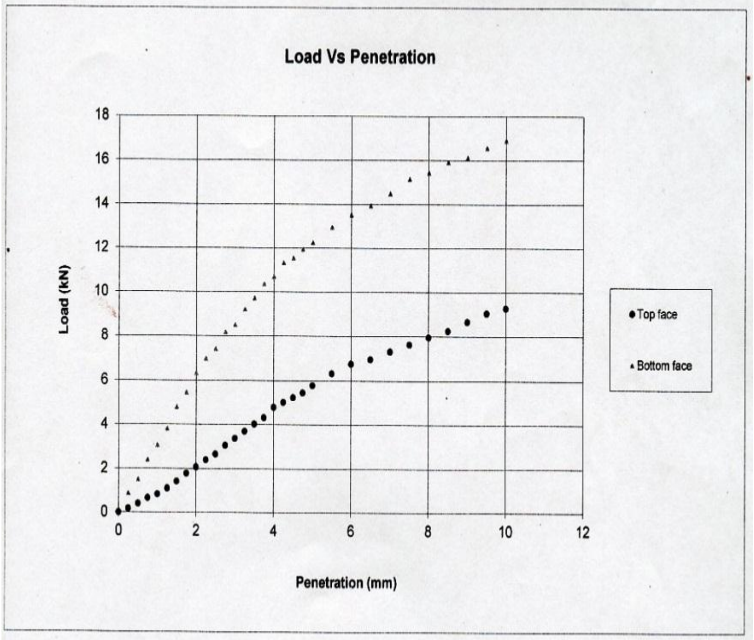
Test Method : BS 1377 : 1990 (Part 4)			
Sample No.	00165	Specimen No.	-
Test on top face	Unsoaked	Test Condition	
Test on bottom face	Unsoaked	Sample Type	Bottam Ash



		Top face	Bottom face	Accepted CBR %
CBR % at penetraion of	2.5mm	64.39	128.79	129
	5.0mm	92.50	126.50	

Figure 3.10 Unsoaked CBR Value for the bottom ash Sample S3

Test Method : BS 1377			
Sample No.	**Sample 01**	Specimen No.	**GEL/2017/00785**
Test on top face	Soaked	Test Condition	Soaked
Test on bottom face	Soaked	Sample Type	Bottom Ash Bulk Sample



		Top face	Bottom face	Accepted CBR %
CBR % at penetration of	2.5mm	25.57	58.71	74
	5.0mm	33.75	73.75	

Figure 3.11 Soaked CBR Value for the bottom ash Sample S3

3.8 Concluding comments

Basic characteristics of bottom ash samples were studied considering samples of bottom ash S1, S2 and S3, three different types of bottom ash available in Sri lanka. The samples differ due to origin of the coal used in the process.

The particle size distribution provided the coefficient of uniformity and coefficient of curvature of the samples. Based on these values the bottom ash can be classified as generally well graded sandy soil. Bottom ash is a non-plastic material and plastic limit cannot be determined. Liquid limit is 43% as obtained from cone penetration method. Specific gravity generally has been within 1.8 to 2.2. Therefore, based on those characteristics this material is apparently seen as a granular material.

The compaction characteristics showed that the dry densities are low close to that of water and optimum moisture content is quite high as for a highly plastic soil. A closer examination of these results and location of zero air void line with respect to compaction curve confirms that the bottom ash is having a porous structure. This had been reported by some earlier researches also. Thus the bottom ash can be considered as a granular fill material of lower density or a light weight fill material. The quite high CBR value confirms its suitability as a material for construction of road embankments. The high value of permeability in the range of sandy soils confirms the fact that it can be considered as a granular fill.

4.0 COMPRESSIBILITY CHARACTERISTICS OF THE BOTTOM ASH

4.1 Introduction and loading procedure

Another important characteristic of an appropriate fill material is that it should be quite stiff when compacted. This could be assessed by determining the compressibility of the compacted bottom ash. The compressibility characteristics of bottom ash were determined by one-dimensional consolidation test. Compressibility measured here accounts for the consolidation or settlement characteristics of the material under long-term loading conditions.

Specimen for the consolidation tests were extruded from the sample compacted in the proctor mould under modified proctor compaction effort. To obtain the compressibility characteristics three samples; S1, S2, and S3 were subjected to following loading sequence.

i. For the sample S1:
   a) One sample of S1 was tested under applying loading only. Applied Loading increments are ; 25kN/m^2 , 50kN/m^2 ,100kN/m^2 and 200kN/m^2

ii. For the sample S2:
   a) One samples of S2 was tested under loading only. Applied Loading increments are ;25kN/m^2 , 50kN/m^2 ,100kN/m^2 and 200kN/m^2
   b) A second sample of S2 was tested by applying much higher Loads. Applied Higher Loading increments are; 250kN/m^2, 500kN/m^2, 1000kN/m^2 and 2000kN/m^2.

   Loading: 250 kN/m^2 ➔ 500 kN/m^2 ➔ 1000kN/m^2 ➔2000kN/m^2

Unloading: 2000kN/m^2 → 1000kN/m^2 → 100kN/m^2

Reloading:100kN/m^2→250kN/m^2→500kN/m^2→1000kN/m^2→2000kN/m^2

iii. For the sample S3:

a) Three samples of S3 were tested under conditions of Loading, Unloading and Reloading and applied loading increments are 12.5kN/m^2, 25kN/m^2, 50kN/m^2, 100kN/m^2, 200kN/m^2 and 400kN/m^2.

Loading: 12.5 kN/m^2 → 25 kN/m^2 → 50kN/m^2 → 100kN/m^2

→ 200kN/m^2 → 400kN/m^2

Unloading: 400kN/m^2 → 100kN/m^2 → 25kN/m^2

Reloading: 25kN/m^2 → 50kN/m^2 →100kN/m^2 →200kN/m^2

→400kN/m^2 → 800kN/m^2

4.2 Compressibility characteristics of bottom ash Sample S1 at loading only

Consolidation test have been done for the Sample S1 by considering loading with consolidation only. Respective Graphs and tables are given below and other data table such as root time, dial reading and the settlement for each load are attached in Appendix B.

The settlement variations for the root time for loads of 25kN/m^2, 50kN/m^2, 100kN/m^2, 200kN/m^2 are presented in Figure 4.1.Coefficient of consolidation and the volume compressibility calculated for the increments are presented in Table 4.1. The plot of m_v with stress level is presented in Figure 4.2 and the Plot of C_v with Stress level are presented in Figure 4.3.The void ratio with stress level Plot is present in Figure 4.5.

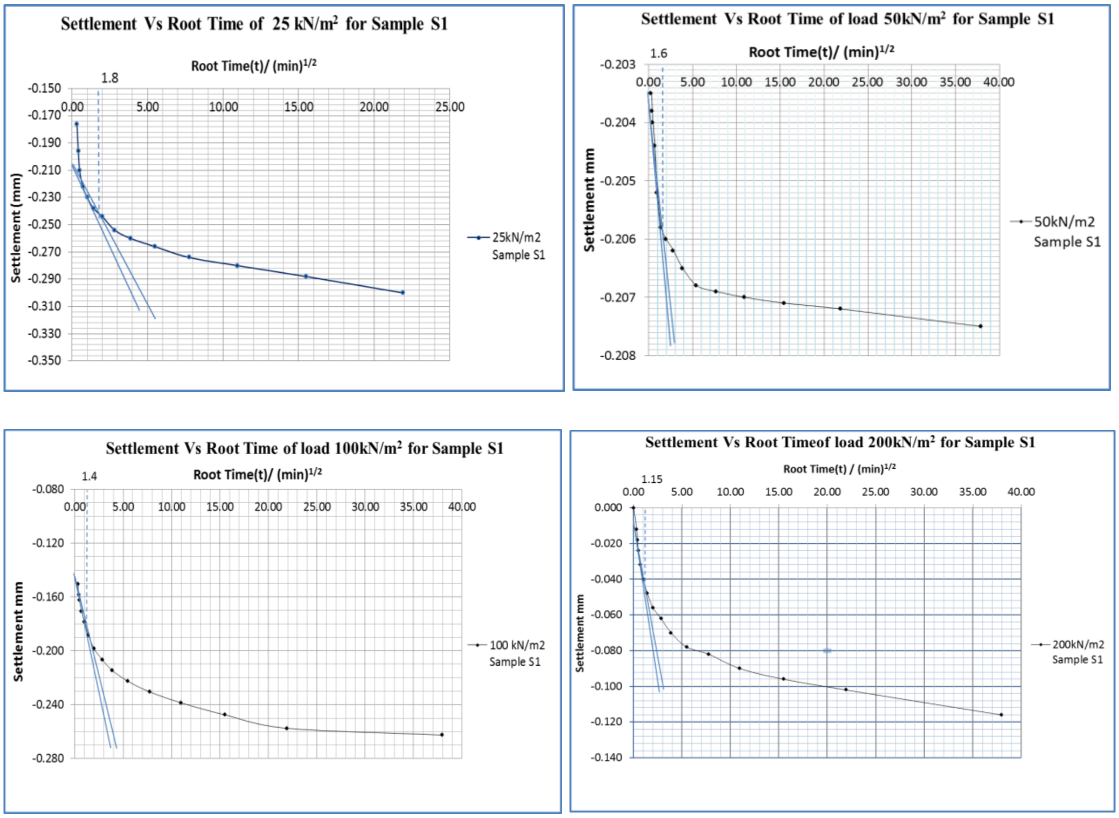


Figure 4.1 :Settlement with Root Time for sample S1 for load increment 25kN/m^2, 50kN/m^2, 100kN/m^2, 200kN/m^2

Table 4.1 Calculated value for coefficient of consolidation and volume compressibility for sample S1

Current load increment	0 kN/m^2 25kN/m^2	25kN/m^2 50kN/m^2	50kN/m^2 100kN/m^2	100kN/m^2 200kN/m^2
Coefficient of Volume Compressibility (m_v) (10^{-4} m^2/kN)	6.00	2.09	1.30	0.30
Coefficient of Consolidation (C_v) (m^2/year)	13.8	17.2	22.0	31.8

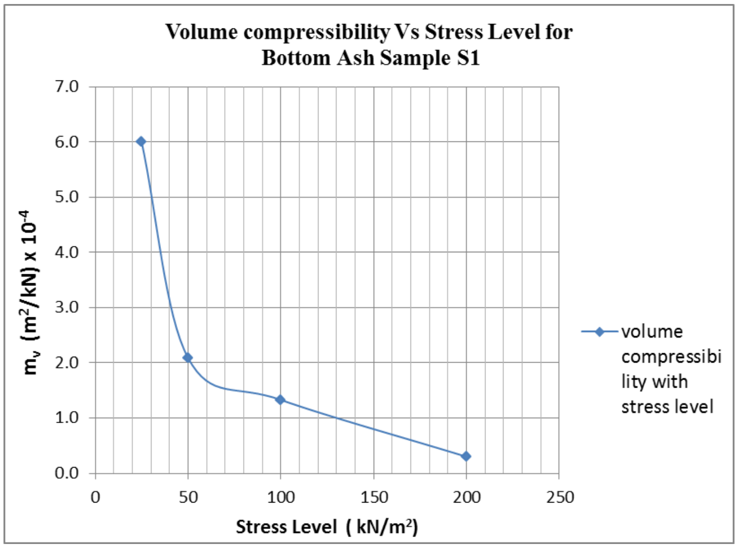


Figure 4.2: m_v with Stress level for sample S1

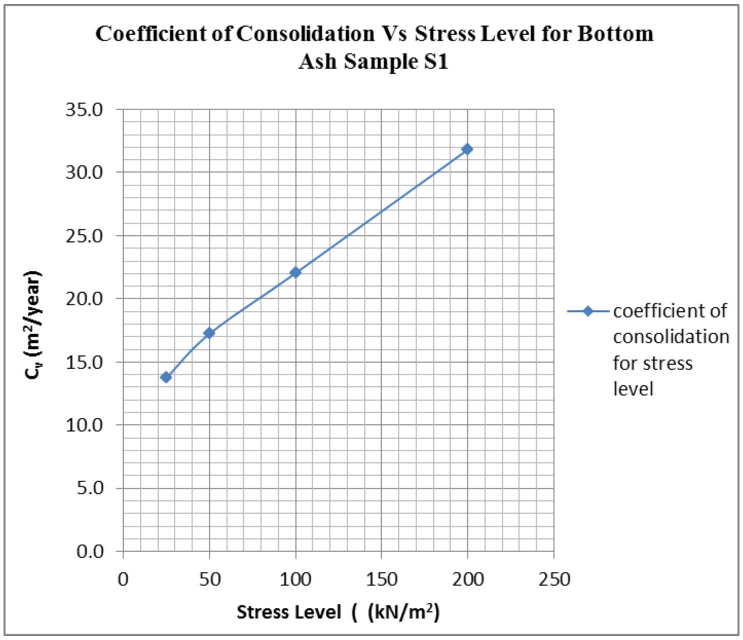


Figure 4.3: C_v with Stress level for sample S1

A sequence of pressure increments were applied on the sample, each being double the previous value. Each pressure was normally maintained over a period of 24 hours and vertical compression of the sample was measured. It is assumed that the pore pressure increment due to each loading increment dissipates within 24 hours and the total applied stress is equal to the effective stress in the sample.

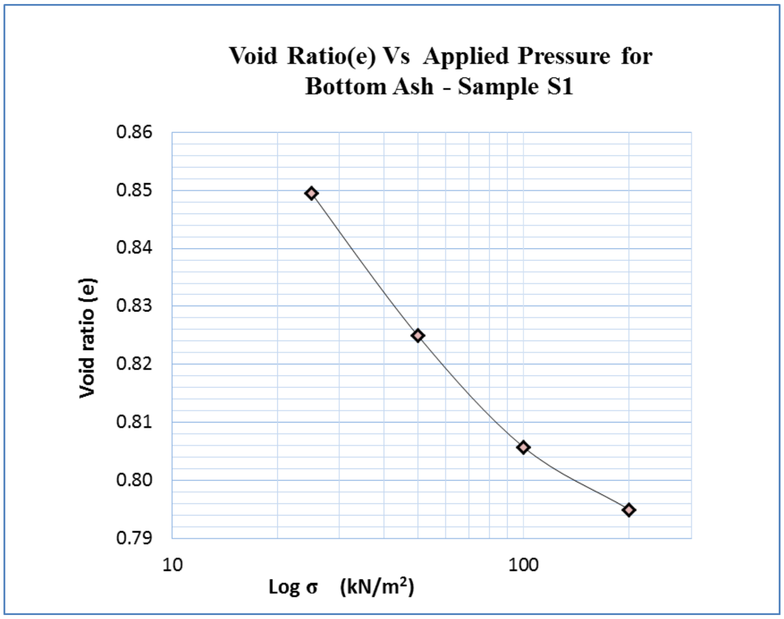


Fig. 4.5: Void ratio with Applied pressure for sample S1

The void ratio vs applied pressure is presented at Figure 4.5. Void ratio is decreased from 0.86 to 0.79 according to the applied pressure of $25kN/m^2$ to $200kN/m^2$. The next loading pressure was always doubled than it's presently applied one and 4 numbers of sequences of pressure increments was applied for the sample S1. Compression index and the compression ratio were calculated by using Figure 4.5.

$$C_c = \Delta e / \log(\sigma'_2/\sigma'_1)$$

$$C_c = \underline{\underline{0.061}}$$

$$C_c / (1+e_o) = \underline{\underline{0.033}}$$

The compression index C_c is 0.061 and the compression ratio $C_c / (1+e_0)$ is 0.033. Both these parameters and the m_v value clearly indicate that the bottom ash sample is of low compressibility. The C_v values indicate that the rate of consolidation is high. This confirms that the bottom ash can be considered as free draining material as indicated by the permeability values.

4.3 Compressibility characteristics of bottom ash Sample S2 at Loading

Consolidation test have been conducted for the bottom ash Sample S2 by considering loading with consolidation only. The settlement vs √time plots are presented in Figure 4.6. The variation of the volume compressibility m_v with stress level is presented in Figure 4.7. The variation of coefficient of consolidation with stress level is presented in Figure 4.8. The values of void ratio for each applied pressure are graphically presented at Figure 4.9.

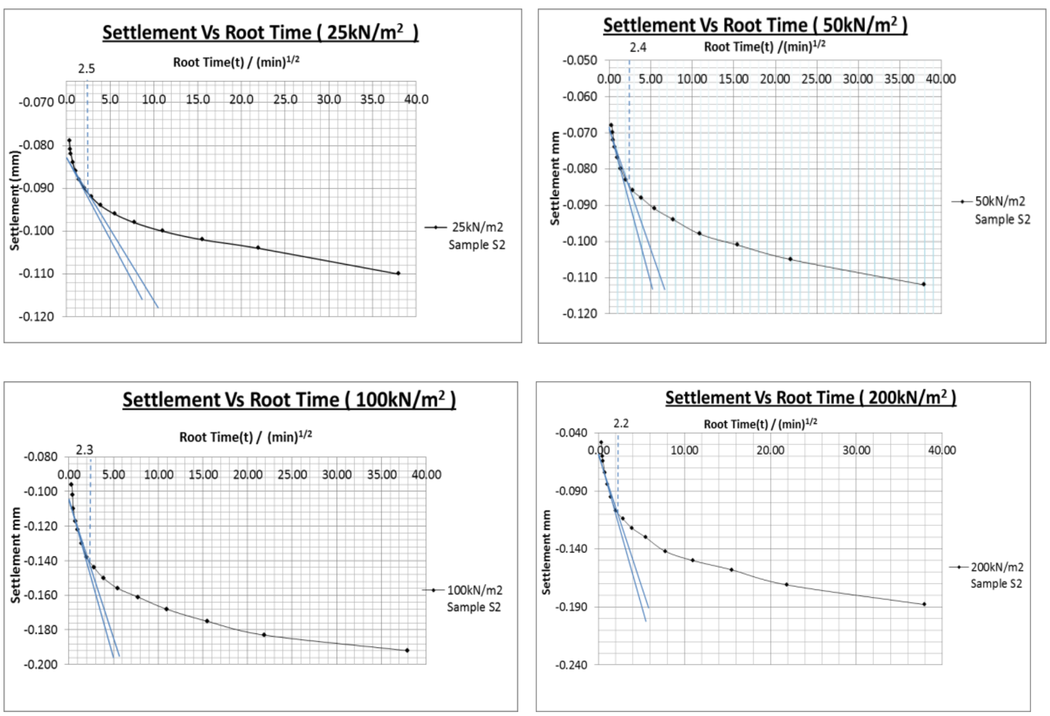


Figure 4.6 : Settlement with Root Time for sample S2

For load increment 25kN/m^2, 50kN/m^2, 100kN/m^2, 200kN/m^2

Table 4.2 : Calculated values for coefficient of consolidation and volume compressibility for sample S2

Current load increment	0 kN/m^2 25kN/m^2	25kN/m^2 50kN/m^2	50kN/m^2 100kN/m^2	100kN/m^2 200kN/m^2
Coefficient of Volume Compressibility (m_v) (10^{-4} m^2/kN)	2.20	1.13	0.97	0.48
Coefficient of Consolidation (C_v) (m^2/year)	7.1	7.7	8.2	8.8

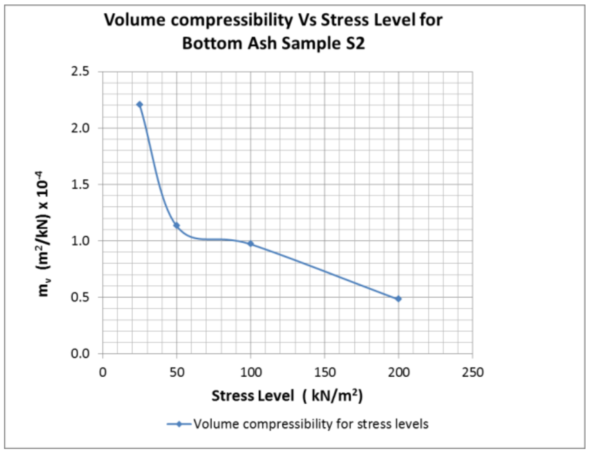


Figure 4.7: m_v with Stress level for sample S2

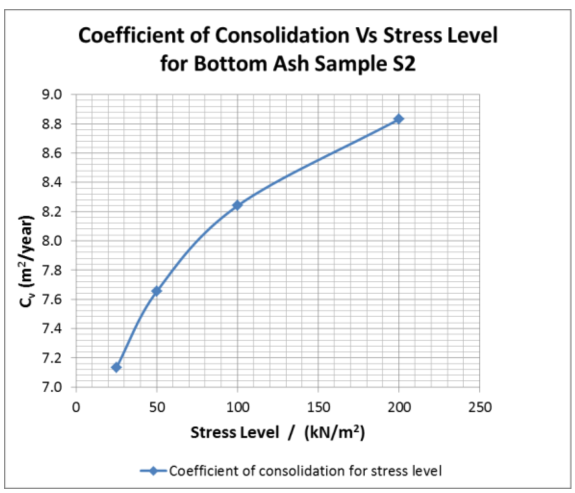


Figure 4.8: C_v with Stress level for sample S2

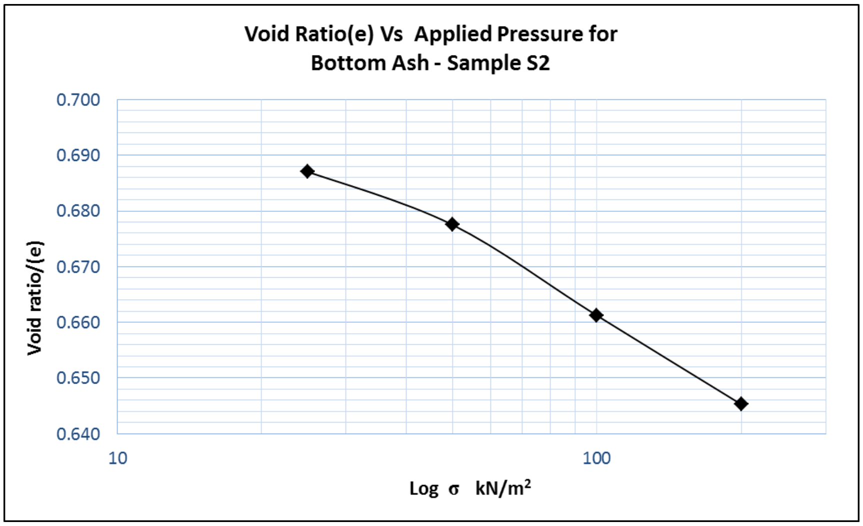


Figure 4.9: Void ratio Vs Applied pressure for sample S2

$$C_c = 0.052$$

$$C_c / (1+e_o) = 0.031$$

4.4 Compressibility of sample S2 at higher loads for loading, Unloading and Reloading

Sample S2 was subjected to higher loading intensities of; 250kN/m^2, 500kN/m^2, 1000kN/m^2 and 2000kN/m^2. Also it was subjected to unloading and reloading thereafter.

Loading increments: 250 kN/m^2 ➔ 500 kN/m^2 ➔ 1000kN/m^2 ➔2000kN/m^2

Unloading increments: 2000kN/m^2 ➔ 1000kN/m^2 ➔ 100kN/m^2

Reloading increments:100kN/m^2➔250kN/m^2 ➔ 500kN/m^2➔1000kN/m^2➔2000kN/m^2

Settlement vs root time plots are presented in Figure 4.10. The variation of coefficient of consolidation C_v and coefficient of volume compressibility m_v with stress level is presented in Table 4.3 and graphically presented in Figure 4.11 and Figure 4.12.

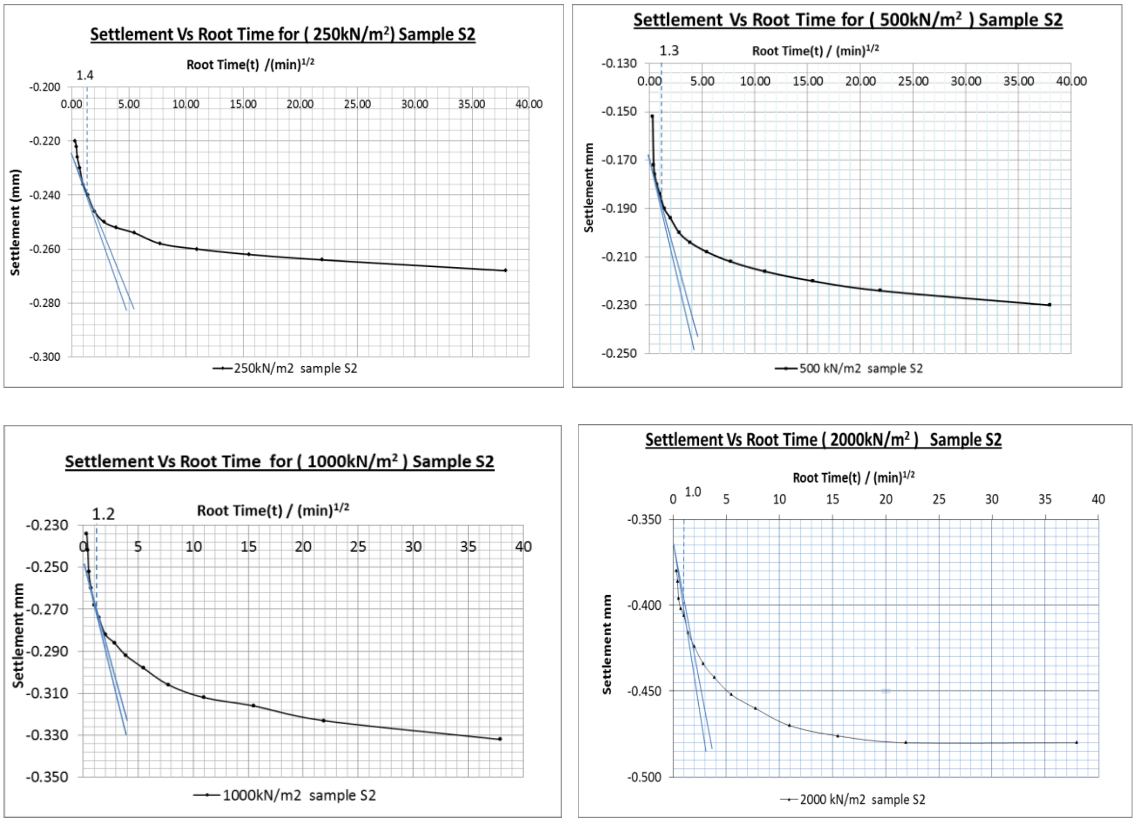


Figure 4.10: Settlement with Root Time for higher load cases for sample S2

Table 4.3: Calculated value for coefficient of consolidation and volume compressibility for higher load case for sample S2

Current load increment	0kN/m^2 250kN/m^2	250kN/m^2 500kN/m^2	500kN/m^2 1000kN/m^2	1000kN/m^2 2000kN/m^2
Coefficient of Volume Compressibility (m_v) (10^{-5} m^2/kN)	5.4	2.3	1.7	1.3
Coefficient of Consolidation (C_v) (m^2/year)	22.7	25.7	29.4	40.9

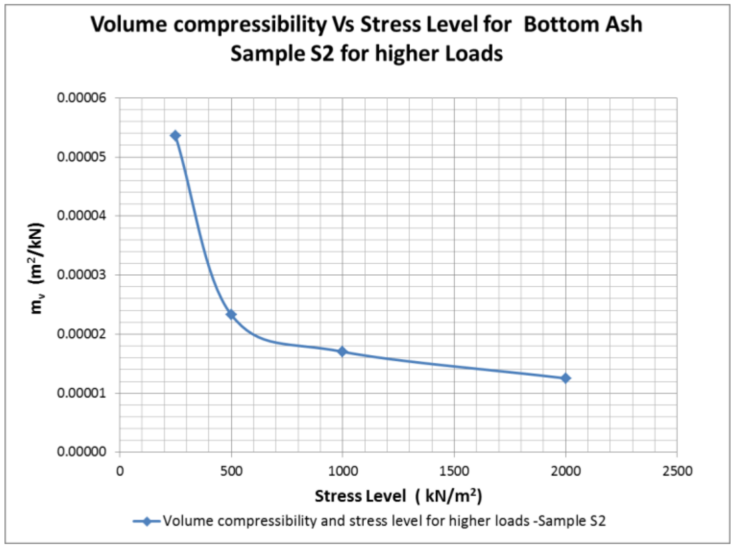


Figure 4.11: m_v with Stress level for sample S2

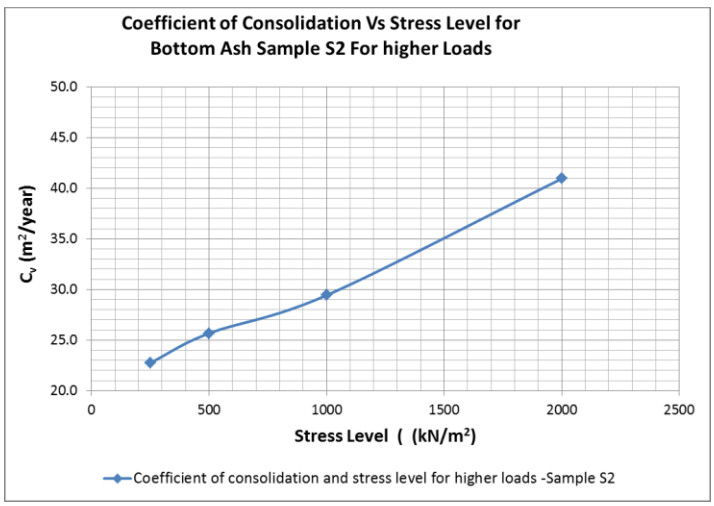


Figure 4.12: C_v with Stress level for sample S2

The sample S2 was investigated by applying lesser load increment as well as higher load increments. The coefficient of volume compressibility for higher loads showed lesser values compared with lower load case as indicted in Figure 4.7 and Figure 4.11. The coefficient of consolidation has higher values for higher load case and comparatively it was lesser in the case of lower loads as indicated in the Figure 4.8 and Figure 4.12.

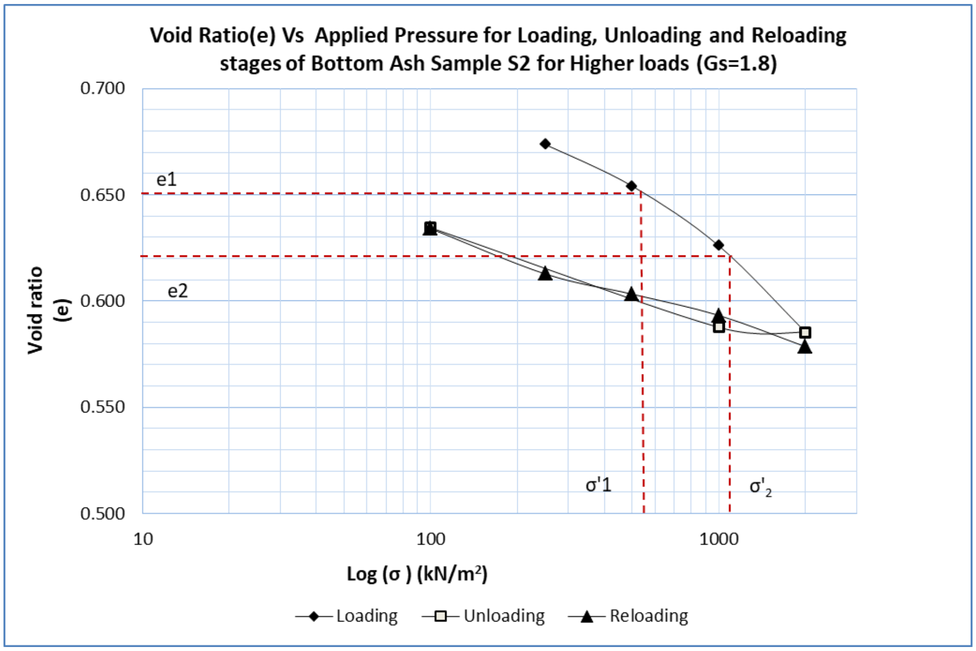


Figure 4.14: Void ratio with Applied pressure of higher loads for Loading, Unloading and Reloading of sample S2

C_c = 0.108 $C_c / (1+e_o)$ = 0.064

C_r = 0.044 $C_r / (1+e_o)$ = 0.026

4.5 Compressibility of sample S3 at loading, Unloading, Reloading

Compressibility testing at Loading, Unloading and Reloading was done for the Sample S3 only due to recently available coal fired bottom ash samples at the Lakvijaya power plant. That coal is being supplied by South Africa. Set of samples namely Sample S3-1, S3-2 and S3-3 were extruded from the sample compacted in the proctor mould under modified proctor compaction effort.

Loading Increment : 12.5 kN/m^2 ➔25 kN/m^2➔ 50kN/m^2 ➔100kN/m^2 ➔200 kN/m^2 ➔400kN/m^2

Unloading Increment : 400kN/m^2 ➔ 100kN/m^2 ➔ 25kN/m^2

Reloading Increment : 25kN/m^2➔50kN/m^2 ➔ 100kN/m^2 ➔200kN/m^2 ➔ 400kN/m^2 ➔800kN/m^2

Settlement vs root time plots are presented in Figure 4.15, Figure 4.19 and Figure 4.23 for Sample S3-1,S3-2 and S3-3 respectively.

The variation of coefficient of consolidation C_v with stress level is graphically presented in Figure 4.16, Figure 4.20, Figure 4.24 for samples S3-1, S3-2 and S3-3.The coefficient of volume compressibility m_v with stress level is presented in Figure 4.17, Figure 4.21, Figure 4.25 for samples S3-1,S3-2 and S3-3 respectively. The values are summarized in Table 4.4, Table 4.5 and Table 4.6 for sample S3-1, S3-2 and S3-3.

4.5.1 Compressibility Characteristics of Sample S3-1

Sample S3-1 was conducted for the consolidation test for the bottom ash by considering loading, unloading and reloading increments. Respective Graphs and tables are given below and the other data tables for each load are attached in Appendices.

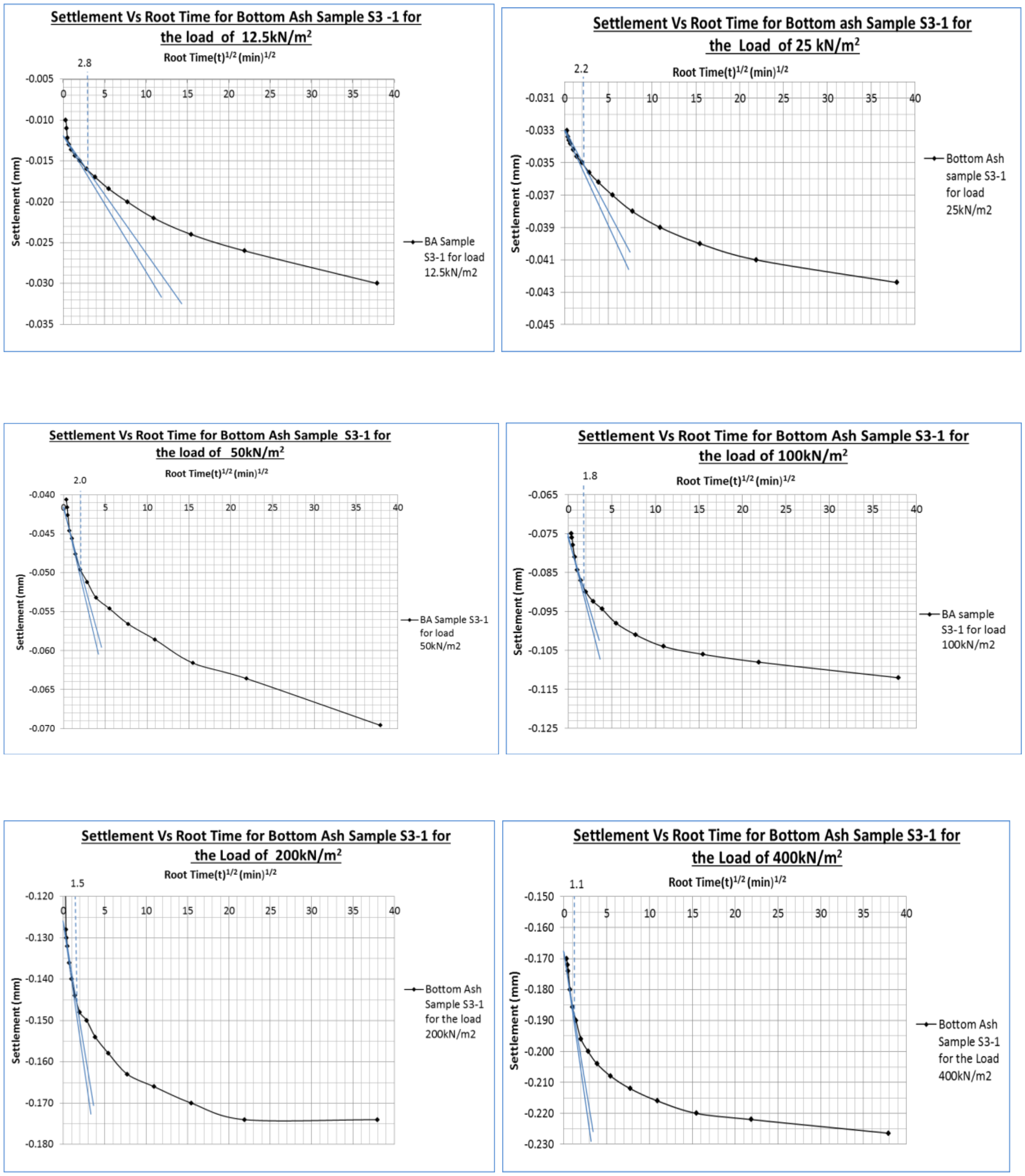


Fig.4.15: Settlement with Root Time for sample S3-1 for load increment 12.5kN/m^2, 25kN/m^2, 50kN/m^2, 100kN/m^2, 200kN/m^2, 400kN/m^2

Table 4.4: Calculated value for coefficient of consolidation and volume compressibility for load cases for sample S3-1

Current load increment	$0kN/m^2$ $12.5kN/m^2$	$12.5kN/m^2$ $25kN/m^2$	$25kN/m^2$ $50kN/m^2$	$50kN/m^2$ $100kN/m^2$	$100kN/m^2$ $200kN/m^2$	$100kN/m^2$ $400kN/m^2$
Coefficient of Volume Compressibility (m_v)($10^{-5}m^2/kN$)	12.0	8.5	7.0	5.6	4.4	2.9
Coefficient of Consolidation (C_v) (m^2/year)	5.7	9.2	11.1	13.6	19.3	35.3

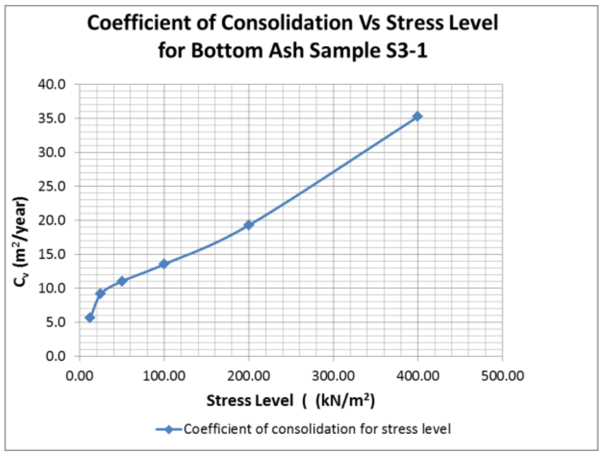


Figure 4.16 : C_v with Stress level for sample S3-1

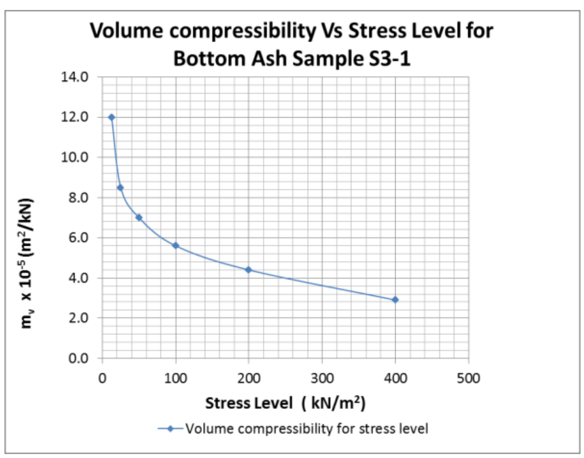


Figure 4.17 : m_v with Stress level for sample S3-1

Sequences of pressure increments are applied on the sample, each being double the previous value. Each pressure is normally maintained over a period of 24 hours, and vertical compression of the sample is measured at suitable intervals during this period. Other required data are attached in Appendices.

The void ratio values for loading, unloading and reloading are graphically presented in Figure 4.18.

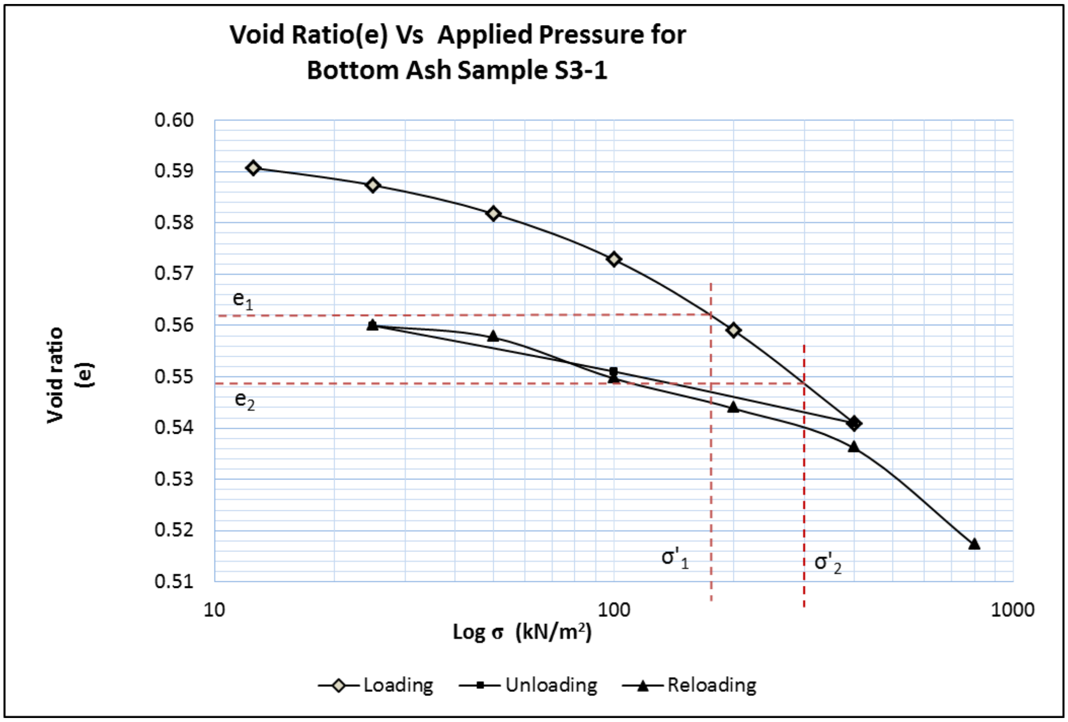


Figure 4.18 : Void ratio with Applied pressure for Loading, Unloading and Reloading to the sample S3-1

C_c	= 0.062	$C_c / (1+e_o)$	= 0.039
C_r	= 0.008	$C_r / (1+e_o)$	= 0.005

4.5.2 Compressibility Characteristics of Sample S3-2

Consolidation test have been done for the bottom ash Sample S3-2 by considering loading unloading and Reloading.

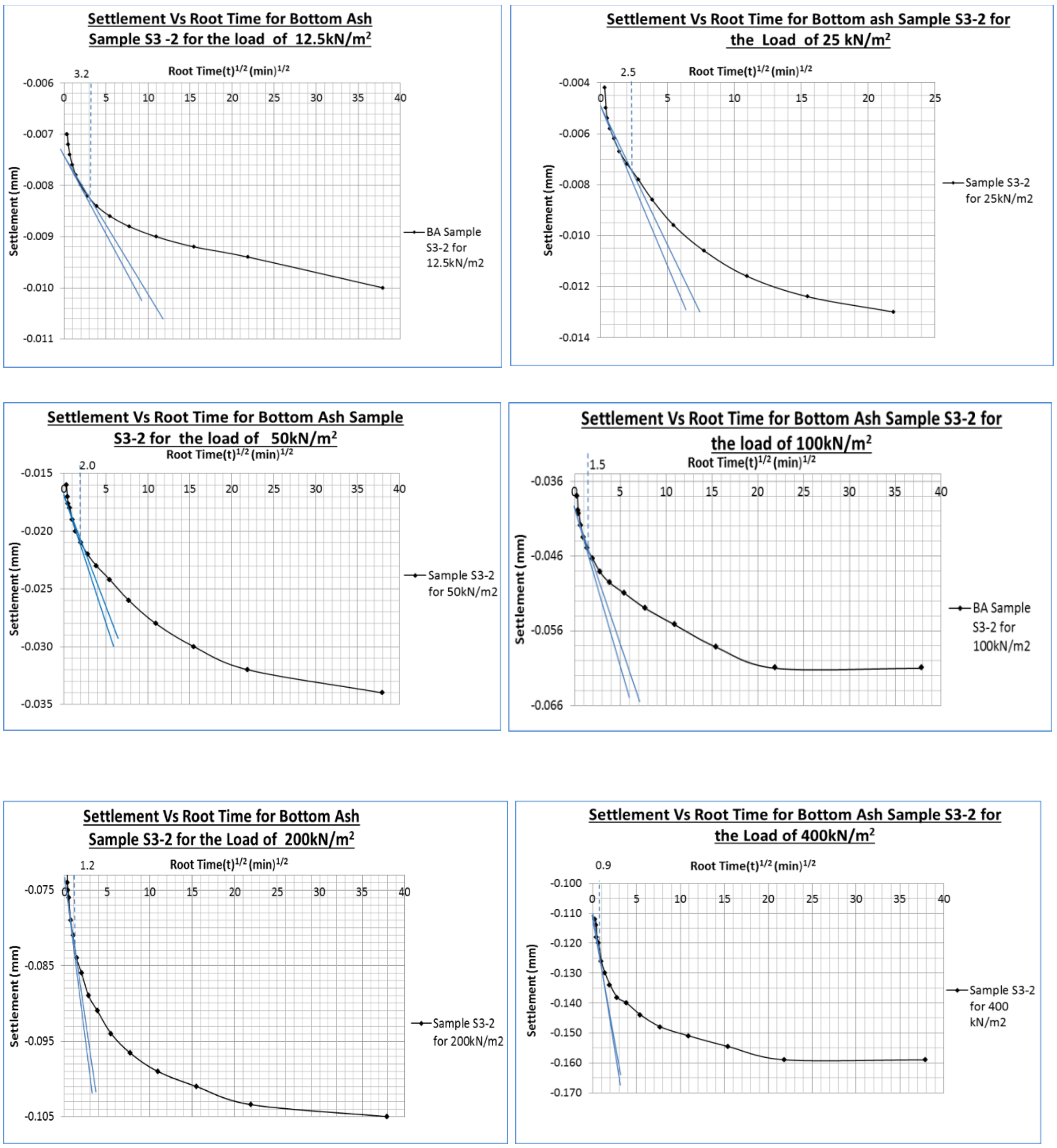


Figure4.19: Settlement with Root Time for sample S3-2 for load increment 12.5kN/m^2, 25kN/m^2, 50kN/m^2, 100kN/m^2,200kN/m^2,400kN/m^2

Table 4.5: Calculated values for coefficient of consolidation and volume compressibility for load case for sample S3-2

Current load increment	0kN/m^2 12.5kN/m^2	12.5kN/m^2 25kN/m^2	25kN/m^2 50kN/m^2	50kN/m^2 100kN/m^2	100kN/m^2 200kN/m^2	100kN/m^2 400kN/m^2
Coefficient of Volume Compressibility (m_v)($10^{-5}m^2/kN$)	4.0	3.6	3.4	3.1	2.6	2.0
Coefficient of Consolidation (C_v) (m^2/year)	4.4	7.1	11.1	19.7	30.6	53.8

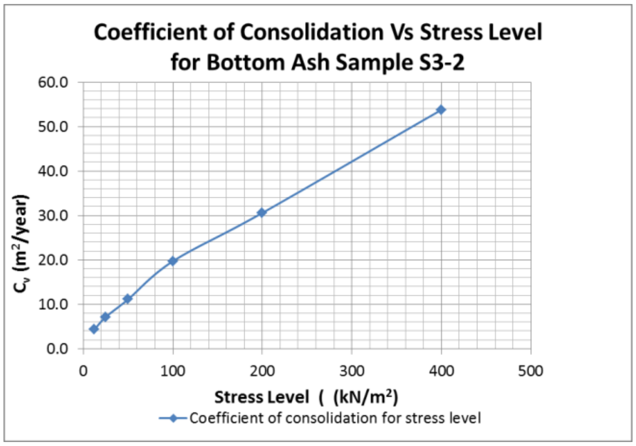


Figure 4.20 : C_v with Stress level for sample S3-2

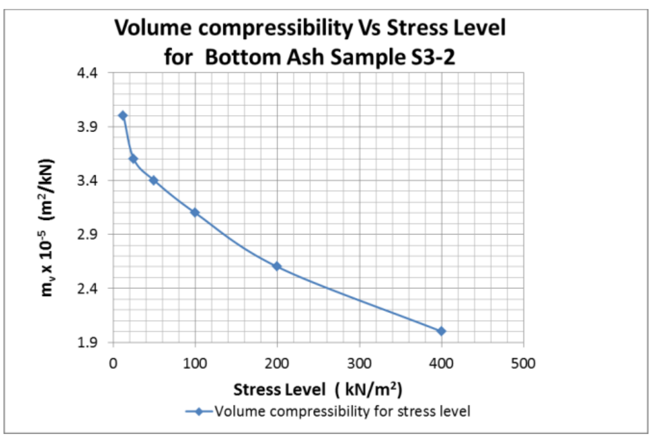


Figure 4.21: m_v with Stress level for sample S3-2

Void ratio with applied pressure for loading, unloading and reloading of the sample S3-2 is presented in the Figure 4.22.

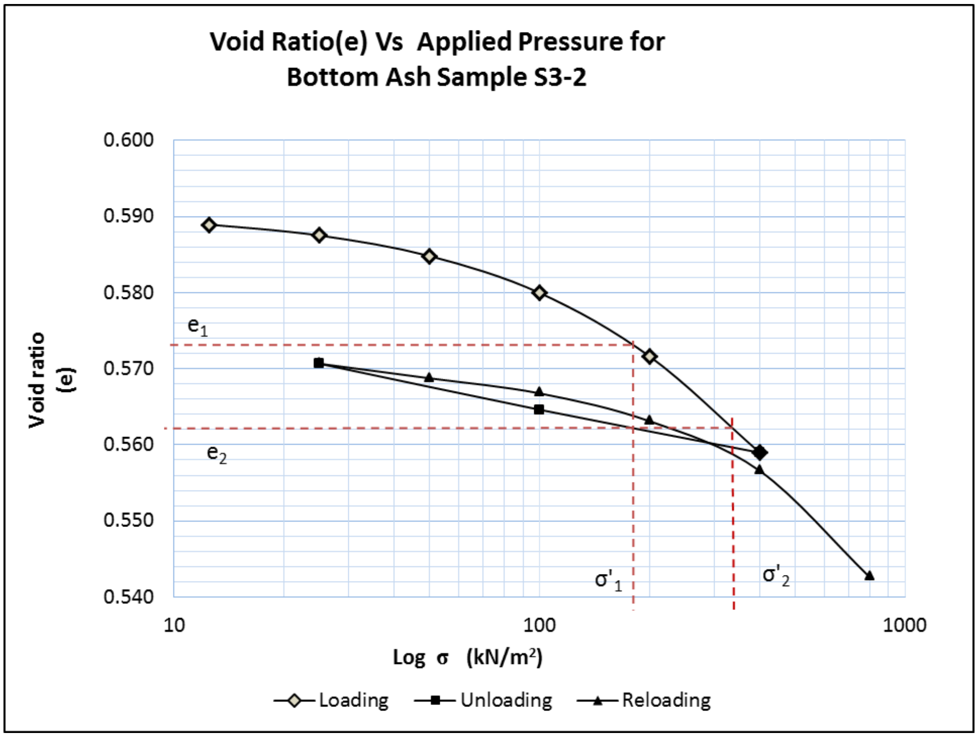


Figure 4.22: Void ratio with Applied pressure for Loading, Unloading and Reloading to the sample S3-2

C_c = 0.042 $C_c / (1+e_o)$ = 0.027

C_r = 0.005 $C_r / (1+e_o)$ = 0.003

4.5.3 Compressibility Characteristics of Sample S3-3

Sample S3-3 was conducted for the consolidation test for the bottom ash by considering loading, unloading and reloading increments.

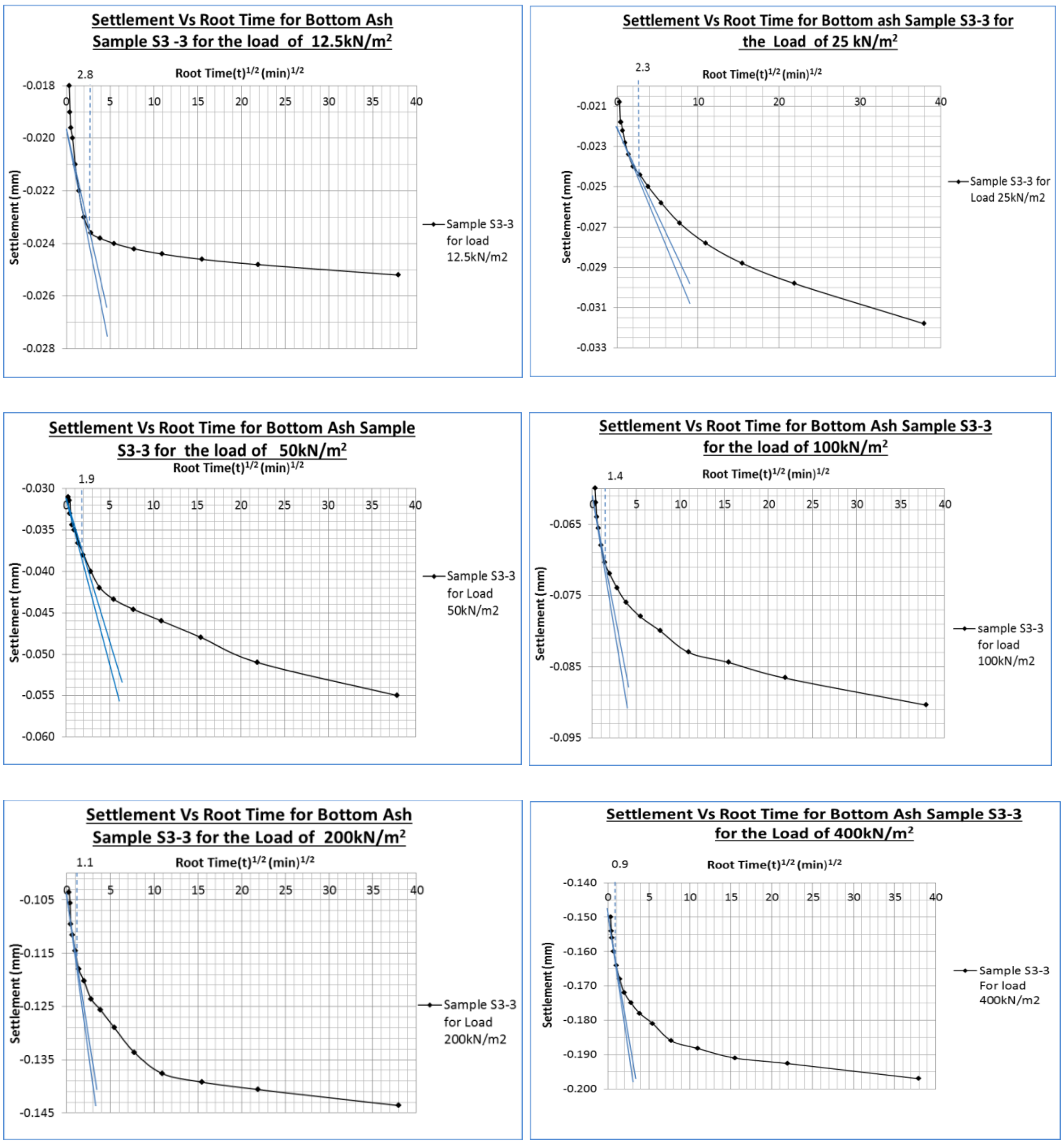


Figure 4.23 : Settlement with Root Time for sample S3-3 for load increment $12.5kN/m^2$, $25kN/m^2$, $50kN/m^2$, $100kN/m^2$,$200kN/m^2$,$400kN/m^2$

Table 4.6: Calculated value for coefficient of consolidation and volume compressibility for load case for sample S3-3

Current load increment	0kN/m^2 12.5kN/m^2	12.5kN/m^2 25kN/m^2	25kN/m^2 50kN/m^2	50kN/m^2 100kN/m^2	100kN/m^2 200kN/m^2	100kN/m^2 400kN/m^2
Coefficient of Volume Compressibility (m_v)($10^{-5}m^2/kN$)	10.0	6.4	5.5	4.5	3.6	2.5
Coefficient of Consolidation (C_v) ($m^2/year$)	5.7	8.4	12.3	22.5	36.1	53.1

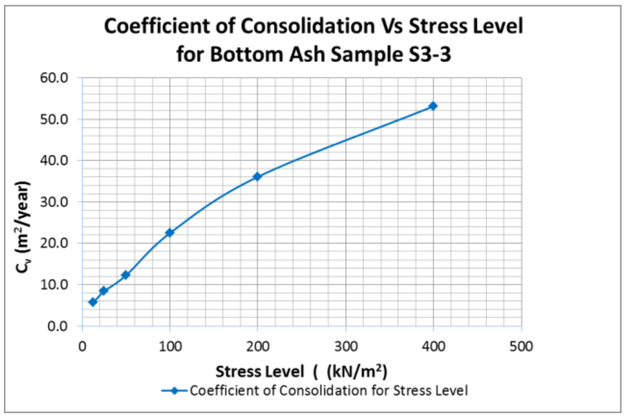


Figure 4.24 : C_v with Stress level for sample S3-3

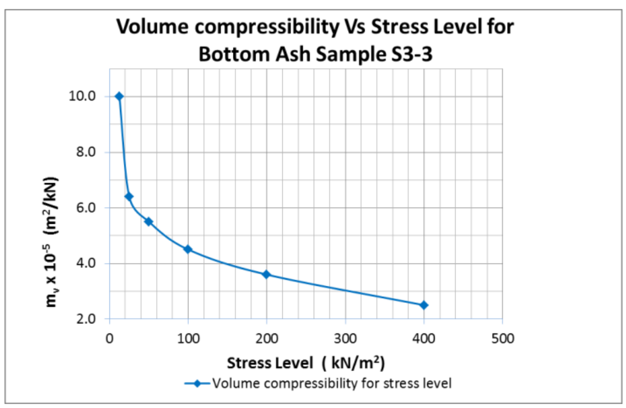


Figure 4.25: m_v with Stress level for sample S3-3

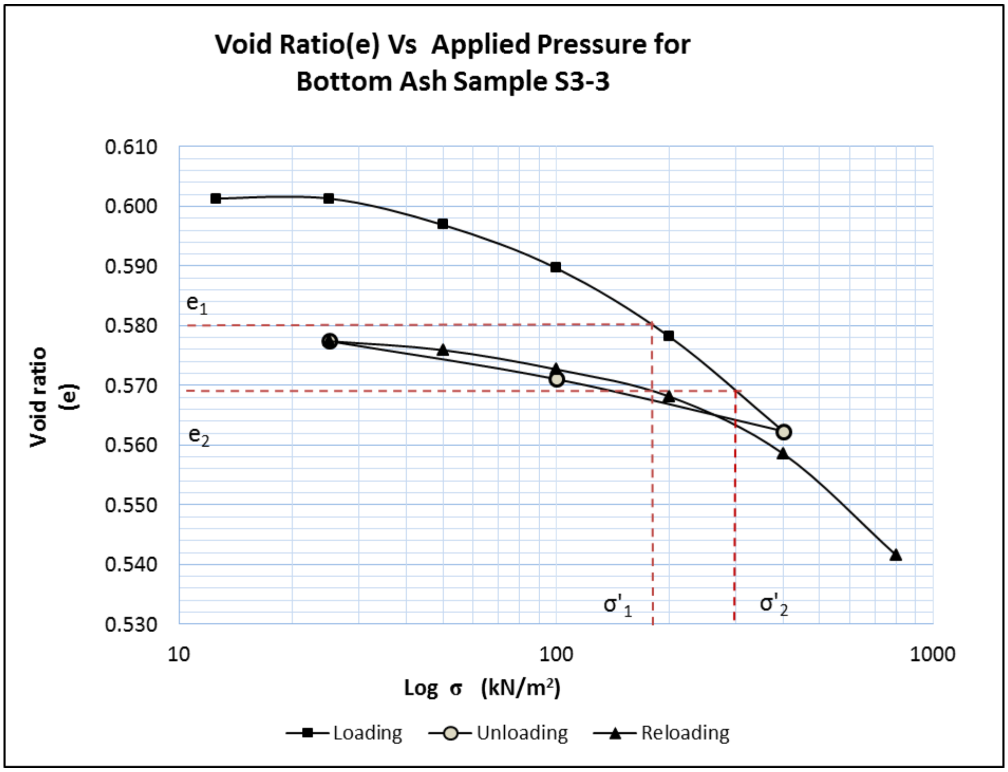


Figure 4.26: Void ratio with Applied pressure for Loading, Unloading and Reloading for sample S3-3

C_c	= 0.045	$C_c / (1+e_0)$	= 0.028
C_r	= 0.005	$C_r / (1+e_0)$	= 0.003

4.6 Concluding Comments

The variation of coefficient of volume compressibility with stress level is presented in Figure 4.27. The compressibility of samples S3-1, S3-2 and S3-3 are much lower than that of S1 and S2. For Sample S2, Consolidation test was done using higher stress levels up to 2000kN/m^2 to investigate whether the water absorbed into the pore structure would come out at these stress levels. The compressibility values at these stress levels are further lower confirming that water in the pores will not be expelled even at higher stress levels. Therefore subsequent tests of sample S3 were not conducted at such higher stress levels.

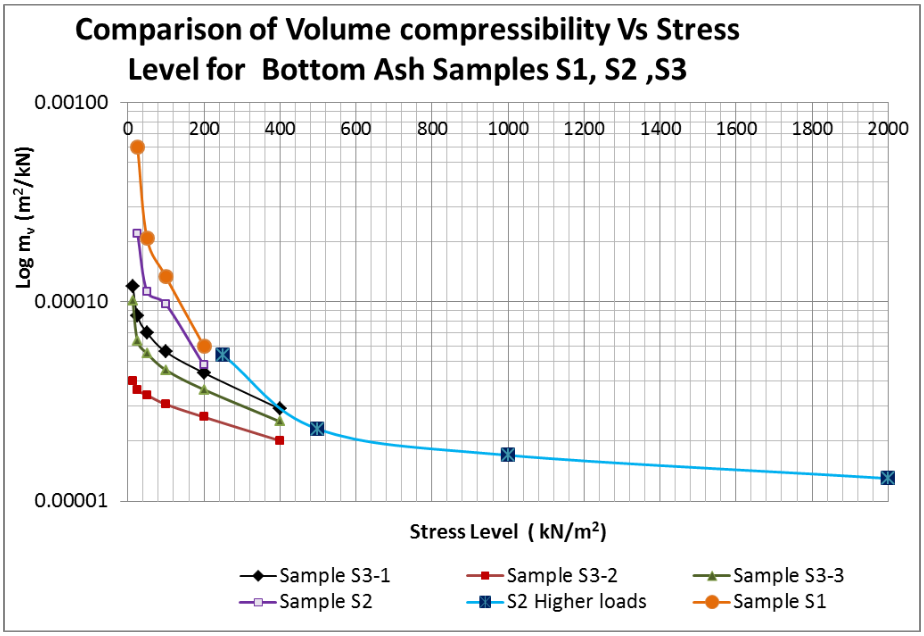


Figure 4.27: Summary of Comparisons of Volume compressibility with stress level of all type of bottom ash samples

The compression index C_c and the Compression ratio $C_c/(1+e_o)$ and Recompression index C_r and the Recompression ratio $C_r/(1+e_o)$ values for the different bottom ash samples are summarized in Table 4.7. These values are quite low corresponding to a soil of very low compressibility. Therefore, if bottom ash is used for the construction of an embankment by compacting in layers, further settlement due to application of pavement and traffic loads will be quite small. The e vs log σ plots show some pre consolidation effect introduced by the compaction process. Bottom ash followed the normal behaviors of a soil in loading, unloading and reloading cycles.

Table 4.7 Summary of C_c and C_r values for loading and reloading stages

Sample Name	C_c	C_c / (1+e_o)	C_r	C_r / (1+e_o)
S1	0.061	0.033	Not done	Not done
S2	0.052	0.031	Not done	Not done
S2 - Higher loads	0.108	0.064	0.044	0.026
S3-1	0.062	0.039	0.008	0.005
S3-2	0.042	0.027	0.005	0.003
S3-3	0.045	0.028	0.005	0.003

Coefficient of consolidation values are summarized in Figure 4.28. Higher coefficients of consolidation of bottom ash indicate that any settlements would dissipate rapidly.

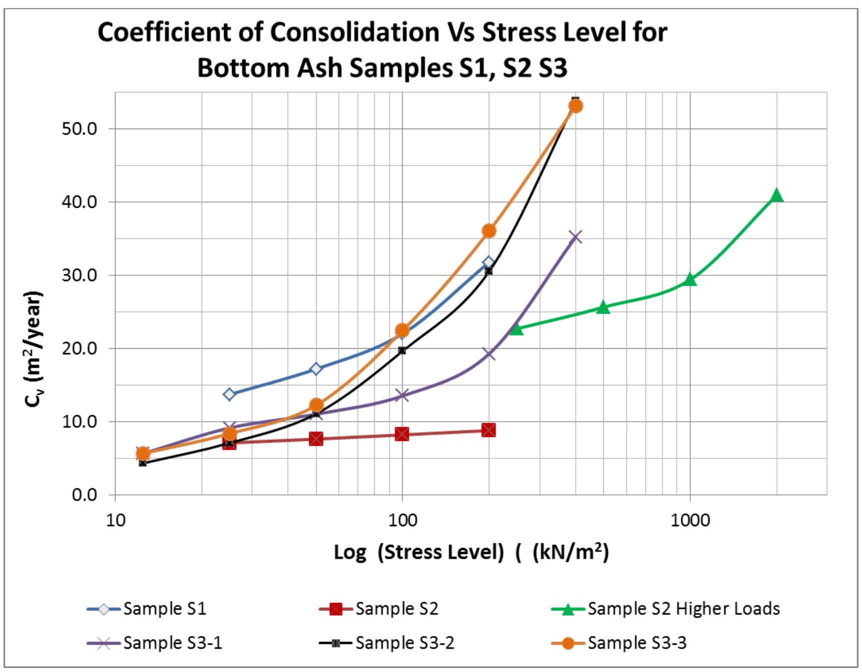


Figure 4.28: Summary of Comparisons of Coefficient of consolidation with stress level of all type of bottom ash samples

5.0 DETERMINATION OF SHEAR STRENGTH PARAMETERS OF THE BOTTOM ASH

Shear strength is one of the most important parameters for construction of embankments. If bottom ash to be used for the construction of embankments the compacted material should be of sufficient shear strength. This could be assessed by conducting direct shear test on samples of compacted bottom ash.

This was done by extruding specimen for direct shear test from the samples of bottom ash compacted in the proctor mould. The soil samples were saturated prior to the testing. The Direct shear tests were done under consolidated drained condition using a shear rate of 0.2 mm/minutes. The test setup is presented in Figure 5.1. The normal loads used are 50kN/m^2, 100kN/m^2, and 300kN/m^2 for the bottom ash sample S2 and 50kN/m^2, 100kN/m^2, 150kN/m^2, 200kN/m^2 and 300kN/m^2 for bottom ash sample S3. The test was performed on Sample S2 and the Sample S3 due to recently availability at coal power plant premises. The shear stress vs shear displacement and volume changes vs shear displacement graphs were plotted.

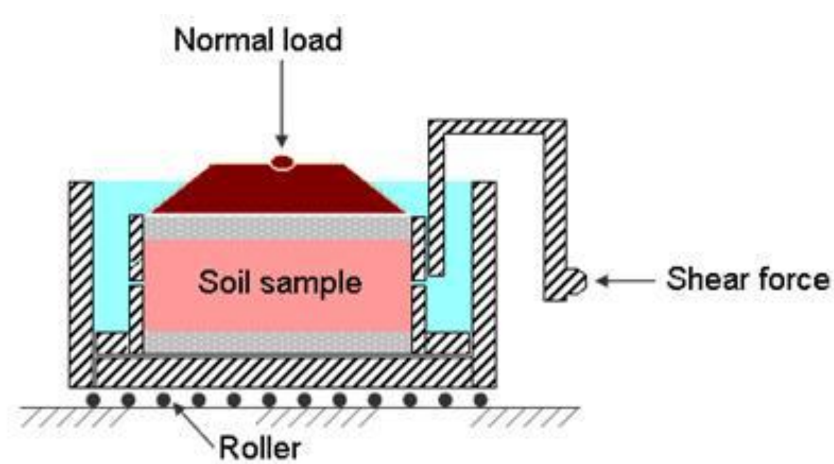


Figure 5.1 Soil sample and main loads at Direct shear test

5.1 Direct shear test conducted on bottom ash sample S2

The development of shear resistance with the shear displacement and change of volume (void ratio) with the shear displacement for the three normal load intensities are calculated and attached in Appendices. The results are graphically presented in Figure 5.2 to Figure 5.3.

The graph of shear resistance resembles that for loose sand or NC clay. There is no drop of shear resistance after reaching the peak value. The samples have experienced compression during shearing.

5.1.1 Shear parameters for Sample S2

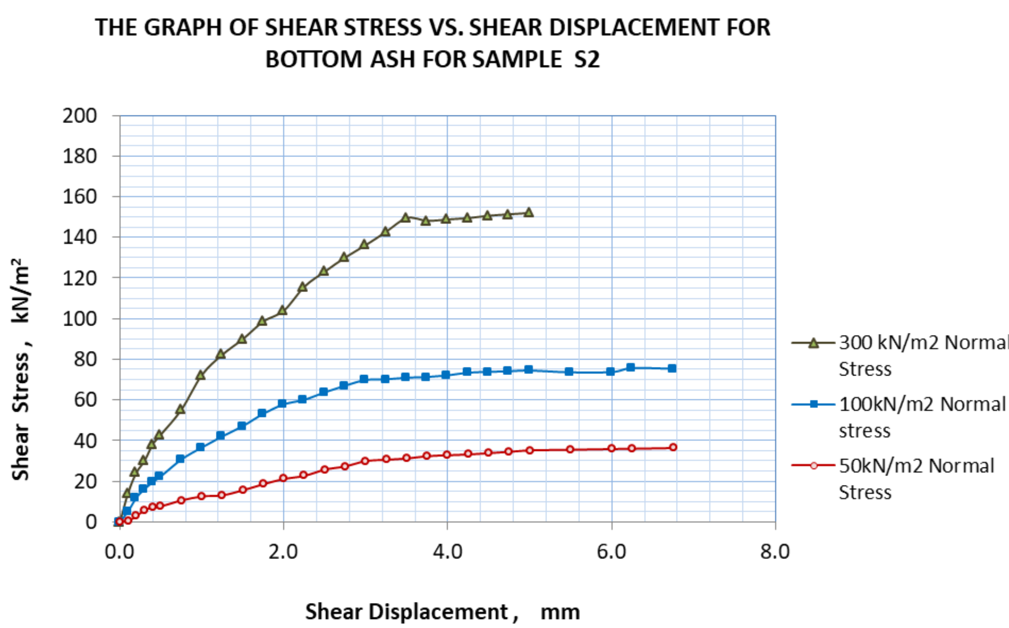


Figure 5.2 : Shear displacement vs Shear stress of Sample S2

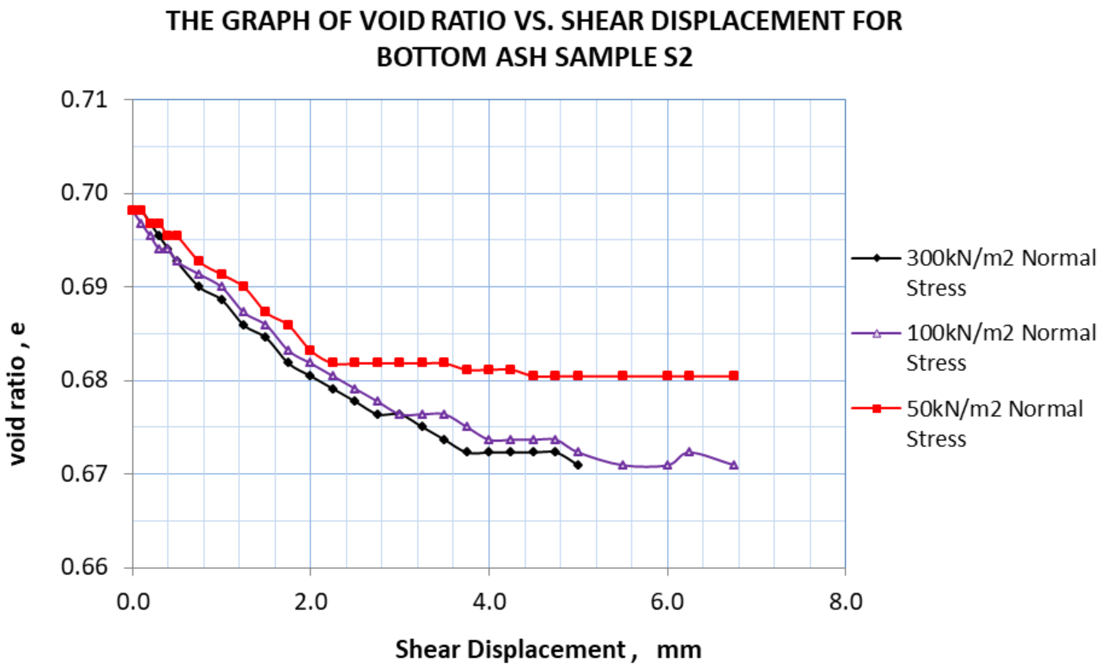


Figure 5.3 : Void ratio (e) vs Shear Displacement of Sample S2

The peak shear stress corresponding to different normal stresses are presented in Table 5.1. The data are graphically presented in Figure 5.4. The testing was conducted under considering drained conditions and hence drained parameters are obtained.

Table 5.1: Shear stress values for normal stresses for Sample S2

Normal Stress kN/m^2	Shear Stress, kN/m^2
50	36
100	76
300	150

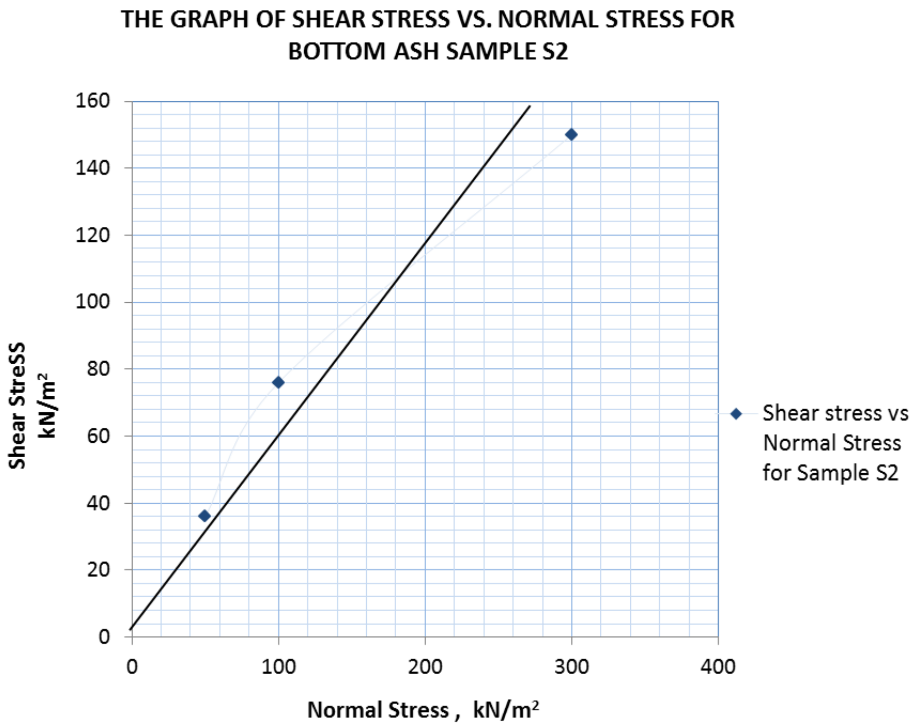


Figure 5.4 : Shear stress at failure vs normal stress for Sample S2

Friction angle, ϕ_d is found as 31^0 and the cohesion C_d , is found around zero. The values are showed good for construction of embankment with considerable drained parameters.

5.2 Direct shear test conducted on bottom ash sample S3

Sample S3 was subjected to the direct shear and the displacement for five normal load intensities are calculated and attached in Appendices. The results are graphically presented in Figure 5.5 to Figure 5.6.

Tests were conducted under the normal stresses of 50kN/m^2, 100kN/m^2, 150kN/m^2, 200kN/m^2 and 300kN/m$^{2.}$ Samples were underlying compression throughout shearing, and resembling the behavior of a loose sand. There was no reduction of shear strength after achieving the peak strength.

5.2.1 Shear parameters for sample S3

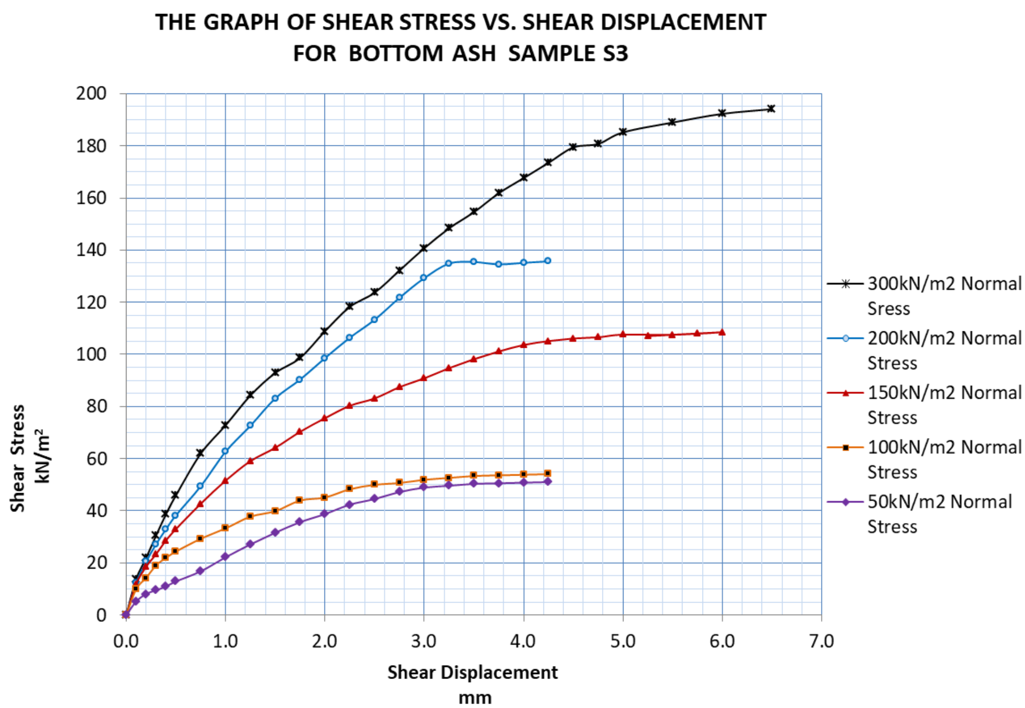


Fig. 5.5: Shear stress vs Shear displacement for sample S3

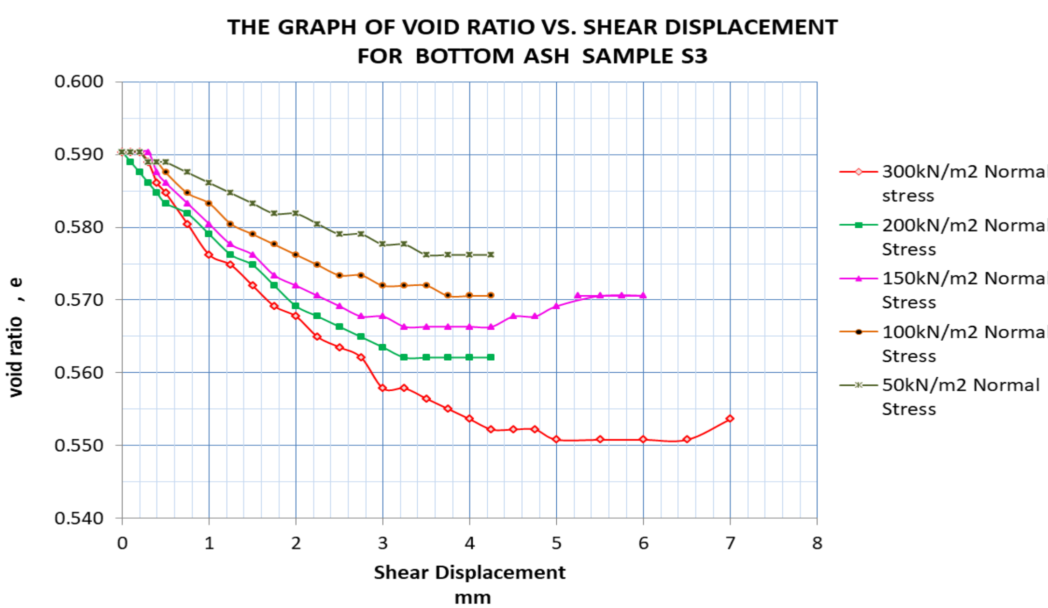


Fig. 5.6: Void ratio vs Shear displacement for bottom ash Sample S3

Shear stresses at failure stage for the corresponding normal load are summarized in Table 5.2 and corresponding shear stress vs Normal stress graph is presented in Figure 5.7. Testing was done under drained conditions and drained parameters are obtained.

Table 5.2: Shear stress values for normal stresses for Sample S3

Normal Stress kN/m2	Shear Stress, kN/m2
50	51
100	54
150	108
200	135.8
300	192.3

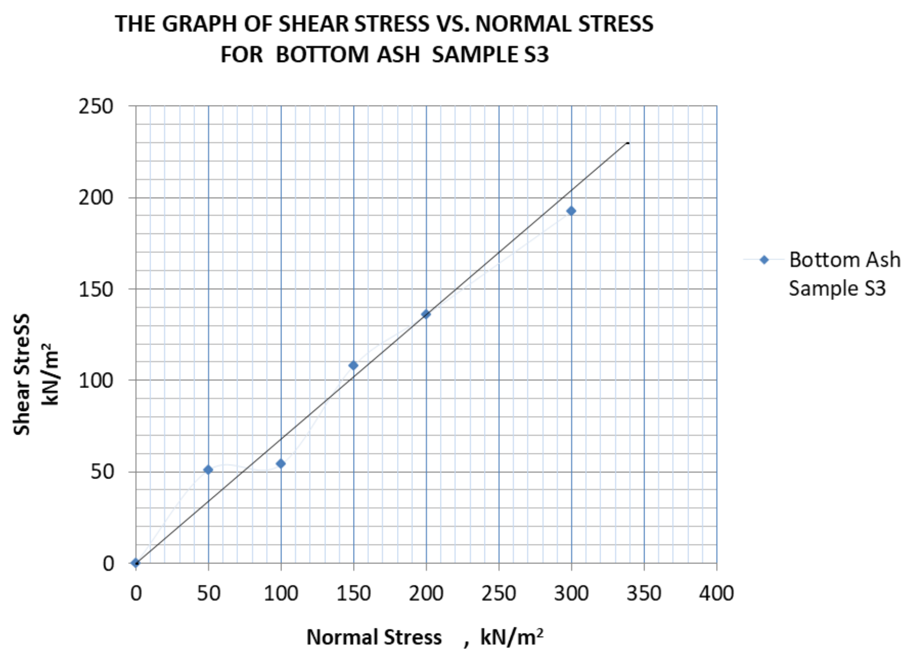


Fig. 5.7: Shear stress vs Normal stress for bottom ash Sample S3

5.3 Concluding comments

The results of the direct shear tests on compacted and saturated samples of bottom ash for sample S2 and S3 are showed in Table 5.3. The bottom ash has behaved as a normally consolidated soil around zero cohesion. The friction values are sufficiently high to enable construction of embankments.

Table 5.3 : Result values of friction angle and the cohesion

Sample	C_d/ kN/m^2	ϕ_d
S2	0	31^0
S3	0	34.3^0

6.0 CHEMICAL, MICROSTRUCTURAL AND RADIOACTIVITY PROPERTIES OF THE BOTTOM ASH

The series of tests on compressibility (using consolidation test) and shear strength (using direct shear test) clearly indicate that the compacted bottom ash possess suitable characteristics to be used as a fill material for the construction of embankments.

However, when such embankments are constructed, they interact with the natural environment. Bottom ash is a product of a burning process relatively unknown. Therefore, it is essential to conduct a chemical study to assess whether it contains any chemical that are harmful to the environment and all living beings.

In this chapter, the results of the tests conducted to determine basic chemical element compositions, Toxicity Characteristics, leaching elements, pH values of element, microstructural morphology and radioactivity of material are presented. Tests were done with sample S3 only.

6.1 Type of coal source

Research was basically conducted with the sample S3 which is the currently available coal burn byproduct at the power plant. This bituminous coal sample S3 was imported from South Africa. Sri Lanka coal power plant uses Bituminous coal as its main fuel. The fuel Gross Calorific Value is around 6300 kCal/kg.

6.2 Basic Chemical properties

Bottom ash was tested for chemical composition and heavy metal composition. Chemical properties were evaluated through tests conducted at Industrial technology institute (ITI). Basic chemical properties of bottom ash are tabulated on the Table 6.1.

The chemical composition of bottom ash particles is controlled by the source of the coal and not by the type of furnace (Benson and Bradshaw (2011)). Coal ash is composed primarily of silica (SiO_2), ferric oxide (Fe_2O_3), and alumina (Al_2O_3), with smaller quantities of calcium oxide (CaO), sodium oxide (Na_2O), and sulfur trioxide (SO_3). As per investigation it seems to be the silica content is higher in the bottom ash.

Table 6.1 Basic Chemical Properties of Bottom Ash

Test Unit	Results
Sulfuric Anhydride (SO_3) %	0.04
Chloride content (Cl`)%	0.097
Silica (SiO_2)%	35.79
Aluminum Oxide (Al_2O_3)%	17.94
Ferrous Oxide (Fe_2O_3)%	7.85
Calcium Oxide (CaO)%	1.85
Total Alkali Content (Na_2O)%	0.37
Lead (Pb) mg/kg	Not detected
Cadmium (Cd) mg/kg	Not detected
Chromium (Cr) mg/kg	0.9
Mercury (Hg) mg/kg	Not detected
Arsenic (As) mg/kg	0.5

6.3 Toxicity Characteristics leaching Procedure (TCLP) for Sample S3

The leaching concentrations of metals in Bottom Ash were determined and their toxicity was assessed using the Toxicity Characteristic Leaching Procedure (TCLP). The TCLP method is a currently recognized international method for evaluation of heavy metal pollution in soils. The U.S. Environmental Protection Agency (USEPA) has identified toxic chemicals that can cause harm when products containing them are disposed in landfills and the chemicals leach out. To determine the potential of specific wastes to leach dangerous concentrations of toxic chemicals into groundwater, the Environmental

Protection Agency (EPA) has developed a protocol known as the Toxicity Characteristic Leaching Procedure (TCLP). Heavy metals are of great concern at soil or materials add to the ground as soil, because they can threaten the health of human beings and animals through the food chain. The results of testing done to determine the toxicity characteristics in bottom ash are presented in Table 6.2.

Table 6.2 Toxicity Characteristics leaching limits of Bottom Ash

Parameters	Test Results	Regulatory Level (USEPA) (USEPA- U.S.Environmental Protection Agency)
Arsenic (As)	Not Detected	5 mg/L
Chromium (Cr)	0.08 mg/L	5 mg/L
Cadmium (Cd)	Not Detected	1 mg/L
Lead (Pb)	0.04 mg/L	5 mg/L
Selenium (Se)	Not Detected	1 mg/L
Mercury (Hg)	Not Detected	0.2 mg/L
Barium (Ba)	3.26 mg/L	100 mg/L
Iorn (Fe)	0.04 mg/L	Not Given
Silver (Ag)	Not Detected	5 mg/L
Sulphur	Not Detected	Not Given
Sulfite content ($SO^{2-}{}_{3}$)	Not Detected	Not Given
Sulfate content ($SO^{2-}{}_{4}$)	Not Detected	Not Given

The concentrations after leaching procedure, Chromium (Cr) , Lead (Pb), and Barium (Ba) are very small amount in Bottom ash and are well below in regulatory values with USEPA. Other metals like Arsenic (As), Cadmium (Cd), Selenium (Se), Mercury (Hg) and Silver (Ag) are not detected. Therefore, the Sample S3 is suitable for application as an embankment material considering non-leaching of toxic heavy metal to the ground.

6.4 pH Value of Bottom Ash

The pH value of bottom ash was found to be as 8.2 and slightly basic material. It is well within the required range for disposal. As such its presence is not harmful to the environment.

Table 6.3 pH value of Bottom Ash

Sample	Available pH	Standard pH Requirement for wastewater discharged on to land
Bottom Ash sample S3	8.2	5.5 - 9.0

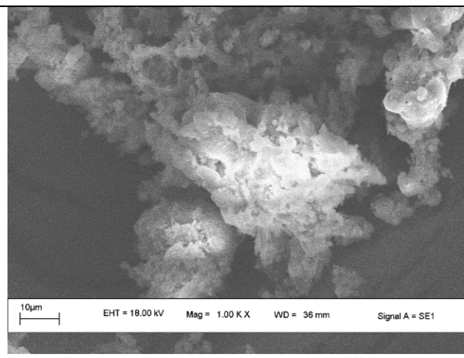
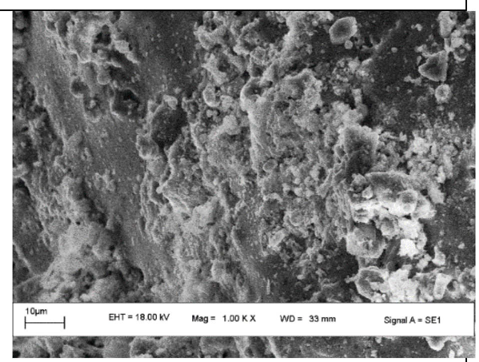
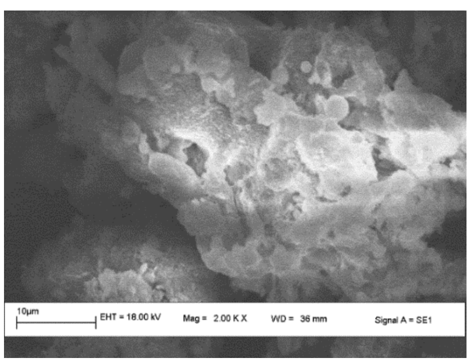
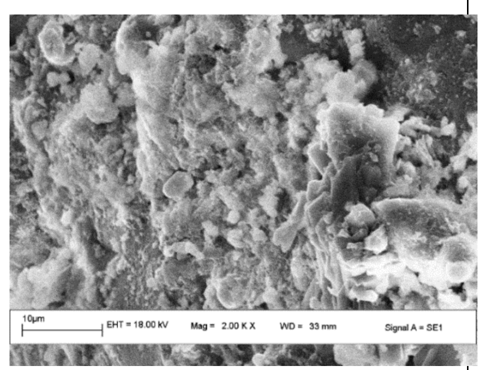
6.5 Microstructure of bottom ash

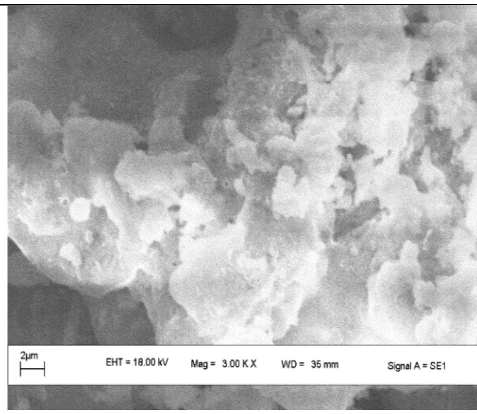
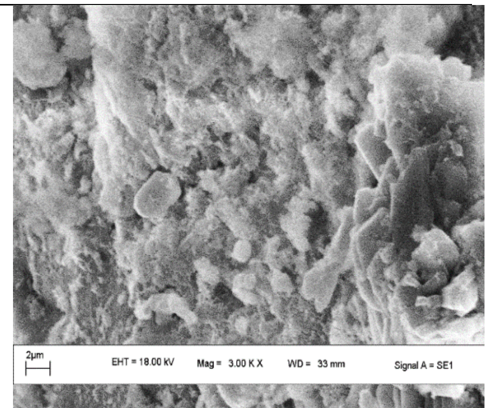
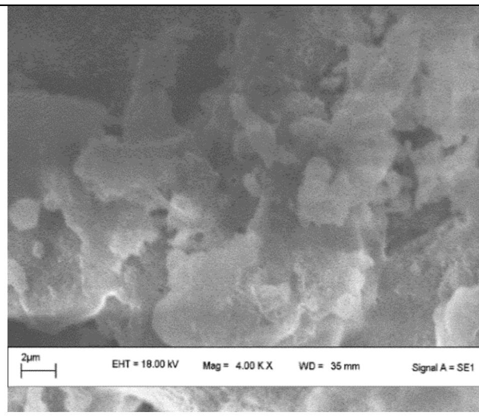
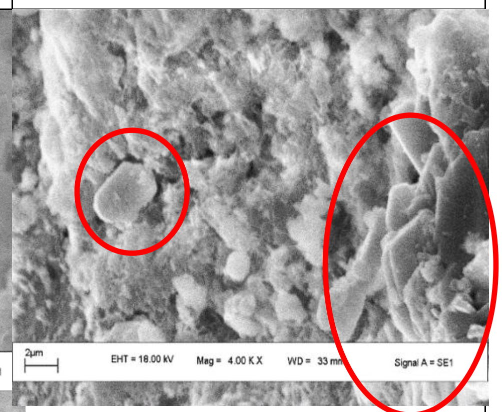
Microstructural morphology was determined by Scanning Electron Microscopy (SEM) in which the under different levels of magnifications. Sample (1k to 4k) was exposed to a sputter conducting of gold to ionize the sample. Then the sample is load into the SEM machine (model LEO1420V) holder that consisted of tungsten filament that can achieve maximum 20kV voltage.

The micrographs of different scales of magnification are present from Table 6.4. Tests were done on samples of Bottom Ash S2 and S3. Microstructure of the tested bottom ash samples shows freely available scattered popcorn like structure. Fiber elements have not been indicated in the images while some unburned carbon (or char) residues are present in S3 samples (refer to Table 6.4).

Bottom ash particles exhibit irregular and rough surface texture and internal porous structure is clearly evident.

Table 6.4 SEM images of Bottom ash with varied magnifications for Sample S2 & S3

	Sample S2	Sample S3
1k		
2k		

3k		
4k		
Average pore Size	1.05µm	0.92µm

Note : The circled areas show the unburned carbon (char).

Kim et al (2005) expressed that the bottom ash has a lower specific gravity than the fly ash due to the presence of highly porous popcorn-like micro-structure of the bottom ash compared to fly ash. Further, Jinwoo et al (2014) also proposed that the porosity of bottom ash is closely related to the Specific gravity and unit weight. This phenomenon is further confirmed during the current study as well. For example, the samples S2 illustrates an under developed pore structure with larger pores of an average pore size of [average pore size of S2] 1.05 µm (The working distance of S2 sample is 36 mm and that for S3 sample is 33 mm). Further, S3 samples display a well-developed pore structure with a comparatively lower average pore size of 0.92 µm compared to S2. In addition, the specific gravities of these bottom ash samples are 1.8 for S2 and 1.91 for S3. Hence, the specific gravity of the bottom ash specimens depends on the pore structure of them.

According to the results in Chapter 4 [Compressibility characteristics of the bottom ash], coefficients of volume compressibility values of S3 were slightly lower than that of S2. Interestingly, this observation can also be explained by the obtained pore structures for those samples. For instance, S2 has an under-developed pore structure which is lesser in matrix strength and leads for a slightly higher volume compressibility than the well-developed S3 pore structure. Further the higher shear strength parameters (Refer Table 5.3) of S3 confirm the well-developed strengthened pore structure than the comparatively weaker pore structure of S2.

6.6 Radioactivity Analysis of Bottom Ash

Coal is one of the main energy sources for electricity generation in the world. Coal Combustion process generates large amounts of fly and bottom ashes. Radiation risks due to natural radioactivity in samples of bottom ash collected from Lakvijaya thermal power plant was also assessed. Analysis was performed by Atomic Energy Board. Possible presence of potentially radioactive material Ra-226, Pb-210, Th-232, Cs-137, U-235 and K-40 were presented in Table 6.4.

The radio nuclide of Ra-226, Pb-210, Th-232, and K-40 were seen in bottom ash sample as radio activity. The Radioactivity of bottom ash is well below that detected in natural soil sample in some locations Sri Lanka as presented in Table 6.5 that was obtained from the tables was written by Seneviratne et al (2012) that was published Sri lanka Association for the Advancement of science (SLAAS).

Table 6.4 : Radioactivity analysis of bottom ash [Appendix D]

Radio Nuclide	RadioActivity (Bq/kg)
Cs-137	Not Detected
Pb-210	2.0 ± 0.3
Ra-226	4.6 ± 0.2
Th-232	5.3 ± 0.4
K-40	19.0 ± 1.0
U-235	Not Detected

Table 6.5 : Selective datas from the source in Radioactivity concentration of soil in Sri lanka

[Source of the data from study paper Seneviratne et al (2012)]

Place	Radio activity in Soil(Bq/kg)			
	K-40	Ra-226	Th-232	Cs-137
Kaduwela	448	32	61	4
Thissamaharama	600	19	45	1
Kahawatta	473	44	68	0.74
Piliyandala	27	29	134	2.3

Further, the International Atomic Energy Agency (IAEA) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) published safety standards for "Radiation Protection and Safety of Radiation Sources" as guidance for available radioactivity for protection people and the environment. When considering datas , it can be said that radioactivity consisted of bottom ash is very less than that are naturally available at the environment.

7.0 DISCUSSUION AND CONCLUSION

Possible use of Coal combustion bottom ash as an embankment fill material was studied in this Research. Significant quantities of coal bottom ash are produced in Sri Lanka every year. This is a waste material that needs to be disposed properly. On the other hand many infrastructure development projects in the country needs fill material in large quantities. With the constraints and restriction that are imposed on excavation and transport of soil, with the intention of preserving the environment, a scarcity of fill material has developed. Under this background it would be very beneficial to identify alternate fill material. The bottom ash being a waste product of coal power generation is available in large quantities. If that can be used as an alternate fill it will solve two burning issues.

In this content, initially the suitability of bottom ash as a fill material was assessed establishing the engineering characteristics. It is found to be a granular material of high permeability and hence free draining. The density of bottom ash is comparatively low. Density achieved by compaction is much lower than conventional fill material due to its pore structure. This pore structure was confirmed by the studies done with the SEM. A large quantity of water is absorbed into the pores' structure causing the optimum water content to be high. However, even at such water contents the material was very workable. It did not show any plasticity characteristics.

The high water content will cause the bulk density to increase, but the values are lower than that of conventional fill material. Hence it will have additional benefits when being used for construction on soft ground. The compacted bottom ash had quite low compressibility as indicated by values of C_c and m_v. Hence the further compaction of the embankment under the loads of road pavement and traffic will be very small.

It has a high coefficient of consolidation indicating that any settlements within it will dissipate rapidly. The high CBR value of bottom ash indicates that it will satisfy all the requirements of highway designs. The compacted bottom ash had significantly high angle of internal friction so that the shear failure through the embankment can be prevented. Since it has no cohesion, the embankment will have to be done at a slope of 1: 2 or lower.

In addition to the strength & compressibility, the toxicity characteristics have also been tested. The content of the leached out toxic materials such as Arsenic, Chromium, Cadmium, Lead, and Mercury are not detected or well below the acceptable limit. Radioactivity of the bottom ash sample is also below the desirable level. Even normal soils from some regions of Sri Lanka have shown higher radioactivity than bottom ash. The pH value of the bottom ash is within the acceptable limits and satisfies the environmental requirement. Tested data of the samples show that there are no harmful chemicals in bottom ash.

Sri Lanka coal power plant uses bituminous type coal material. Though the Physical and mechanical properties tested has not been governed by the coal sources, chemical properties are related with the coal source and the power generation method. As such, bituminous type coal by product bottom ash, can be recommended to be used as a potential fill material.

In conclusion, to assess whether bottom ash derived from the process of burning at a coal power plant is suitable as a construction material, it is necessary to conduct a test of basic properties, compressibility and strength. This must be followed with a study of chemical composition, identifying possibilities of presence of harmful chemicals such as heavy metals. Radioactivity and the pH should also be studied. This chemical study is essential in addition to the study of mechanical characteristics. A check list of tests that should be conducted before the approval of the use of bottom ash for construction is presented in table 7.1.

Table 7.1 Check list of types of tests of bottom ash prior to construction of Embankment

No	Main Property	Properties have to check
01	Basic Properties	Partical size distribution
		Liquid limit Characteristics
		Specific Gravity
		Compaction Characteristics
		Coefficient of permeability
		CBR Value
02	Compressibility Characteristics	Coefficient of Volume compressibility (m_v)
		Coefficient of consolidation (c_v)
		Compression index (Cc)
		Compression ratio
		Recompression index (Cr)
		Recompression ratio
03	Shear strength parameters	Cohesion (C_d)
		Friction angle (ϕ_d)
04	Chemical, microstructural and Radioactivity Properties	Type of Coal Source
		Basic Chemical properties of Bottom ash
		Toxicity Characteristics leaching procedure (TCLP) for bottom ash
		pH Value
		Microstructure analysis
		Radioactivity analysis

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APPENDICES

Appendix A – Basic Characteristics data

Particle size distribution for Bottom Ash sample S1

Sieve Size (mm)	Mass of Bottom ash (g)	Cumulative mass (g)	Percent Retained (%)	Percent Passing (%)
10	91.0	91.0	8.99	91.01
5	84.5	175.5	8.35	82.66
2.36	237.7	413.2	23.49	59.17
1.18	257.5	670.7	25.44	33.73
0.6	159.3	830.0	15.74	17.98
0.425	86.0	916.0	8.50	9.49
0.3	47.7	963.7	4.71	4.77
0.15	34.4	998.1	3.40	1.37
0.075	9.1	1007.2	0.91	0.47

Particle size distribution of sample S2

Sieve Size (mm)	Mass of Bottom ash (g)	Cumulative mass (g)	Percent Retained(%)	Percent Passing (%)
10	14.3	14.3	1.43	98.57
5	55.1	69.4	5.51	93.06
2.36	656.5	725.9	65.69	27.37
1.18	161.6	887.5	16.17	11.20
0.6	60.6	948.1	6.06	5.13
0.425	25.8	973.9	2.58	2.55
0.3	15.6	989.5	1.56	0.99
0.15	6.8	996.3	0.68	0.31
0.075	2.4	998.7	0.24	0.07

Particle size distribution of S3

Sieve Size (mm)	Mass of Bottom ash (g)	Cumulative mass (g)	Percent Retained (%)	Percent Passing (%)
10	21.7	21.7	2.17	97.83
5	87.7	109.4	8.77	89.06
2.36	584.0	693.4	58.41	30.65
1.18	63.9	757.3	6.39	24.26
0.6	102.4	859.7	10.24	14.02
0.425	71.5	931.2	7.15	6.87
0.3	43.8	975.0	4.38	2.49
0.15	16.9	991.9	1.69	0.80
0.075	6.2	998.1	0.62	0.18

Liquid Limit by cone Penetration method for sample S3

Sample No	Can No	Mass of Can	Mass of Wet soil+ Can	Mass of Dry soil+ Can	mc %	Penetration mm
1	5A	16.82	39.62	32.23	47.96	25
2	GPI	19.27	40.95	33.87	48.49	32.5
3	500	19.46	44.66	36.24	50.18	36.5
4	B6	16.88	37.69	30.52	52.57	42

Table for Specific Gravity of types of bottom ash

Sample Name	Specific Gravity
Bottom Ash Sample S1	2.19
Bottom Ash Sample S2	1.8
Bottom Ash Sample S3	1.91
Fly Ash Sample (FA)	2.18
75% FA+25% BA	2.0

Tables of Dry Density and Moisture content relations

Bottom Ash Sample S1 (Gs = 2.19)

Procedure	4.5 kg Hand Rammer, 5 Layers, 27Blows per Layer, 1L Mould,	Mould Diameter (cm)				10.150				
		Mould Height (cm)				11.510				
		Mould Volume (cm^3)				997				
Test Number		***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***
Volume of adding water	ml	50	250	450	650	850	1050	1250	1450	1650
Mass of Mould + Base + Com. Specimen(m_2)	g	4398.3	4450.3	4508.4	4616.6	4728.4	4777.7	4804.6	4793.7	4819.7
Mass of Mould + Base(m_1)	g	3217.0	3217.0	3217.0	3217.0	3217.0	3217.0	3217.0	3217.0	3217.0
Mass of the Com. Specimen (m_2-m_1)	g	1181.3	1233.3	1291.4	1399.6	1511.4	1560.7	1587.6	1576.7	1602.7
Bulk Density p = (m_2-m_1)/V	g/cm^3	1.185	1.24	1.30	1.40	1.52	1.57	1.59	1.58	1.61
Moisture Content Container No:		***3***	***4***	***5***	***6***	***7***	***4***	***5***	***6***	
Mass of Container	g	42.5	41.0	42.3	37.8	45.8	38.9	38.3	40.4	39.6
Mass of Container + Wet Soil	g	157.0	144.3	158.6	163.5	136.6	142.3	163.4	190.4	213.9
Mass of Container + Dry Soil	g	155.0	136.0	143.4	140.7	115.9	116.6	127.5	141.6	155.1
Moisture Content (w)	%	1.78	8.74	15.03	22.16	29.53	33.08	40.25	48.22	50.91
Dry Density P_d = 100p/(100+w)	g/cm^3	1.164	1.138	1.126	1.149	1.170	1.176	1.135	1.067	1.065
	kg/m3	1164.16	1137.62	1126.00	1149.18	1170.35	1176.32	1135.41	1066.95	1065.23

Bulk Density (kg/m3) p = (m2-m1)/V	m/c %	Dry Density (kg/m3) Pd = 100p/(100+w)	Zero air Void A=0 Pd = GsYw[1-A] / 1+wGs	5% air Void A=0.05 Pd = GsYw[1-A] / 1+wGs	10% air Void A=0.1 Pd = GsYw[1-A] / 1+wGs
1184.85	1.78	1164.16	2107.93	2002.53	1897.14
1237.01	8.74	1137.62	1838.27	1746.36	1654.44
1295.29	15.03	1126.00	1647.54	1565.16	1482.78
1403.81	22.16	1149.18	1474.50	1400.78	1327.05
1515.95	29.53	1170.35	1329.94	1263.44	1196.95
1565.40	33.08	1176.32	1270.03	1206.53	1143.03
1592.38	40.25	1135.41	1164.03	1105.82	1047.62
1581.44	48.22	1066.95	1065.15	1011.89	958.64
1607.52	50.91	1065.23	1035.51	983.73	931.95

Dry Density and Moisture content relations BA Sample S2 (Gs = 1.8)

Procedure	4.5 kg Hand Rammer, 5 Layers, 27Blows per Layer, 1L Mould,	Mould Diameter (cm)				10.300								
		Mould Height (cm)				11.400								
		Mould Volume (cm^3)				997								
Test Number		***B7***	***B6***	***B5***	***B8***	***B1***	***B2***	***B3***	***1***	***2***	***4***	***5***	***6***	***7***
Mass of Mould + Base + Com. Specimen(m_2)	g	4945.0	4953.0	4978.0	5006.0	5015.0	5031.0	5069.0	4424.0	4498.8	4700.0	4703.2	4720.0	4704.8
Mass of Mould + Base(m_1)	g	4013.0	4013.0	4013.0	4013.0	4013.0	4013.0	4013.0	3224.8	3224.8	3224.8	3224.8	3224.8	3224.8
Mass of the Com. Specimen (m_2-m_1)	g	932.0	940	965	993	1002	1018	1056.0	1199.2	1274	1475.2	1478.4	1495.2	1480
Bulk Density p = (m_2-m_1)/V	g/cm^3	0.935	0.94	0.97	1.00	1.01	1.02	1.06	1.203	1.28	1.48	1.48	1.50	1.48
Moisture Content Container No:		*3*	*4*	*5*	*6*	*7*	*6*	*7*	*3*	*4*	*6*	*7*	*6*	*7*
Mass of Container	g	14.99	16.94	17.51	14.21	14.02	15.22	29.00	37.9	38.4	44.4	37.1	26.0	45.9
Mass of Container + Wet Soil	g	46.16	40.42	69.45	44.69	40.38	44.68	58.31	175.7	233.3	157.5	146.3	89.1	246.3
Mass of Container + Dry Soil	g	45.26	39.46	66.56	42.57	38.14	41.87	55.13	151.7	192.4	125.5	111.4	67.6	165.6
Moisture Content (w)	%	2.97	4.26	5.89	7.48	9.29	10.54	12.17	21.09	26.56	39.46	46.97	51.68	67.42
Dry Density P_d = 100p/(100+w)	g/cm^3	0.908	0.904	0.914	0.927	0.920	0.924	0.944	0.993	1.010	1.061	1.009	0.989	0.887

Bulk Density (kg/m3) p = (m2-m1)/V	m/c %	Dry Density Pd = p/(1+w/100)	Zero air Void A=0 Pd = GsYw[1-A] / 1+wGs	5% air Void A=0.05 Pd = GsYw[1-A] / 1+wGs	10% air Void A=0.1 Pd = GsYw[1-A] / 1+wGs
934.80	2.97	907.81	1708.56	1623.13	1537.70
942.83	4.26	904.28	1671.73	1588.14	1504.55
967.90	5.89	914.05	1627.41	1546.04	1464.66
995.99	7.48	926.71	1586.52	1507.20	1427.87
1005.02	9.29	919.61	1542.20	1465.09	1387.98
1021.06	10.54	923.67	1512.87	1437.22	1361.58
1059.18	12.17	944.26	1476.55	1402.72	1328.89
1202.81	21.09	993.32	1304.71	1239.48	1174.24
1277.83	26.56	1009.68	1217.82	1156.93	1096.04
1479.64	39.46	1061.00	1052.49	999.86	947.24
1482.85	46.97	1008.93	975.35	926.58	877.82
1499.70	51.68	988.71	932.50	885.88	839.25
1484.45	67.42	886.67	813.18	772.52	731.86

Dry Density and Moisture content relations BA Sample S3 (Gs = 1.91)

Procedure	4.5 kg Hand Rammer, 5 Layers, 27Blows per Layer, 1L Mould,	Mould Diameter (cm)				10.150			
		Mould Height (cm)				11.510			
		Mould Volume (cm^3)				997			
Test Number		***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
Volume of adding water	ml	50	250	450	650	850	1050	1250	1450
Mass of Mould + Base + Com. Specimen(m_2)	g	4377.9	4454.7	4524.0	4648.6	4754.9	4782.9	4801.5	4805.3
Mass of Mould + Base(m_1)	g	3222.8	3222.8	3222.8	3222.8	3222.8	3222.7	3222.7	3222.8
Mass of the Com. Specimen (m_2-m_1)	g	1155.1	1231.9	1301.2	1425.8	1532.1	1560.2	1578.8	1582.5
Bulk Density p = (m_2-m_1)/V	g/cm^3	1.159	1.24	1.31	1.43	1.54	1.56	1.58	1.59
Moisture Content Container No:		***3***	***4***	***5***	***6***	***7***	***4***	***5***	***6***
Mass of Container	g	33.7	30.0	41.0	42.3	39.3	41.3	40.0	38.4
Mass of Container + Wet Soil	g	80.0	88.5	108.4	133.1	130.8	115.8	108.1	131.8
Mass of Container + Dry Soil	g	79.2	83.8	99.9	117.2	110.8	96.7	88.8	101.7
Moisture Content (w)	%	1.76	8.74	14.43	21.23	27.97	34.48	39.55	47.55
Dry Density P_d = 100p/(100+w)	g/cm^3	1.139	1.136	1.141	1.180	1.201	1.164	1.135	1.076
	kg/m3	1138.56	1136.34	1140.52	1179.67	1200.82	1163.69	1134.76	1075.74

Bulk Density (kg/m3) p = (m2-m1)/V	m/c %	Dry Density Pd = p/(1+w/100)	Zero air Void	5% air Void	10% air Void
			A=0	A=0.05	A=0.1
			Pd = GsYw[1-A] / 1+wGs	Pd = GsYw[1-A] / 1+wGs	Pd = GsYw[1-A] / 1+wGs
1158.58	1.76	1138.56	1847.94	1755.54	1663.15
1235.61	8.74	1136.34	1636.87	1555.03	1473.19
1305.12	14.43	1140.52	1497.29	1422.43	1347.56
1430.09	21.23	1179.67	1358.99	1291.04	1223.09
1536.71	27.97	1200.82	1244.90	1182.65	1120.41
1564.89	34.48	1163.69	1151.64	1094.06	1036.48
1583.55	39.55	1134.76	1088.08	1033.67	979.27
1587.26	47.55	1075.74	1000.93	950.88	900.83

Comparison of Dry Density and optimum Moisture content Bottom Ash sample S1, sample S2, sample S3

Sample S1 - 100% BA		
Maximum Dry Density	1177	kg/m3
Optimum Moisture content	32	%
Yw	1000	
Gs	2.19	
m/c %	Dry Density (kg/m3) Pd = 100p/(100+w)	
1.78	1164.16	
8.74	1137.62	
15.03	1126.00	
22.16	1149.18	
29.53	1170.35	
33.08	1176.32	
40.25	1135.41	
48.22	1066.95	
50.91	1065.23	

Sample S2 - 100% BA		
Maximum Dry Density	1060	kg/m3
Optimum Moisture content	39.5	%
Yw	1000	
Gs	1.8	
m/c %	Dry Density (kg/m3) Pd = 100p/(100+w)	
3.0	907.8	
4.3	904.3	
5.9	914.0	
7.5	926.7	
9.3	919.6	
10.5	923.7	
12.2	944.3	
21.1	993.3	
26.6	1009.7	
39.5	1061.0	
47.0	1008.9	
51.7	988.7	
67.4	886.7	

Sample S3 - 100% BA		
Maximum Dry Density	1177	kg/m3
Optimum Moisture content	32	%
Yw	1000	
Gs	2.19	
m/c %	Dry Density (kg/m3) Pd = 100p/(100+w)	
1.8	1138.6	
8.7	1136.3	
14.4	1140.5	
21.2	1179.7	
28.0	1200.8	
34.5	1163.7	
39.5	1134.8	
47.6	1075.7	

Permeability Test

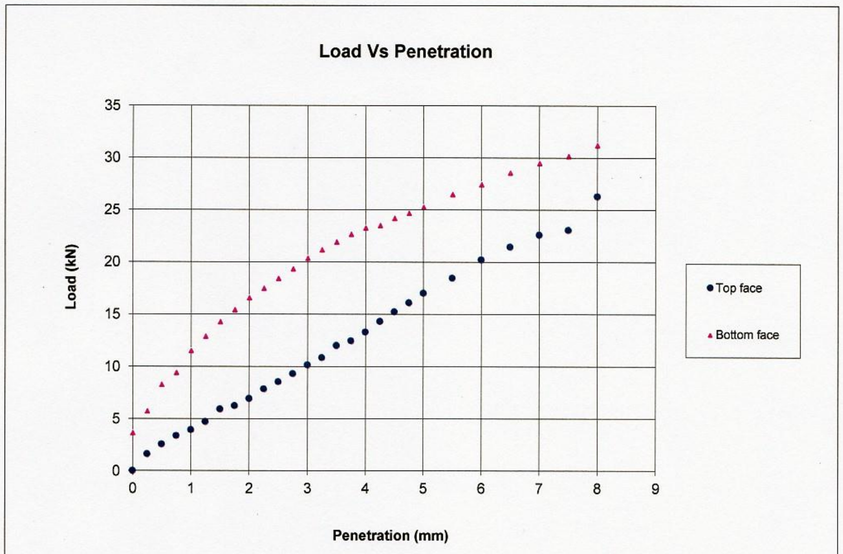
Rate of flow from 8 number of trial sets of constant head perimeter for Sample S3

Set No	Time to collect 1000 ml water (Sec)	h_1 (cm)	h_2 (cm)	h_3(cm)	h_1-h_2 (cm)	h_1-h_3 (cm)	h_2-h_3 (cm)	Rate of Flow (m^3/s)
1	218.0	97.8	82.3	62.5	15.5	35.3	19.8	4.5872E-06
2	235.0	96.1	81.6	62.8	14.5	33.3	18.8	4.2553E-06
3	243.0	91.5	77.5	59.0	14.0	32.5	18.5	4.1152E-06
4	245.0	88.6	74.7	56.3	13.9	32.3	18.4	4.0816E-06
5	250.5	86.8	73.2	55.1	13.6	31.7	18.1	3.9920E-06
6	253.0	84.8	71.3	53.4	13.5	31.4	17.9	3.9526E-06
7	261.0	82.3	69.2	51.7	13.1	30.6	17.5	3.8314E-06
8	269.0	79.9	67.2	50	12.7	29.9	17.2	3.7175E-06

Unsoaked CBR Value for the bottom ash Sample S3

California Bearing Ratio Test	National Building Research Organisation Geotechnical Engineering Division

Project:	Testing of Bottom Ash for Research at University of moratuwa		
Client:	National Engineering Research and Development Centre of Sri Lanka (NERD)		
Project No:	30-25662	Location	-
Test Method : BS 1377 : 1990 (Part 4)			
Sample No.	00165	Specimen No.	-
Test on top face	Unsoaked	Test Condition	
Test on bottom face	Unsoaked	Sample Type	Bottam Ash



		Top face	Bottom face	Accepted CBR %
CBR % at penetraion of	2.5mm	64.39	128.79	129
	5.0mm	92.50	126.50	

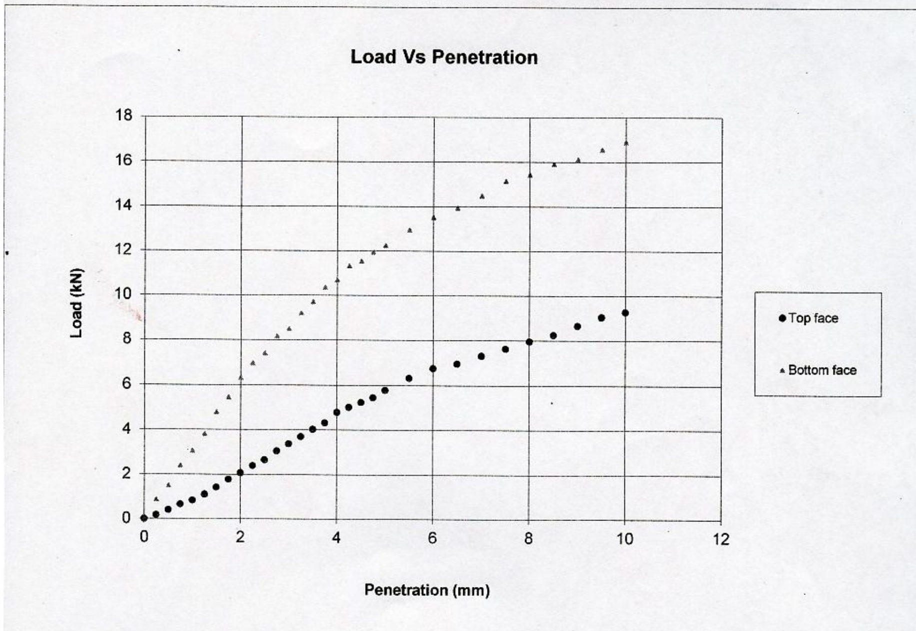
DATE	TESTED BY	CHECKED BY	CERTIFIED	REMARKS
23/05/2015	TAC	PA	CB	

C:\Users\user\Desktop\25662_NERD Centre\[CBR_.xls]Load Vs Penetration

Soaked CBR Value for the bottom ash Sample S3

Annexure I

California Bearing Ratio Test		National Building Research Organisation Geotechnical Engineering Division	
Project:	TESTING OF BOTTOM ASH SAMPLE		
Client:	NERD Center		
Project No:	30-25874	Laboratory Sample No	GEL/2017/00785
Test Method : BS 1377			
Sample No.	Sample 01	Specimen No.	GEL/2017/00785
Test on top face	Soaked	Test Condition	Soaked
Test on bottom face	Soaked	Sample Type	Bottom Ash Bulk Sample



		Top face	Bottom face	Accepted CBR %
CBR % at penetration of	2.5mm	25.57	58.71	74
	5.0mm	33.75	73.75	

Appendix B – Compressibility characteristics data of bottom ash

Consolidation settlement for Bottom Ash sample S1

for loading 25kN/m^2, 50kN/m^2, 100kN/m^2 and 200kN/m^2

Time Elapsed (min)	Root time min$^{1/2}$	25kN/m2		50kN/m2		100kN/m2		200kN/m2	
		Dial Reading	Settlement (mm)	Dial Reading	Settlement (mm)	Dial Reading	Settlement (mm)	Dial Reading	Settlement (mm)
0	0.00	12.000	0.000	11.900	0.000	11.693	0.000	11.430	0.000
0.1	0.32	11.824	-0.176	11.697	-0.204	11.542	-0.151	11.418	-0.012
0.17	0.41	11.804	-0.196	11.696	-0.204	11.534	-0.159	11.412	-0.018
0.25	0.50	11.790	-0.210	11.696	-0.204	11.530	-0.163	11.406	-0.024
0.5	0.71	11.778	-0.222	11.696	-0.204	11.522	-0.171	11.398	-0.032
1	1.00	11.770	-0.230	11.695	-0.205	11.514	-0.179	11.390	-0.040
2	1.41	11.762	-0.238	11.694	-0.206	11.504	-0.189	11.382	-0.048
4	2.00	11.756	-0.244	11.694	-0.206	11.494	-0.199	11.374	-0.056
8	2.83	11.746	-0.254	11.694	-0.206	11.486	-0.207	11.368	-0.062
15	3.87	11.740	-0.260	11.694	-0.207	11.478	-0.215	11.360	-0.070
30	5.48	11.734	-0.266	11.693	-0.207	11.470	-0.223	11.352	-0.078
60	7.75	11.726	-0.274	11.693	-0.207	11.462	-0.231	11.348	-0.082
120	10.95	11.720	-0.280	11.693	-0.207	11.454	-0.239	11.340	-0.090
240	15.49	11.712	-0.288	11.693	-0.207	11.445	-0.248	11.334	-0.096
480	21.91	11.700	-0.300	11.693	-0.207	11.435	-0.258	11.328	-0.102
1440	37.95	11.900	-0.100	11.693	-0.208	11.430	-0.263	11.314	-0.116

Calculated value for coefficient of consolidation and volume compressibility

for sample S1

Current load incriment	0 kN/m^2 25kN/m^2	25kN/m^2 50kN/m^2	50kN/m^2 100kN/m^2	100kN/m^2 200kN/m^2
At the Beginning Sample Thickness (H) mm	20.000	19.900	19.693	19.430
Sample settlement from each load (Δh) mm	0.300	0.208	0.263	0.116
Coefficient of Volume Compressibility (m_v) (10^{-4} m^2/kN)	6.00	2.09	1.30	0.30
$\sqrt{t_{90}}$ (min$^{1/2}$)	1.80	1.60	1.40	1.15
t_{90} (min)	3.24	2.56	1.96	1.32
d = H/2 (mm)	10.00	9.95	9.85	9.72
T_{90}	0.848	0.848	0.848	0.848
Coefficient of Consolidation (C_v) (mm^2/min)	26.17	32.79	41.95	60.52
Coefficient of Consolidation (C_v) (m^2/year)	13.8	17.2	22.0	31.8

Void ratios with relevant applied pressure for sample S1

Applied Pressure (σ) kN/m2	Void Ratio e
	0.86
25	0.85
50	0.83
100	0.81
200	0.79

Consolidation settlement for Bottom Ash sample S2

for time elapsed data for loading 25kN/m^2, 50kN/m^2, 100kN/m^2 and 200kN/m^2.

Time Elapsed (min)	Root time min$^{1/2}$	25kN/m2		50kN/m2		100kN/m2		200kN/m2	
		Dial Reading (mm)	**Settlement (mm)**	**Dial Reading (min)**	**Settlement (mm)**	**Dial Reading (min)**	**Settlement (mm)**	**Dial Reading (min)**	**Settlement (mm)**
0	0.00	12.000	0.000	11.890	0.000	11.778	0.000	11.586	0.000
0.1	0.32	11.921	-0.079	11.822	-0.068	11.682	-0.096	11.538	-0.048
0.17	0.41	11.919	-0.081	11.820	-0.070	11.676	-0.102	11.526	-0.060
0.25	0.50	11.918	-0.082	11.818	-0.072	11.668	-0.110	11.522	-0.064
0.5	0.71	11.916	-0.084	11.816	-0.074	11.661	-0.117	11.512	-0.074
1	1.00	11.914	-0.086	11.813	-0.077	11.656	-0.122	11.502	-0.084
2	1.41	11.912	-0.088	11.810	-0.080	11.648	-0.130	11.491	-0.095
4	2.00	11.910	-0.090	11.807	-0.083	11.640	-0.138	11.479	-0.107
8	2.83	11.908	-0.092	11.804	-0.086	11.634	-0.144	11.472	-0.114
15	3.87	11.906	-0.094	11.802	-0.088	11.628	-0.150	11.464	-0.122
30	5.48	11.904	-0.096	11.799	-0.091	11.622	-0.156	11.456	-0.130
60	7.75	11.902	-0.098	11.796	-0.094	11.617	-0.161	11.444	-0.142
120	10.95	11.900	-0.100	11.792	-0.098	11.610	-0.168	11.436	-0.150
240	15.49	11.898	-0.102	11.789	-0.101	11.603	-0.175	11.428	-0.158
480	21.91	11.896	-0.104	11.785	-0.105	11.595	-0.183	11.415	-0.171
1440	37.95	11.890	-0.110	11.778	-0.112	11.586	-0.192	11.398	-0.188

Calculated values for coefficient of consolidation and volume compressibility for sample S2

Current load incriment	0 kN/m^2 25kN/m^2	25kN/m^2 50kN/m^2	50kN/m^2 100kN/m^2	100kN/m^2 200kN/m^2
At the Beginning Sample Thickness (H) mm	8.000	8.000	8.000	8.000
Sample settlement from each load (Δh) mm	0.110	0.112	0.192	0.188
Coefficient of Volume Compressibility (m_v) (10^{-4} m^2/kN)	2.20	1.13	0.97	0.48
$\sqrt{t_{90}}$ ($min^{1/2}$)	2.50	2.40	2.30	2.20
t_{90} (min)	6.25	5.76	5.29	4.84
d = H/2 (mm)	10.00	9.95	9.89	9.79
T_{90}	0.848	0.848	0.848	0.848
Coefficient of Consolidation (C_v) (mm^2/min)	13.57	14.56	15.68	16.80
Coefficient of Consolidation (C_v) (m^2/year)	7.1	7.7	8.2	8.8

Void ratios with relevant applied pressure for sample S2

Applied Pressure kN/m2	Void Ratio e
	0.696
25	0.687
50	0.678
100	0.661
200	0.645

Calculated value for coefficient of consolidation and volume compressibility for higher load case for sample S2

Current load incriment	0kN/m^2 250kN/m^2	250kN/m^2 500kN/m^2	500kN/m^2 1000kN/m	1000kN/m^2 2000kN/m^2
At the Beginning Sample Thickness (H) mm	20.00	19.732	19.502	19.170
Sample settlement from each load (Δh) mm	0.268	0.230	0.332	0.480
Coefficient of Volume Compressibility (m_v) (10^{-5} m^2/kN)	5.4	2.3	1.7	1.3
$\sqrt{t_{90}}$ ($min^{1/2}$)	1.40	1.30	1.20	1.00
t_{90} (min)	1.96	1.69	1.44	1.00
d = H/2 (mm)	10.00	9.87	9.75	9.59
T_{90}	0.848	0.848	0.848	0.848
Coefficient of Consolidation (C_v) (mm^2/min)	43.27	48.84	55.99	77.91
Coefficient of Consolidation (C_v) (m^2/year)	22.7	25.7	29.4	40.9

Consolidation settlement for Bottom Ash sample S2 for Higher loads

for loading, Unloading and Reloading and relevant void ratios for the applied pressure.

Time Elapsed (min)	Root time $min^{1/2}$	Loading								Unloading				ReLoading							
		250 kN/m2		500 Kn/m2		1000kN/m2		2000kN/m2		2000-1000 kN/m2		1000 - 100 kN/m2		250 kN/m2		500 Kn/m2		1000kN/m2		2000kN/m2	
		Dial Reading (mm)	Settlement (mm) (for 250kN/m2)	Dial Reading (min)	Settlement (mm)	Dial Reading (min)	Settlement (mm)	Dial Reading (min)	Settlement (mm)	Dial Reading (min)	Settlement (mm)	Dial Reading (min)	Settlement (mm)	Dial Reading (mm)	Settlement (mm) (for 250kN/m2)	Dial Reading (min)	Settlement (mm)	Dial Reading (min)	Settlement (mm)	Dial Reading (min)	Settlement (mm)
0	0.00	12.000	0.000	11.732	0.000	11.502	0.000	11.170	0.000	10.690	0.000	10.718	0.000	11.270	0.000	11.014	0.000	10.902	0.000	10.784	0.000
0.1	0.32	11.780	-0.220	11.580	-0.152	11.268	-0.234	10.790	-0.380	10.716	0.026	11.210	0.492	11.120	-0.150	10.914	-0.100	10.800	-0.102	10.656	-0.128
0.17	0.41	11.778	-0.222	11.560	-0.172	11.260	-0.242	10.784	-0.386	10.716	0.026	11.218	0.500	11.080	-0.190	10.914	-0.100	10.798	-0.104	10.652	-0.132
0.25	0.50	11.774	-0.226	11.556	-0.176	11.250	-0.252	10.774	-0.396	10.716	0.026	11.220	0.502	11.040	-0.230	10.914	-0.100	10.798	-0.104	10.650	-0.134
0.5	0.71	11.770	-0.230	11.552	-0.180	11.242	-0.260	10.768	-0.402	10.716	0.026	11.222	0.504	11.024	-0.246	10.912	-0.102	10.798	-0.104	10.648	-0.136
1	1.00	11.764	-0.236	11.548	-0.184	11.234	-0.268	10.764	-0.406	10.716	0.026	11.226	0.508	11.024	-0.246	10.912	-0.102	10.796	-0.106	10.646	-0.138
2	1.41	11.760	-0.240	11.542	-0.190	11.228	-0.274	10.754	-0.416	10.716	0.026	11.230	0.512	11.022	-0.248	10.912	-0.102	10.796	-0.106	10.644	-0.140
4	2.00	11.754	-0.246	11.538	-0.194	11.220	-0.282	10.746	-0.424	10.716	0.026	11.234	0.516	11.020	-0.250	10.910	-0.104	10.792	-0.110	10.640	-0.144
8	2.83	11.750	-0.250	11.532	-0.200	11.216	-0.286	10.736	-0.434	10.716	0.026	11.238	0.520	11.020	-0.250	10.908	-0.106	10.792	-0.110	10.636	-0.148
15	3.87	11.748	-0.252	11.528	-0.204	11.210	-0.292	10.728	-0.442	10.716	0.026	11.242	0.524	11.020	-0.250	10.908	-0.106	10.790	-0.112	10.634	-0.150
30	5.48	11.746	-0.254	11.524	-0.208	11.204	-0.298	10.718	-0.452	10.718	0.028	11.244	0.526	11.018	-0.252	10.908	-0.106	10.790	-0.112	10.632	-0.152
60	7.75	11.742	-0.258	11.520	-0.212	11.196	-0.306	10.710	-0.460	10.718	0.028	11.248	0.530	11.016	-0.254	10.906	-0.108	10.788	-0.114	10.628	-0.156
120	10.95	11.740	-0.260	11.516	-0.216	11.190	-0.312	10.700	-0.470	10.718	0.028	11.250	0.532	11.016	-0.254	10.906	-0.108	10.788	-0.114	10.624	-0.160
240	15.49	11.738	-0.262	11.512	-0.220	11.186	-0.316	10.694	-0.476	10.718	0.028	11.250	0.532	11.016	-0.254	10.904	-0.110	10.786	-0.116	10.622	-0.162
480	21.91	11.736	-0.264	11.508	-0.224	11.179	-0.323	10.690	-0.480	10.718	0.028	11.252	0.534	11.014	-0.256	10.902	-0.112	10.784	-0.118	10.610	-0.174
1440	37.95	11.732	-0.268	11.502	-0.230	11.170	-0.332	10.690	-0.480	10.718	0.028	11.270	0.552	11.014	-0.256	10.902	-0.112	10.784	-0.118	10.610	-0.174

Loading Pattern	Applied Pressure		Final Dial Gauge Reading	Change in Dial Gauge reading	Thickness of soil sample H1 / mm	Equivelent height of voids (H1-Hs)/mm	Void Ratio e=(H1-Hs)/Hs
	kg	kN/m2					
Loading	0.0		12.000	0.000	20.000	8.178	0.692
	5.0	250.0	11.732	0.268	19.732	7.910	0.669
	10.0	500.0	11.502	0.230	19.502	7.680	0.650
	20.0	1000.0	11.170	0.332	19.170	7.348	0.622
	40.0	2000.0	10.690	0.480	18.690	6.868	0.581
Unloading	40.0	2000.0	10.690	1.310	18.690	6.868	0.581
	20.0	1000.0	10.718	-0.028	18.718	6.896	0.583
	2.0	100.0	11.270	-0.552	19.270	7.448	0.630
Reloading	2.0	100.0	11.270	0.730	19.270	7.448	0.630
	5.0	250.0	11.014	0.256	19.014	7.192	0.608
	10.0	500.0	10.902	0.112	18.902	7.080	0.599
	20.0	1000.0	10.784	0.118	18.784	6.962	0.589
	40.0	2000.0	10.610	0.174	18.610	6.788	0.574

Calculated value for void ratios for sample S3-1

Consolidation settlement for Bottom Ash sample S3-1 for loading, Unloading and Reloading and the table of relevant void ratios for the applied pressure.

Loading		12.5 kN/m2 (250g)			25 kN/m2 (500g)			50 kN/m2 (1 kg)			100 kN/m2 (2kg)			200 kN/m2 (4 kg)			400 kN/m2 (8kg)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	0.00	12.000	0.000	15.00	11.970	-0.030	36.20	11.928	-0.042	71.00	11.858	-0.070	27.00	11.746	-0.048	14.00	11.572	-0.080
0.1	0.32	5.00	11.990	-0.010	31.50	11.937	-0.033	56.50	11.887	-0.041	8.50	11.783	-0.075	91.00	11.618	-0.128	99.00	11.402	-0.170
0.17	0.41	5.50	11.989	-0.011	31.70	11.937	-0.033	57.00	11.886	-0.042	9.00	11.782	-0.076	92.00	11.616	-0.130	100.00	11.400	-0.172
0.25	0.50	6.10	11.988	-0.012	31.80	11.936	-0.034	57.50	11.885	-0.043	10.00	11.780	-0.078	93.00	11.614	-0.132	1.00	11.398	-0.174
0.5	0.71	6.50	11.987	-0.013	31.90	11.936	-0.034	58.50	11.883	-0.045	11.50	11.777	-0.081	95.00	11.610	-0.136	4.00	11.392	-0.180
1	1.00	6.80	11.986	-0.014	32.10	11.936	-0.034	59.00	11.882	-0.046	13.20	11.774	-0.084	97.00	11.606	-0.140	6.80	11.386	-0.186
2	1.41	7.20	11.986	-0.014	32.30	11.935	-0.035	60.00	11.880	-0.048	14.50	11.771	-0.087	99.00	11.602	-0.144	9.00	11.382	-0.190
4	2.00	7.50	11.985	-0.015	32.50	11.935	-0.035	61.00	11.878	-0.050	16.00	11.768	-0.090	1.00	11.598	-0.148	12.00	11.376	-0.196
8	2.83	8.00	11.984	-0.016	32.80	11.934	-0.036	61.80	11.876	-0.051	17.20	11.766	-0.092	2.00	11.596	-0.150	14.00	11.372	-0.200
15	3.87	8.50	11.983	-0.017	33.10	11.934	-0.036	62.80	11.874	-0.053	18.20	11.764	-0.094	4.00	11.592	-0.154	16.00	11.368	-0.204
30	5.48	9.20	11.982	-0.018	33.50	11.933	-0.037	63.50	11.873	-0.055	20.00	11.760	-0.098	6.00	11.588	-0.158	18.00	11.364	-0.208
60	7.75	10.00	11.980	-0.020	34.00	11.932	-0.038	64.50	11.871	-0.057	21.50	11.757	-0.101	8.50	11.583	-0.163	20.00	11.360	-0.212
120	10.95	11.00	11.978	-0.022	34.50	11.931	-0.039	65.50	11.869	-0.059	23.00	11.754	-0.104	10.00	11.580	-0.166	22.00	11.356	-0.216
240	15.49	12.00	11.976	-0.024	35.00	11.930	-0.040	67.00	11.866	-0.062	24.00	11.752	-0.106	12.00	11.576	-0.170	24.00	11.352	-0.220
480	21.91	13.00	11.974	-0.026	35.50	11.929	-0.041	68.00	11.864	-0.064	25.00	11.750	-0.108	14.00	11.572	-0.174	25.00	11.350	-0.222
1440	37.95	15.00	11.970	-0.030	36.20	11.928	-0.042	71.00	11.858	-0.070	27.00	11.746	-0.112	14.00	11.572	-0.174	27.20	11.346	-0.226

Unloading		400 kN/m2 - 100kN/m2 (2kg)			100 kN/m2 - 25kN/m2 (500g)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	27.20	11.346	0.000	64.00	11.472	0.000
0.1	0.32	71.00	11.458	0.112	17.50	11.565	0.093
0.17	0.41	70.00	11.460	0.114	17.20	11.566	0.094
0.25	0.50	69.50	11.461	0.115	17.00	11.566	0.094
0.5	0.71	69.00	11.462	0.116	16.80	11.566	0.094
1	1.00	68.80	11.462	0.117	16.50	11.567	0.095
2	1.41	67.20	11.466	0.120	16.00	11.568	0.096
4	2.00	67.00	11.466	0.120	14.80	11.570	0.098
8	2.83	66.50	11.467	0.121	14.50	11.571	0.099
15	3.87	66.20	11.468	0.122	14.00	11.572	0.100
30	5.48	66.10	11.468	0.122	13.70	11.573	0.101
60	7.75	66.10	11.468	0.122	13.70	11.573	0.101
120	10.95	65.50	11.469	0.123	12.30	11.575	0.103
240	15.49	64.50	11.471	0.125	11.50	11.577	0.105
480	21.91	64.00	11.472	0.126	8.00	11.584	0.112
1440	37.95	64.00	11.472	0.126	8.00	11.584	0.112

Reloading		50 kN/m2 (1kg)			100 kN/m2 (2kg)			200 kN/m2 (4 kg)			400 kN/m2 (8kg)			800 kN/m2 (16 kg)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	8.00	11.584	0.000	22.60	11.555	0.000	72.50	11.455	0.000	9.50	11.381	0.000	58.00	11.284	0.000
0.1	0.32	20.00	11.560	-0.024	30.20	11.540	-0.015	3.00	11.394	-0.061	44.50	11.311	-0.070	80.00	11.240	-0.044
0.17	0.41	20.20	11.560	-0.024	39.50	11.521	-0.034	3.50	11.393	-0.062	45.00	11.310	-0.071	93.00	11.214	-0.070
0.25	0.50	21.00	11.558	-0.026	46.00	11.508	-0.047	4.00	11.392	-0.063	46.00	11.308	-0.073	96.00	11.208	-0.076
0.5	0.71	21.00	11.558	-0.026	58.00	11.484	-0.071	4.00	11.392	-0.063	46.20	11.308	-0.073	99.00	11.202	-0.082
1	1.00	21.50	11.557	-0.027	66.00	11.468	-0.087	4.00	11.392	-0.063	47.00	11.306	-0.075	45.00	11.110	-0.174
2	1.41	21.80	11.556	-0.028	67.00	11.466	-0.089	4.80	11.390	-0.065	49.00	11.302	-0.079	56.00	11.088	-0.196
4	2.00	21.90	11.556	-0.028	67.60	11.465	-0.090	5.00	11.390	-0.065	49.50	11.301	-0.080	60.00	11.080	-0.204
8	2.83	22.00	11.556	-0.028	68.00	11.464	-0.091	6.00	11.388	-0.067	50.00	11.300	-0.081	61.00	11.078	-0.206
15	3.87	22.00	11.556	-0.028	72.00	11.456	-0.099	6.50	11.387	-0.068	51.00	11.298	-0.083	64.00	11.072	-0.212
30	5.48	22.10	11.556	-0.028	72.00	11.456	-0.099	7.00	11.386	-0.069	51.30	11.297	-0.084	67.00	11.066	-0.218
60	7.75	22.20	11.556	-0.028	72.00	11.456	-0.099	7.20	11.386	-0.069	53.80	11.292	-0.089	68.50	11.063	-0.221
120	10.95	22.30	11.555	-0.029	72.00	11.456	-0.099	8.50	11.383	-0.072	54.00	11.292	-0.089	70.60	11.059	-0.225
240	15.49	22.40	11.555	-0.029	72.00	11.456	-0.099	9.00	11.382	-0.073	55.00	11.290	-0.091	73.00	11.054	-0.230
480	21.91	22.60	11.555	-0.029	72.50	11.455	-0.100	9.00	11.382	-0.073	55.00	11.290	-0.091	73.00	11.054	-0.230
1440	37.95	22.60	11.555	-0.029	72.50	11.455	-0.100	9.50	11.381	-0.074	58.00	11.284	-0.097	76.50	11.047	-0.237

Load Pattern	Applied Pressure		Final Dial Guage	Change in Dial gauge	Thickness of soil Sample	Equivalent height of	Void Ratio
	kg	kN/m2	Reading	Reading	H1/(mm)	voids (H1-Hs)/(mm)	e=(H1-Hs)/Hs
Loading	0.00		12.000	0.000	20.000	7.446	0.593
	0.25	12.50	11.970	0.030	19.970	7.416	0.591
	0.50	25.00	11.928	0.042	19.928	7.374	0.587
	1.00	50.00	11.858	0.070	19.858	7.304	0.582
	2.00	100.00	11.746	0.112	19.746	7.192	0.573
	4.00	200.00	11.572	0.174	19.572	7.018	0.559
	8.00	400.00	11.346	0.226	19.346	6.792	0.541
	Applied Pressure		Final Dial Guage	Change in Dial gauge	Thickness of soil Sample	Equivalent height of	Void Ratio
	kg	kN/m2	Reading	Reading	H1/(mm)	voids (H1-Hs)/(mm)	e=(H1-Hs)/Hs
Unloading	8.00	400.00	11.346	0.654	19.346	6.792	0.541
	2.00	100.00	11.472	-0.126	19.472	6.918	0.551
	0.50	25.00	11.584	-0.112	19.584	7.030	0.560
	Applied Pressure		Final Dial Guage	Change in Dial gauge	Thickness of soil Sample	Equivalent height of	Void Ratio
	kg	kN/m2	Reading	Reading	H1/(mm)	voids (H1-Hs)/(mm)	e=(H1-Hs)/Hs
Re -Loading	0.50	25	11.584	0.416	19.584	7.030	0.560
	1.00	50.00	11.555	0.029	19.555	7.001	0.558
	2.00	100.00	11.455	0.100	19.455	6.901	0.550
	4.00	200.00	11.381	0.074	19.381	6.827	0.544
	8.00	400.00	11.284	0.097	19.284	6.730	0.536
	16.00	800.00	11.047	0.237	19.047	6.493	0.517

Consolidation settlement for Bottom Ash sample S3-2for loading, Unloading and Reloading and the table of relevant void ratios for the applied pressure.

Loading		12.5 kN/m2 (250g)			25 kN/m2 (500g)			50 kN/m2 (1 kg)			100 kN/m2 (2kg)			200 kN/m2 (4 kg)			400 kN/m2 (8kg)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	0.00	12.000	0.000	5.00	11.990	-0.010	14.00	11.972	-0.018	31.00	11.938	-0.034	61.50	11.877	-0.048	14.00	11.772	-0.080
0.1	0.32	3.50	11.993	-0.007	7.10	11.986	-0.004	22.00	11.956	-0.016	50.00	11.900	-0.038	98.50	11.803	-0.074	70.00	11.660	-0.112
0.17	0.41	3.50	11.993	-0.007	7.50	11.985	-0.005	22.50	11.955	-0.017	51.00	11.898	-0.040	99.00	11.802	-0.075	71.00	11.658	-0.114
0.25	0.50	3.60	11.993	-0.007	7.70	11.985	-0.005	22.80	11.954	-0.018	51.20	11.898	-0.040	99.50	11.801	-0.076	73.00	11.654	-0.118
0.5	0.71	3.70	11.993	-0.007	7.90	11.984	-0.006	23.00	11.954	-0.018	52.00	11.896	-0.042	1.00	11.798	-0.079	74.00	11.652	-0.120
1	1.00	3.80	11.992	-0.008	8.10	11.984	-0.006	23.50	11.953	-0.019	52.80	11.894	-0.044	2.00	11.796	-0.081	77.00	11.646	-0.126
2	1.41	3.90	11.992	-0.008	8.35	11.983	-0.007	24.00	11.952	-0.020	53.50	11.893	-0.045	3.50	11.793	-0.084	79.00	11.642	-0.130
4	2.00	4.00	11.992	-0.008	8.60	11.983	-0.007	24.50	11.951	-0.021	54.20	11.892	-0.046	4.50	11.791	-0.086	81.00	11.638	-0.134
8	2.83	4.10	11.992	-0.008	8.90	11.982	-0.008	25.00	11.950	-0.022	55.10	11.890	-0.048	6.00	11.788	-0.089	83.10	11.634	-0.138
15	3.87	4.20	11.992	-0.008	9.30	11.981	-0.009	25.50	11.949	-0.023	55.80	11.888	-0.050	7.00	11.786	-0.091	84.00	11.632	-0.140
30	5.48	4.30	11.991	-0.009	9.80	11.980	-0.010	26.10	11.948	-0.024	56.50	11.887	-0.051	8.50	11.783	-0.094	86.00	11.628	-0.144
60	7.75	4.40	11.991	-0.009	10.30	11.979	-0.011	27.00	11.946	-0.026	57.50	11.885	-0.053	9.80	11.780	-0.097	88.00	11.624	-0.148
120	10.95	4.50	11.991	-0.009	10.80	11.978	-0.012	28.00	11.944	-0.028	58.60	11.883	-0.055	11.00	11.778	-0.099	89.50	11.621	-0.151
240	15.49	4.60	11.991	-0.009	11.20	11.978	-0.012	29.00	11.942	-0.030	60.10	11.880	-0.058	12.00	11.776	-0.101	91.30	11.617	-0.155
480	21.91	4.70	11.991	-0.009	11.50	11.977	-0.013	30.00	11.940	-0.032	61.50	11.877	-0.061	13.20	11.774	-0.103	93.50	11.613	-0.159
1440	37.95	5.00	11.990	-0.010	14.00	11.972	-0.018	31.00	11.938	-0.034	61.50	11.877	-0.061	14.00	11.772	-0.105	93.50	11.613	-0.159

Unloading		400 kN/m2 - 100kN/m2 (2kg)			100 kN/m2 - 25kN/m2 (500g)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	93.50	11.613	0.000	58.00	11.684	0.000
0.1	0.32	70.00	11.660	0.047	29.00	11.742	0.058
0.17	0.41	69.00	11.662	0.049	28.70	11.743	0.059
0.25	0.50	68.80	11.662	0.049	28.50	11.743	0.059
0.5	0.71	68.50	11.663	0.050	28.50	11.743	0.059
1	1.00	68.80	11.662	0.049	28.20	11.744	0.060
2	1.41	67.80	11.664	0.051	28.00	11.744	0.060
4	2.00	67.20	11.666	0.053	28.00	11.744	0.060
8	2.83	67.00	11.666	0.053	27.50	11.745	0.061
15	3.87	67.00	11.666	0.053	27.50	11.745	0.061
30	5.48	67.00	11.666	0.053	27.20	11.746	0.062
60	7.75	67.00	11.666	0.053	27.00	11.746	0.062
120	10.95	62.00	11.676	0.063	27.00	11.746	0.062
240	15.49	58.00	11.684	0.071	26.50	11.747	0.063
480	21.91	58.00	11.684	0.071	20.00	11.760	0.076
1440	37.95	58.00	11.684	0.071	20.00	11.760	0.076

Reloading		50 kN/m2 (1kg)			100 kN/m2 (2kg)			200 kN/m2 (4 kg)			400 kN/m2 (8kg)			800 kN/m2 (16 kg)		
Time Elapsed (min)	**Root time $min^{1/2}$**	**Dial Reading**	**Dial Reading (mm)**	**Settlement (mm)**	**Dial Reading**	**Dial Reading (mm)**	**Settlement (mm)**	**Dial Reading**	**Dial Reading (mm)**	**Settlement (mm)**	**Dial Reading**	**Dial Reading (mm)**	**Settlement (mm)**	**Dial Reading**	**Dial Reading (mm)**	**Settlement (mm)**
0	0.00	20.00	11.760	0.000	32.00	11.736	0.000	44.50	11.711	0.000	67.50	11.665	0.000	8.50	11.583	0.000
0.1	0.32	26.00	11.748	-0.012	34.60	11.731	-0.005	63.50	11.673	-0.038	94.50	11.611	-0.054	15.00	11.570	-0.013
0.17	0.41	26.80	11.746	-0.014	36.10	11.728	-0.008	64.00	11.672	-0.039	95.00	11.610	-0.055	28.00	11.544	-0.039
0.25	0.50	26.80	11.746	-0.014	38.30	11.723	-0.013	64.50	11.671	-0.040	95.20	11.610	-0.055	60.00	11.480	-0.103
0.5	0.71	26.80	11.746	-0.014	42.00	11.716	-0.020	65.00	11.670	-0.041	96.00	11.608	-0.057	65.00	11.470	-0.113
1	1.00	27.00	11.746	-0.014	43.00	11.714	-0.022	65.00	11.670	-0.041	96.00	11.608	-0.057	76.00	11.448	-0.135
2	1.41	27.00	11.746	-0.014	43.10	11.714	-0.022	65.20	11.670	-0.041	96.50	11.607	-0.058	81.00	11.438	-0.145
4	2.00	27.20	11.746	-0.014	43.30	11.713	-0.023	65.50	11.669	-0.042	97.50	11.605	-0.060	90.00	11.420	-0.163
8	2.83	27.50	11.745	-0.015	43.30	11.713	-0.023	65.50	11.669	-0.042	98.00	11.604	-0.061	90.00	11.420	-0.163
15	3.87	27.50	11.745	-0.015	43.30	11.713	-0.023	65.60	11.669	-0.042	98.20	11.604	-0.061	90.20	11.420	-0.163
30	5.48	27.80	11.744	-0.016	43.30	11.713	-0.023	65.70	11.669	-0.042	98.40	11.603	-0.062	90.20	11.420	-0.163
60	7.75	27.90	11.744	-0.016	43.40	11.713	-0.023	65.90	11.668	-0.043	99.00	11.602	-0.063	90.20	11.420	-0.163
120	10.95	28.00	11.744	-0.016	43.60	11.713	-0.023	66.10	11.668	-0.043	0.00	11.600	-0.065	91.90	11.416	-0.167
240	15.49	30.00	11.740	-0.020	43.60	11.713	-0.023	67.00	11.666	-0.045	6.50	11.587	-0.078	94.50	11.411	-0.172
480	21.91	30.00	11.740	-0.020	43.60	11.713	-0.023	67.00	11.666	-0.045	6.50	11.587	-0.078	94.50	11.411	-0.172
1440	37.95	32.00	11.736	-0.024	44.50	11.711	-0.025	67.50	11.665	-0.046	8.50	11.583	-0.082	96.50	11.407	-0.176

Load Pattern	Applied Pressure		Final Dial Guage	Change in Dial gauge Reading	Thickness of soil Sample H1/(mm)	Equivalent height of voids (H1-Hs)/(mm)	Void Ratio e=(H1-Hs)/Hs
	kg	kN/m2	Reading				
Loading	0.00		12.000	0.000	20.000	7.419	0.590
	0.25	12.50	11.990	0.010	19.990	7.409	0.589
	0.50	25.00	11.972	0.018	19.972	7.391	0.588
	1.00	50.00	11.938	0.034	19.938	7.357	0.585
	2.00	100.00	11.877	0.061	19.877	7.296	0.580
	4.00	200.00	11.772	0.105	19.772	7.191	0.572
	8.00	400.00	11.613	0.159	19.613	7.032	0.559

	Applied Pressure		Final Dial Guage	Change in Dial gauge Reading	Thickness of soil Sample H1/(mm)	Equivalent height of voids (H1-Hs)/(mm)	Void Ratio e=(H1-Hs)/Hs
	kg	kN/m2	Reading				
Unloading	8.00	400.00	11.613	0.387	19.613	7.032	0.559
	2.00	100.00	11.684	-0.071	19.684	7.103	0.565
	0.50	25.00	11.760	-0.076	19.760	7.179	0.571

	Applied Pressure		Final Dial Guage	Change in Dial gauge Reading	Thickness of soil Sample H1/(mm)	Equivalent height of voids (H1-Hs)/(mm)	Void Ratio e=(H1-Hs)/Hs
	kg	kN/m2	Reading				
Re - Loading	0.50	25	11.760	0.240	19.760	7.179	0.571
	1.00	50.00	11.736	0.024	19.736	7.155	0.569
	2.00	100.00	11.711	0.025	19.711	7.130	0.567
	4.00	200.00	11.665	0.046	19.665	7.084	0.563
	8.00	400.00	11.583	0.082	19.583	7.002	0.557
	16.00	800.00	11.407	0.176	19.407	6.826	0.543

Consolidation settlement for Bottom Ash sample S3-3 for loading, Unloading and Reloading and the table of relevant void ratios for the applied pressure.

Loading		12.5 kN/m2 (250g)			25 kN/m2 (500g)			50 kN/m2 (1 kg)			100 kN/m2 (2kg)			200 kN/m2 (4 kg)			400 kN/m2 (8kg)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	0.00	12.000	0.000	12.60	11.975	-0.025	28.50	11.943	-0.032	56.00	11.888	-0.055	1.20	11.798	-0.048	73.00	11.654	-0.080
0.1	0.32	9.00	11.982	-0.018	23.00	11.954	-0.021	44.00	11.912	-0.031	86.00	11.828	-0.060	53.00	11.694	-0.104	48.00	11.504	-0.150
0.17	0.41	9.50	11.981	-0.019	23.50	11.953	-0.022	44.20	11.912	-0.031	87.00	11.826	-0.062	54.00	11.692	-0.106	50.00	11.500	-0.154
0.25	0.50	9.80	11.980	-0.020	23.50	11.953	-0.022	45.00	11.910	-0.033	88.00	11.824	-0.064	56.00	11.688	-0.110	51.00	11.498	-0.156
0.5	0.71	10.00	11.980	-0.020	23.70	11.953	-0.022	45.70	11.909	-0.034	88.80	11.822	-0.066	57.00	11.686	-0.112	53.00	11.494	-0.160
1	1.00	10.50	11.979	-0.021	24.00	11.952	-0.023	46.00	11.908	-0.035	90.00	11.820	-0.068	58.50	11.683	-0.115	55.00	11.490	-0.164
2	1.41	11.00	11.978	-0.022	24.30	11.951	-0.023	46.80	11.906	-0.037	91.20	11.818	-0.070	60.20	11.680	-0.118	57.00	11.486	-0.168
4	2.00	11.50	11.977	-0.023	24.60	11.951	-0.024	47.50	11.905	-0.038	92.00	11.816	-0.072	61.30	11.677	-0.120	59.00	11.482	-0.172
8	2.83	11.80	11.976	-0.024	24.80	11.950	-0.024	48.50	11.903	-0.040	93.00	11.814	-0.074	63.00	11.674	-0.124	60.50	11.479	-0.175
15	3.87	11.90	11.976	-0.024	25.10	11.950	-0.025	49.50	11.901	-0.042	94.00	11.812	-0.076	64.00	11.672	-0.126	62.00	11.476	-0.178
30	5.48	12.00	11.976	-0.024	25.50	11.949	-0.026	50.20	11.900	-0.043	95.00	11.810	-0.078	65.70	11.669	-0.129	63.50	11.473	-0.181
60	7.75	12.10	11.976	-0.024	26.00	11.948	-0.027	50.80	11.898	-0.045	96.00	11.808	-0.080	68.00	11.664	-0.134	66.00	11.468	-0.186
120	10.95	12.20	11.976	-0.024	26.50	11.947	-0.028	51.50	11.897	-0.046	97.50	11.805	-0.083	70.00	11.660	-0.138	67.10	11.466	-0.188
240	15.49	12.30	11.975	-0.025	27.00	11.946	-0.029	52.50	11.895	-0.048	98.20	11.804	-0.084	70.80	11.658	-0.139	68.50	11.463	-0.191
480	21.91	12.40	11.975	-0.025	27.50	11.945	-0.030	54.00	11.892	-0.051	99.30	11.801	-0.087	71.50	11.657	-0.141	69.30	11.461	-0.193
1440	37.95	12.60	11.975	-0.025	28.50	11.943	-0.032	56.00	11.888	-0.055	1.20	11.798	-0.090	73.00	11.654	-0.144	71.50	11.457	-0.197

Unloading		400 kN/m2 - 100kN/m2 (2kg)			100 kN/m2 - 25kN/m2 (500g)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	71.50	11.457	0.000	17.20	11.566	0.000
0.1	0.32	24.00	11.552	0.095	86.00	11.628	0.062
0.17	0.41	23.50	11.553	0.096	85.50	11.629	0.063
0.25	0.50	23.20	11.554	0.097	85.00	11.630	0.064
0.5	0.71	23.00	11.554	0.097	84.80	11.630	0.065
1	1.00	22.80	11.554	0.097	84.20	11.632	0.066
2	1.41	22.50	11.555	0.098	83.50	11.633	0.067
4	2.00	22.20	11.556	0.099	83.20	11.634	0.068
8	2.83	22.00	11.556	0.099	82.50	11.635	0.069
15	3.87	22.00	11.556	0.099	82.00	11.636	0.070
30	5.48	21.50	11.557	0.100	81.80	11.636	0.071
60	7.75	20.50	11.559	0.102	81.20	11.638	0.072
120	10.95	20.00	11.560	0.103	80.80	11.638	0.073
240	15.49	17.80	11.564	0.107	79.50	11.641	0.075
480	21.91	17.20	11.566	0.109	77.50	11.645	0.079
1440	37.95	17.20	11.566	0.109	77.50	11.645	0.079

Reloading		50 kN/m2 (1kg)			100 kN/m2 (2kg)			200 kN/m2 (4 kg)			400 kN/m2 (8kg)			800 kN/m2 (16 kg)		
Time Elapsed (min)	Root time $min^{1/2}$	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)	Dial Reading	Dial Reading (mm)	Settlement (mm)
0	0.00	77.50	11.645	0.000	86.80	11.626	0.000	7.00	11.586	0.000	35.50	11.529	0.000	95.00	11.410	0.000
0.1	0.32	85.00	11.630	-0.015	89.00	11.622	-0.004	30.00	11.540	-0.046	69.00	11.462	-0.067	10.00	11.380	-0.030
0.17	0.41	85.20	11.630	-0.015	93.00	11.614	-0.012	30.50	11.539	-0.047	70.00	11.460	-0.069	20.00	11.360	-0.050
0.25	0.50	85.20	11.630	-0.015	99.00	11.602	-0.024	31.00	11.538	-0.048	70.50	11.459	-0.070	50.00	11.300	-0.110
0.5	0.71	85.50	11.629	-0.016	1.00	11.598	-0.028	32.00	11.536	-0.050	71.00	11.458	-0.071	70.00	11.260	-0.150
1	1.00	85.80	11.628	-0.017	4.00	11.592	-0.034	32.20	11.536	-0.050	71.20	11.458	-0.071	75.00	11.250	-0.160
2	1.41	85.90	11.628	-0.017	4.00	11.592	-0.034	32.50	11.535	-0.051	72.00	11.456	-0.073	83.00	11.234	-0.176
4	2.00	86.00	11.628	-0.017	4.10	11.592	-0.035	33.00	11.534	-0.052	73.00	11.454	-0.075	86.00	11.228	-0.182
8	2.83	86.00	11.628	-0.017	4.90	11.590	-0.036	33.10	11.534	-0.052	73.50	11.453	-0.076	87.00	11.226	-0.184
15	3.87	86.00	11.628	-0.017	5.00	11.590	-0.036	33.50	11.533	-0.053	74.00	11.452	-0.077	89.00	11.222	-0.188
30	5.48	86.10	11.628	-0.017	5.00	11.590	-0.036	34.00	11.532	-0.054	74.00	11.452	-0.077	92.00	11.216	-0.194
60	7.75	86.50	11.627	-0.018	5.10	11.590	-0.037	34.10	11.532	-0.054	75.00	11.450	-0.079	93.00	11.214	-0.196
120	10.95	86.60	11.627	-0.018	5.70	11.589	-0.038	34.50	11.531	-0.055	76.00	11.448	-0.081	95.90	11.208	-0.202
240	15.49	86.70	11.627	-0.018	6.00	11.588	-0.038	35.00	11.530	-0.056	92.00	11.416	-0.113	98.30	11.203	-0.207
480	21.91	86.70	11.627	-0.018	6.00	11.588	-0.038	35.00	11.530	-0.056	92.00	11.416	-0.113	98.30	11.203	-0.207
1440	37.95	86.80	11.626	-0.019	7.00	11.586	-0.040	35.50	11.529	-0.057	95.00	11.410	-0.119	1.50	11.197	-0.213

Load Pattern	Applied Pressure kg	Applied Pressure kN/m2	Final Dial Guage Reading	Change in Dial gauge Reading	Thickness of soil Sample H1/(mm)	Equivalent height of voids (H1-Hs)/(mm)	Void Ratio e=(H1-Hs)/Hs
Loading	0.00		12.000	0.000	20.000	7.526	0.603
	0.25	12.50	11.975	0.025	19.975	7.501	0.601
	0.50	25.00	11.943	0.032	19.975	7.501	0.601
	1.00	50.00	11.888	0.055	19.920	7.446	0.597
	2.00	100.00	11.798	0.090	19.829	7.355	0.590
	4.00	200.00	11.654	0.144	19.686	7.212	0.578
	8.00	400.00	11.457	0.197	19.489	7.015	0.562

Load Pattern	Applied Pressure kg	Applied Pressure kN/m2	Final Dial Guage Reading	Change in Dial gauge Reading	Thickness of soil Sample H1/(mm)	Equivalent height of voids (H1-Hs)/(mm)	Void Ratio e=(H1-Hs)/Hs
Unloading	8.00	400.00	11.457	0.543	19.489	7.015	0.562
	2.00	100.00	11.566	-0.109	19.597	7.123	0.571
	0.50	25.00	11.645	-0.079	19.677	7.203	0.577

Load Pattern	Applied Pressure kg	Applied Pressure kN/m2	Final Dial Guage Reading	Change in Dial gauge Reading	Thickness of soil Sample H1/(mm)	Equivalent height of voids (H1-Hs)/(mm)	Void Ratio e=(H1-Hs)/Hs
Re -Loading	0.50	25	11.645	0.355	19.677	7.203	0.577
	1.00	50.00	11.626	0.019	19.658	7.184	0.576
	2.00	100.00	11.586	0.040	19.618	7.144	0.573
	4.00	200.00	11.529	0.057	19.561	7.087	0.568
	8.00	400.00	11.410	0.119	19.442	6.968	0.559
	16.00	800.00	11.197	0.213	19.229	6.755	0.542

Calculated value for coefficient of consolidation and volume compressibility for load cases for sample S3-1

Current load incriment	0kN/m² 12.5kN/m²	12.5kN/m² 25kN/m²	25kN/m² 50kN/m²	50kN/m² 100kN/m²	100kN/m² 200kN/m²	100kN/m² 400kN/m²
At the Beginning Sample Thickness (H) mm	20.00	19.970	19.928	19.858	19.746	19.572
Sample settlement from each load (Δh) mm	0.030	0.042	0.070	0.112	0.174	0.226
Coefficient of Volume Compressibility(m_v)($10^{-5}m^2$/kN)	12.0	8.5	7.0	5.6	4.4	2.9
$\sqrt{t_{90}}$ ($min^{1/2}$)	2.80	2.20	2.00	1.80	1.50	1.10
t_{90} (min)	7.84	4.84	4.00	3.24	2.25	1.21
d = H/2 (mm)	10.00	9.99	9.96	9.93	9.87	9.79
T_{90}	0.848	0.848	0.848	0.848	0.848	0.848
Coefficient of Consolidation (C_v) (mm^2/min)	10.82	17.47	21.05	25.80	36.74	67.12
Coefficient of Consolidation (C_v) (m^2/year)	5.7	9.2	11.1	13.6	19.3	35.3

Calculated values for coefficient of consolidation and volume compressibility for load case for sample S3-2

Current load incriment	0kN/m2 12.5kN/m2	12.5kN/m² 25kN/m²	25kN/m² 50kN/m²	50kN/m² 100kN/m²	100kN/m² 200kN/m²	100kN/m² 400kN/m²
At the Beginning Sample Thickness (H) mm	20.00	19.990	19.972	19.938	19.877	19.772
Sample settlement from each load (Δh) mm	0.010	0.018	0.034	0.061	0.105	0.159
Coefficient of Volume Compressibility(m_v)($10^{-5}m^2$/kN)	4.0	3.6	3.4	3.1	2.6	2.0
$\sqrt{t_{90}}$ ($min^{1/2}$)	3.20	2.50	2.00	1.50	1.20	0.90
t_{90} (min)	10.24	6.25	4.00	2.25	1.44	0.81
d = H/2 (mm)	10.00	10.00	9.99	9.97	9.94	9.89
T_{90}	0.848	0.848	0.848	0.848	0.848	0.848
Coefficient of Consolidation (C_v) (mm^2/min)	8.28	13.55	21.14	37.46	58.17	102.32
Coefficient of Consolidation (C_v) (m^2/year)	4.4	7.1	11.1	19.7	30.6	53.8

Calculated value for coefficient of consolidation and volume compressibility for load case for sample S3-3

Current load incriment	0kN/m² 12.5kN/m²	12.5kN/m² 25kN/m²	25kN/m² 50kN/m²	50kN/m² 100kN/m²	100kN/m² 200kN/m²	100kN/m² 400kN/m²
At the Beginning Sample Thickness (H) mm	20.00	19.975	19.943	19.888	19.798	19.654
Sample settlement from each load (Δh) mm	0.025	0.032	0.055	0.090	0.144	0.197
Coefficient of Volume Compressibility(m_v)($10^{-5}m^2$/kN)	10.0	6.4	5.5	4.5	3.6	2.5
$\sqrt{t_{90}}$ ($min^{1/2}$)	2.80	2.30	1.90	1.40	1.10	0.90
t_{90} (min)	7.84	5.29	3.61	1.96	1.21	0.81
d = H/2 (mm)	10.00	9.99	9.97	9.94	9.90	9.83
T_{90}	0.848	0.848	0.848	0.848	0.848	0.848
Coefficient of Consolidation (C_v) (mm^2/min)	10.82	15.99	23.36	42.78	68.67	101.10
Coefficient of Consolidation (C_v) (m^2/year)	5.7	8.4	12.3	22.5	36.1	53.1

Appendix C - Shear strength parameters of the Bottom Ash

Tabulation of direct shear test data for the bottom ash sample S2

Normal load 50 kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0.0	0.0	0.0000	0.0000	0.6981	0	0.00	3600	0.00
10	1.0	0.0	0.0000	0.0000	0.6981	0.174	0.10	3594	0.47
20	6.0	1.0	0.0254	0.0014	0.6968	1.044	0.20	3588	2.85
30	12.0	1.0	0.0254	0.0014	0.6968	2.088	0.30	3582	5.72
40	15.0	2.0	0.0508	0.0027	0.6954	2.610	0.40	3576	7.16
50	16.0	2.0	0.0508	0.0027	0.6954	2.784	0.50	3570	7.65
75	22.0	4.0	0.1016	0.0054	0.6927	3.828	0.75	3555	10.56
100	26.0	5.0	0.1270	0.0068	0.6913	4.524	1.00	3540	12.54
125	27.0	6.0	0.1524	0.0082	0.6900	4.698	1.25	3525	13.07
150	32.0	8.0	0.2032	0.0109	0.6872	5.568	1.50	3510	15.56
175	38.0	9.0	0.2286	0.0122	0.6859	6.612	1.75	3495	18.56
200	43.0	11.0	0.2794	0.0149	0.6832	7.482	2.00	3480	21.09
225	46.0	12.0	0.3048	0.0163	0.6818	8.004	2.25	3465	22.66
250	52.0	12.0	0.3048	0.0163	0.6818	9.048	2.50	3450	25.73
275	55.0	12.0	0.3048	0.0163	0.6818	9.570	2.75	3435	27.33
300	60.0	12.0	0.3048	0.0163	0.6818	10.440	3.00	3420	29.95
325	61.0	12.0	0.3048	0.0163	0.6818	10.614	3.25	3405	30.58
350	62.0	12.0	0.3048	0.0163	0.6818	10.788	3.50	3390	31.22
375	64.0	12.5	0.3175	0.0170	0.6811	11.136	3.75	3375	32.37
400	64.5	12.5	0.3175	0.0170	0.6811	11.223	4.00	3360	32.77
425	65.0	12.5	0.3175	0.0170	0.6811	11.310	4.25	3345	33.17
450	66.0	13.0	0.3302	0.0177	0.6805	11.484	4.50	3330	33.83
475	67.0	13.0	0.3302	0.0177	0.6805	11.658	4.75	3315	34.50
500	68.0	13.0	0.3302	0.0177	0.6805	11.832	5.00	3300	35.17
550	68.0	13.0	0.3302	0.0177	0.6805	11.832	5.50	3270	35.50
600	68.0	13.0	0.3302	0.0177	0.6805	11.832	6.00	3240	35.82
625	68.0	13.0	0.3302	0.0177	0.6805	11.832	6.25	3225	35.99
675	68.0	13.0	0.3302	0.0177	0.6805	11.832	6.75	3195	36.33

Normal load 100 kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0	0	0.00000	0.6981	0	0.0000	3600	0.00
10	11	1	0.0254	0.00136	0.6968	1.91400	0.1000	3594	5.22
20	25	2	0.0508	0.00272	0.6954	4.35000	0.2000	3588	11.89
30	34	3	0.0762	0.00408	0.6940	5.91600	0.3000	3582	16.20
40	41	3	0.0762	0.00408	0.6940	7.13400	0.4000	3576	19.57
50	47	4	0.1016	0.00543	0.6927	8.17800	0.5000	3570	22.47
75	64	5	0.127	0.00679	0.6913	11.13600	0.7500	3555	30.73
100	76	6	0.1524	0.00815	0.6900	13.22400	1.0000	3540	36.65
125	87	8	0.2032	0.01087	0.6872	15.13800	1.2500	3525	42.13
150	97	9	0.2286	0.01223	0.6859	16.87800	1.5000	3510	47.17
175	109	11	0.2794	0.01494	0.6832	18.96600	1.7500	3495	53.24
200	118	12	0.3048	0.01630	0.6818	20.53200	2.0000	3480	57.88
225	122	13	0.3302	0.01766	0.6805	21.22800	2.2500	3465	60.10
250	129	14	0.3556	0.01902	0.6791	22.44600	2.5000	3450	63.82
275	135	15	0.381	0.02038	0.6777	23.49000	2.7500	3435	67.08
300	140	16	0.4064	0.02174	0.6764	24.36000	3.0000	3420	69.87
325	140	16	0.4064	0.02174	0.6764	24.36000	3.2500	3405	70.18
350	141	16	0.4064	0.02174	0.6764	24.53400	3.5000	3390	71.00
375	141	17	0.4318	0.02309	0.6750	24.53400	3.7500	3375	71.31
400	142	18	0.4572	0.02445	0.6737	24.70800	4.0000	3360	72.14
425	144	18	0.4572	0.02445	0.6737	25.05600	4.2500	3345	73.48
450	144	18	0.4572	0.02445	0.6737	25.05600	4.5000	3330	73.81
475	144	18	0.4572	0.02445	0.6737	25.05600	4.7500	3315	74.15
500	144	19	0.4826	0.02581	0.6723	25.05600	5.0000	3300	74.48
550	141	20	0.508	0.02717	0.6709	24.53400	5.5000	3270	73.60
600	140	20	0.508	0.02717	0.6709	24.36000	6.0000	3240	73.76
625	143	19	0.4826	0.02581	0.6723	24.88200	6.2500	3225	75.69
675	141	20	0.508	0.02717	0.6709	24.53400	6.7500	3195	75.33

Normal load 300kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0	0	0.00000	0.6981	0.00	0.000	3600	0.00
10	30	0	0	0.00000	0.6981	5.22	0.100	3594	14.25
20	51	1	0.0254	0.00136	0.6968	8.87	0.200	3588	24.26
30	63	2	0.0508	0.00272	0.6954	10.96	0.300	3582	30.02
40	80	3	0.0762	0.00408	0.6940	13.92	0.400	3576	38.19
50	90	4	0.1016	0.00543	0.6927	15.66	0.500	3570	43.03
75	115	6	0.1524	0.00815	0.6900	20.01	0.750	3555	55.22
100	150	7	0.1778	0.00951	0.6886	26.10	1.000	3540	72.33
125	170	9	0.2286	0.01223	0.6859	29.58	1.250	3525	82.32
150	185	10	0.254	0.01358	0.6845	32.19	1.500	3510	89.97
175	202	12	0.3048	0.01630	0.6818	35.15	1.750	3495	98.66
200	212	13	0.3302	0.01766	0.6805	36.89	2.000	3480	103.99
225	235	14	0.3556	0.01902	0.6791	40.89	2.250	3465	115.77
250	249	15	0.381	0.02038	0.6777	43.33	2.500	3450	123.20
275	262	16	0.4064	0.02174	0.6764	45.59	2.750	3435	130.19
300	273	16	0.4064	0.02174	0.6764	47.50	3.000	3420	136.26
325	285	17	0.4318	0.02309	0.6750	49.59	3.250	3405	142.87
350	297	18	0.4572	0.02445	0.6737	51.68	3.500	3390	149.55
375	293	19	0.4826	0.02581	0.6723	50.98	3.750	3375	148.19
400	293	19	0.4826	0.02581	0.6723	50.98	4.000	3360	148.85
425	293	19	0.4826	0.02581	0.6723	50.98	4.250	3345	149.52
450	294	19	0.4826	0.02581	0.6723	51.16	4.500	3330	150.70
475	294	19	0.4826	0.02581	0.6723	51.16	4.750	3315	151.38
500	294	20	0.5080	0.02717	0.6709	51.16	5.000	3300	152.07

Tabulation of direct shear test data for the bottom ash sample S3

Normal load 50kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0.0	0.0000	0.00000	0.5903	0	0.0	3600	0.0
10	11	0.0	0.0000	0.00000	0.5903	1.914	0.1	3594	5.2
20	17	0.0	0.0000	0.00000	0.5903	2.958	0.2	3588	8.1
30	20	1.0	0.0254	0.00141	0.5889	3.480	0.3	3582	9.5
40	23	1.0	0.0254	0.00141	0.5889	4.002	0.4	3576	11.0
50	27	1.0	0.0254	0.00141	0.5889	4.698	0.5	3570	12.9
75	35	2.0	0.0508	0.00282	0.5875	6.090	0.8	3555	16.8
100	46	3.0	0.0762	0.00424	0.5861	8.004	1.0	3540	22.2
125	56	4.0	0.1016	0.00565	0.5847	9.744	1.3	3525	27.1
150	65	5.0	0.1270	0.00706	0.5833	11.310	1.5	3510	31.6
175	73	6.0	0.1524	0.00847	0.5819	12.702	1.8	3495	35.7
200	79	6.0	0.1524	0.00847	0.5819	13.746	2.0	3480	38.7
225	86	7.0	0.1778	0.00988	0.5805	14.964	2.3	3465	42.4
250	90	8.0	0.2032	0.01130	0.5790	15.660	2.5	3450	44.5
275	95	8.0	0.2032	0.01130	0.5790	16.530	2.8	3435	47.2
300	98	9.0	0.2286	0.01271	0.5776	17.052	3.0	3420	48.9
325	99	9.0	0.2286	0.01271	0.5776	17.226	3.3	3405	49.6
350	100	10.0	0.2540	0.01412	0.5762	17.400	3.5	3390	50.4
375	100	10.0	0.2540	0.01412	0.5762	17.400	3.8	3375	50.6
400	100	10.0	0.2540	0.01412	0.5762	17.400	4.0	3360	50.8
425	100	10.0	0.2540	0.01412	0.5762	17.400	4.3	3345	51.0

Normal load 100kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0.0	0.0000	0.00000	0.5903	0	0.0	3600	0.0
10	21	0.0	0.0000	0.00000	0.5903	3.65400	0.1	3594	10.0
20	30	0.0	0.0000	0.00000	0.5903	5.22000	0.2	3588	14.3
30	40	1.0	0.0254	0.00141	0.5889	6.96000	0.3	3582	19.1
40	46	1.0	0.0254	0.00141	0.5889	8.00400	0.4	3576	22.0
50	51	2.0	0.0508	0.00282	0.5875	8.87400	0.5	3570	24.4
75	61	4.0	0.1016	0.00565	0.5847	10.61400	0.8	3555	29.3
100	69	5.0	0.1270	0.00706	0.5833	12.00600	1.0	3540	33.3
125	78	7.0	0.1778	0.00988	0.5805	13.57200	1.3	3525	37.8
150	82	8.0	0.2032	0.01130	0.5790	14.26800	1.5	3510	39.9
175	90	9.0	0.2286	0.01271	0.5776	15.66000	1.8	3495	44.0
200	92	10.0	0.2540	0.01412	0.5762	16.00800	2.0	3480	45.1
225	98	11.0	0.2794	0.01553	0.5748	17.05200	2.3	3465	48.3
250	101	12.0	0.3048	0.01694	0.5734	17.57400	2.5	3450	50.0
275	102	12.0	0.3048	0.01694	0.5734	17.74800	2.8	3435	50.7
300	104	13.0	0.3302	0.01835	0.5720	18.09600	3.0	3420	51.9
325	105	13.0	0.3302	0.01835	0.5720	18.27000	3.3	3405	52.6
350	106	13.0	0.3302	0.01835	0.5720	18.44400	3.5	3390	53.4
375	106	14.0	0.3556	0.01977	0.5706	18.44400	3.8	3375	53.6
400	106	14.0	0.3556	0.01977	0.5706	18.44400	4.0	3360	53.8
425	106	14.0	0.3556	0.01977	0.5706	18.44400	4.3	3345	54.1

Normal load 150kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0.0	0.0000	0.00000	0.5903	0.00000	0.0	3600	0.0
10	25	0.0	0.0000	0.00000	0.5903	4.35000	0.1	3594	11.9
20	39	0.0	0.0000	0.00000	0.5903	6.78600	0.2	3588	18.6
30	49	0.0	0.0000	0.00000	0.5903	8.52600	0.3	3582	23.4
40	60	2.0	0.0508	0.00282	0.5875	10.44000	0.4	3576	28.6
50	69	3.0	0.0762	0.00424	0.5861	12.00600	0.5	3570	33.0
75	89	5.0	0.1270	0.00706	0.5833	15.48600	0.8	3555	42.7
100	107	7.0	0.1778	0.00988	0.5805	18.61800	1.0	3540	51.6
125	122	9.0	0.2286	0.01271	0.5776	21.22800	1.3	3525	59.1
150	132	10.0	0.2540	0.01412	0.5762	22.96800	1.5	3510	64.2
175	144	12.0	0.3048	0.01694	0.5734	25.05600	1.8	3495	70.3
200	154	13.0	0.3302	0.01835	0.5720	26.79600	2.0	3480	75.5
225	163	14.0	0.3556	0.01977	0.5706	28.36200	2.3	3465	80.3
250	168	15.0	0.3810	0.02118	0.5692	29.23200	2.5	3450	83.1
275	176	16.0	0.4064	0.02259	0.5678	30.62400	2.8	3435	87.5
300	182	16.0	0.4064	0.02259	0.5678	31.66800	3.0	3420	90.8
325	189	17.0	0.4318	0.02400	0.5663	32.88600	3.3	3405	94.7
350	195	17.0	0.4318	0.02400	0.5663	33.93000	3.5	3390	98.2
375	200	17.0	0.4318	0.02400	0.5663	34.80000	3.8	3375	101.2
400	204	17.0	0.4318	0.02400	0.5663	35.49600	4.0	3360	103.6
425	206	17.0	0.4318	0.02400	0.5663	35.84400	4.3	3345	105.1
450	207	16.0	0.4064	0.02259	0.5678	36.01800	4.5	3330	106.1
475	207	16.0	0.4064	0.02259	0.5678	36.01800	4.8	3315	106.6
500	208	15.0	0.3810	0.02118	0.5692	36.19200	5.0	3300	107.6
550	206	14.0	0.3556	0.01977	0.5706	35.84400	5.5	3270	107.5
600	206	14.0	0.3556	0.01977	0.5706	35.84400	6.0	3240	108.5
525	206	14.0	0.3556	0.01977	0.57057	35.84400	5.3	3285	107.0
575	206	14.0	0.3556	0.01977	0.57057	35.84400	5.8	3255	108.0

Normal load 200kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0.0	0.00	0.00000	0.5903	0.0000	0.0	3600	0.0
10	26	1.0	0.03	0.00141	0.5889	4.5240	0.1	3594	12.3
20	43	2.0	0.05	0.00282	0.5875	7.4820	0.2	3588	20.5
30	57	3.0	0.08	0.00424	0.5861	9.9180	0.3	3582	27.2
40	69	4.0	0.10	0.00565	0.5847	12.0060	0.4	3576	32.9
50	80	5.0	0.13	0.00706	0.5833	13.9200	0.5	3570	38.3
75	103	6.0	0.15	0.00847	0.5819	17.9220	0.8	3555	49.5
100	130	8.0	0.20	0.01130	0.5790	22.6200	1.0	3540	62.7
125	150	10.0	0.25	0.01412	0.5762	26.1000	1.3	3525	72.6
150	171	11.0	0.28	0.01553	0.5748	29.7540	1.5	3510	83.2
175	185	13.0	0.33	0.01835	0.5720	32.1900	1.8	3495	90.4
200	201	15.0	0.38	0.02118	0.5692	34.9740	2.0	3480	98.6
225	216	16.0	0.41	0.02259	0.5678	37.5840	2.3	3465	106.4
250	229	17.0	0.43	0.02400	0.5663	39.8460	2.5	3450	113.3
275	245	18.0	0.46	0.02541	0.5649	42.6300	2.8	3435	121.7
300	259	19.0	0.48	0.02683	0.5635	45.0660	3.0	3420	129.3
325	269	20.0	0.51	0.02824	0.5621	46.8060	3.3	3405	134.9
350	269	20.0	0.51	0.02824	0.5621	46.8060	3.5	3390	135.4
375	266	20.0	0.51	0.02824	0.5621	46.2840	3.8	3375	134.5
400	266	20.0	0.51	0.02824	0.5621	46.2840	4.0	3360	135.1
425	266	20.0	0.51	0.02824	0.5621	46.2840	4.3	3345	135.7

Normal load 300kN/m^2

Shear Disp. Div	Proving Ring reading	Vertical Gauge reading	Vertical Dis. (mm) ΔH	Change in Void ratio Δe	Void ratio $e=e_0-\Delta e$	Shear force (kg)	Shear Displac. (mm)	Shear Area (mm2)	Shear stress (kN/m2)
0	0	0.0	0.0000	0.00000	0.5903	0.00000	0.0	3600	0.0
10	29	0.0	0.0000	0.00000	0.5903	5.04600	0.1	3594	13.8
20	46	0.0	0.0000	0.00000	0.5903	8.00400	0.2	3588	21.9
30	64	1.0	0.0254	0.00141	0.5889	11.13600	0.3	3582	30.5
40	81	3.0	0.0762	0.00424	0.5861	14.09400	0.4	3576	38.7
50	96	4.0	0.1016	0.00565	0.5847	16.70400	0.5	3570	45.9
75	129	7.0	0.1778	0.00988	0.5805	22.44600	0.8	3555	61.9
100	151	10.0	0.2540	0.01412	0.5762	26.27400	1.0	3540	72.8
125	174	11.0	0.2794	0.01553	0.5748	30.27600	1.3	3525	84.3
150	191	13.0	0.3302	0.01835	0.5720	33.23400	1.5	3510	92.9
175	202	15.0	0.3810	0.02118	0.5692	35.14800	1.8	3495	98.7
200	222	16.0	0.4064	0.02259	0.5678	38.62800	2.0	3480	108.9
225	240	18.0	0.4572	0.02541	0.5649	41.76000	2.3	3465	118.2
250	250	19.0	0.4826	0.02683	0.5635	43.50000	2.5	3450	123.7
275	266	20.0	0.5080	0.02824	0.5621	46.28400	2.8	3435	132.2
300	282	23.0	0.5842	0.03247	0.5579	49.06800	3.0	3420	140.7
325	296	23.0	0.5842	0.03247	0.5579	51.50400	3.3	3405	148.4
350	307	24.0	0.6096	0.03389	0.5565	53.41800	3.5	3390	154.6
375	320	25.0	0.6350	0.03530	0.5550	55.68000	3.8	3375	161.8
400	330	26.0	0.6604	0.03671	0.5536	57.42000	4.0	3360	167.6
425	340	27.0	0.6858	0.03812	0.5522	59.16000	4.3	3345	173.5
450	350	27.0	0.6858	0.03812	0.5522	60.90000	4.5	3330	179.4
475	351	27.0	0.6858	0.03812	0.5522	61.07400	4.8	3315	180.7
500	358	28.0	0.7112	0.03953	0.5508	62.29200	5.0	3300	185.2
550	362	28.0	0.7112	0.03953	0.5508	62.98800	5.5	3270	189.0
600	365	28.0	0.7112	0.03953	0.5508	63.51000	6.0	3240	192.3
650	365	28.0	0.7112	0.03953	0.5508	63.51000	6.5	3210	194.1
700	158	26.0	0.6604	0.03671	0.5536	27.49200	7.0	3180	84.8

Appendix D - Toxicity Characteristics leaching Procedure (TCLP) for Bottom Ash Sample S3

TEST REPORT

Report No: **(7417)202-0317(R)(SL)** Sep 06, 2017

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TEST RESULTS

Parameters	Test Results	LOQ	Requirement	Unit	Method
TCLP Heavy metal Analysis					
Arsenic (As)	ND	0.04	5	mg/L	USEPA Method 1311–TCLP with ICP-MS
Chromium (Cr)	0.08	-	5		
Cadmium (Cd)	ND	0.04	1		
Copper (Cu)	ND	0.06	Not Given		
Lead (Pb)	0.04	-	5		
Manganese (Mn)	1.01	-	Not Given		
Zinc (Zn)	0.04	-	Not Given		
Thallium (Tl)	ND	0.04	Not Given		
Selenium (Se)	ND	0.04	1		
Nickel (Ni)	ND	0.04	Not Given		
Mercury (Hg)	ND	0.007	0.2		
Barium(Ba)	3.26	-	100		
Iron(Fe)	0.04	-	Not Given		
Silver(Ag)	ND	0.04	5		
Sulphur	ND	0.01	Not Given		
Sulfite content (SO^{2-}_3)	ND	1.0	Not Given	mg/kg	AOAC 980.02
Sulfate content (SO^{2-}_4)	ND	1.0	Not Given	mg/kg	

Note:
ND – Not Detected
mg/L – milligrams per Litter
TCLP-Toxicity Characteristics Leaching Procedure
ICP-MS - Inductively Coupled Plasma - Mass Spectrometry
USEPA- United States Environmental Protection Agency
LOQ- Limit of Quantification

Remark:
Test report (7417)202-0317(SL) has been replaced with (7417)202-0317(R)(SL) to add test as per the vendors request.