BIOSOLIDS AS FILL MATERIAL IN ROAD EMBANKMENT
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Under the supervision of

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CERTIFICATE

This is to certify that work which is being presented in the thesis entitled **"BIOSOLIDS AS FILL MATERIAL IN ROAD EMBANKMENT"** in partial fulfillment of the requirement for the award of the degree of Master of Technology in Civil Engineering with specialization in **"Environmental Engineering"** and submitted to Department of Civil Engineering, **Jaypee University of Information Technology, Waknaghat** is an authentic record of work carried out by **Bhawna Thakur** during a period from July, 2016 to May, 2017 under the supervision of **Mr. Saurabh Rawat,** Assistant Professor, Department of Civil Engineering , Jaypee University of Information Technology,Waknaghat,Solan.

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Bhawna

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ABSTRACT

Biosolids are organic solid residues produced through the wastewater treatment process and contain many of the constituents removed from the influent wastewater. Currently, sewage treatment plant is experiencing a massive increase in the amount and composition of waste water and final component from these facilities i.e. biosolids, are constantly increasing and have made the disposal of solids waste a major problem around the world. The unutilized huge quantity of biosolids has drawn the attention of researchers to explore new strategies for bulk utilization. Thus, on account of this reality; reuse of biosolids as construction material for use in engineered fills can significantly reduce the demand for scarce virgin natural resources. Proper analysis on biosolids has pushed the boundaries of geotechnical engineering practice, in terms of identification and assessment of strength and deformation characteristics of biosolids. The engineering properties of biosolids with regards to moisture characteristics and geotechnical stability are of utmost importance. This thesis deals with an extensive suite of geotechnical and chemical laboratory tests which were undertaken on wastewater biosolids collected from the Kankhal Sewage Treatment Plant in India to evaluate their sustainable usage as a fill material in road embankments. As in India current scenario of utilization of biosolids in roads and embankment is relatively unknown. The laboratory tests include particle size distribution, specific gravity, Atterberg limits, compaction, hydraulic conductivity, California bearing ratio, consolidation and direct shear test. The results of an experimental study indicates that biosolids are classified as organic silt-sized particles of medium to high plasticity with high moisture content and liquid limit values. Compacted biosolids indicates very low particle density and high moisture content. CBR test results satisfy the local road authority specification for fill material. With regards to chemical test, the results of heavy metals were within acceptable limits for usage in geotechnical applications. This thesis therefore presents the innovative research study undertaken to analyze the biodegradation settlement characteristics of fresh biosolids by applying an analytical method when used as fill material in road embankment applications. The adopted model shows the effect of changing pH, temperature and moisture content on biodegradation settlement of biosolids layer in road embankment.

Keywords: Biosolids; embankment fill; geotechnical properties; Chemical assessment; Long term settlement.

TABLE OF CONTENTS

List of Figure

List of Tables

List of Symbols

STP	Sewage Treatment Plant
CBR	California Bearing Ratio
US EPA	Unites State Environment Protection Agency
FOS	Factor of Safety
IBR	Illinois Bearing Ratio
ETP	Eastern Treatment Plant
UCS	Unconfined Compressive Strength
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
SDP	Sludge Drying Pan
FA	Fly Ash
LKD	Lime Kiln Dust
WD	Works Debris
CaO	Calcium Oxide
RDA	Road Development Authority
BCC	Biosolids Contaminants Concentration
DDT	Dichloro Diphenyl Trichloroethane
BEPZ	Biyagama Export Processing Zone
IS	Indian Standard
SBR	Sequential Bed Reactor
C_u	Coefficient of Uniformity
C_c	Coefficient of Curvature
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
DST	Direct Shear Test

EPA	Environment Protection Authority
ASTM	American Society for Testing and Materials
MSW	Municipal Solid Waste
IRC	Indian Road Specification
ISC	Indian Standard Classification
NH	National Highway
SH	State Highway
MDR	Major District Road
BCC	biosolids contaminant concentration

CHAPTER 1

INTRODUCTION

1.1 General

This chapter provides the brief introduction of biosolids right from the beginning of generation to disposal. This chapter will define and describe the production and uses of biosolids in road embankment as a fill material.

1.2 Biosolids

Biosolids refers to the solids separated during the treatment of municipal wastewater, resulted from the treatment of wastewater carried through sewer lines from private or community to the treatment plant. Following treatment, the liquid (effluent) is discharged to nearby streams and the solids (biosolids) or a product developed from the solids is removed from the treatment plant for the disposal or the beneficial use, especially as a soil amendment.

According to United States Environmental Protection Agency (US EPA), biosolids are treated sewage sludge that meets the EPA pollutant and pathogen requirements for land applications and the surface disposal (US EPA, 1993). Sludge normally contains up to around 3 % solids where as biosolids, normally contain between 15 % to 90 % solids. Fig. 1.1 shows the flow diagram for waste treatment process which involves three stages, called (a) primary, (b) secondary and (c) tertiary treatment.

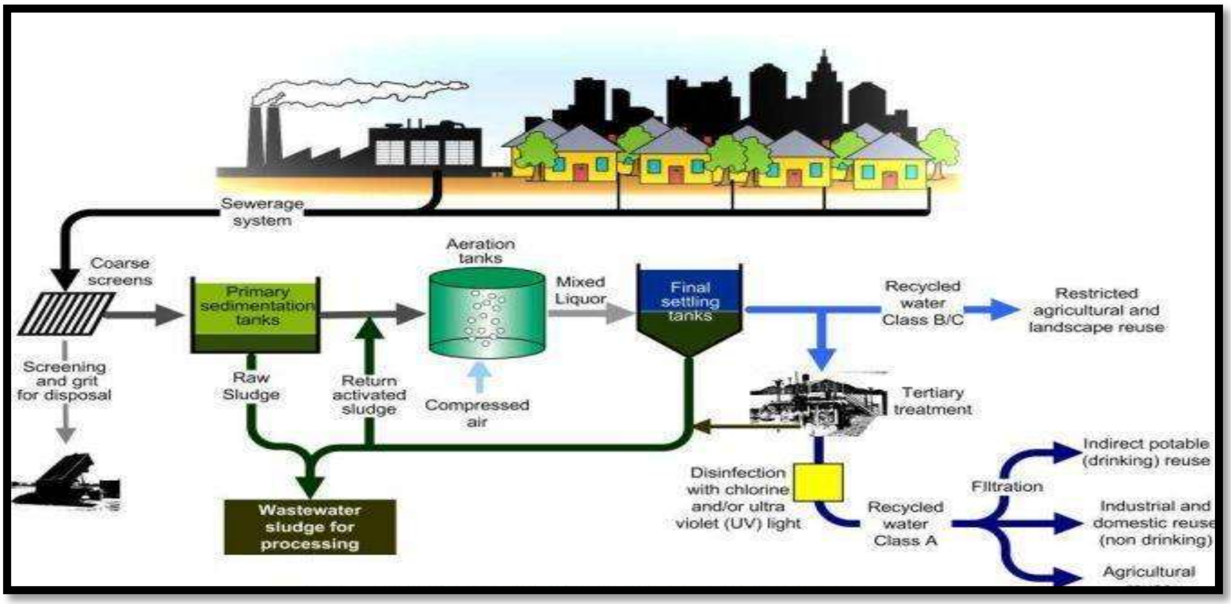


Fig. 1.1 Schematic shows Wastewater Treatment Process (Sharma, 2008)

Once the wastewater sewage is produced, it is then undergone further treatment which is known as stabilisation. Stabilisation accelerates the biodegradation of organic compounds present in biosolids, reduces the microbial population including pathogens and renders the material microbiologically safe for agricultural use. The final product obtained from stabilisation process is termed as “Biosolids” which is known as treated or stabilised sludge. Fig. 1.2 shows the process for biosolids generated from raw sewage sludges.

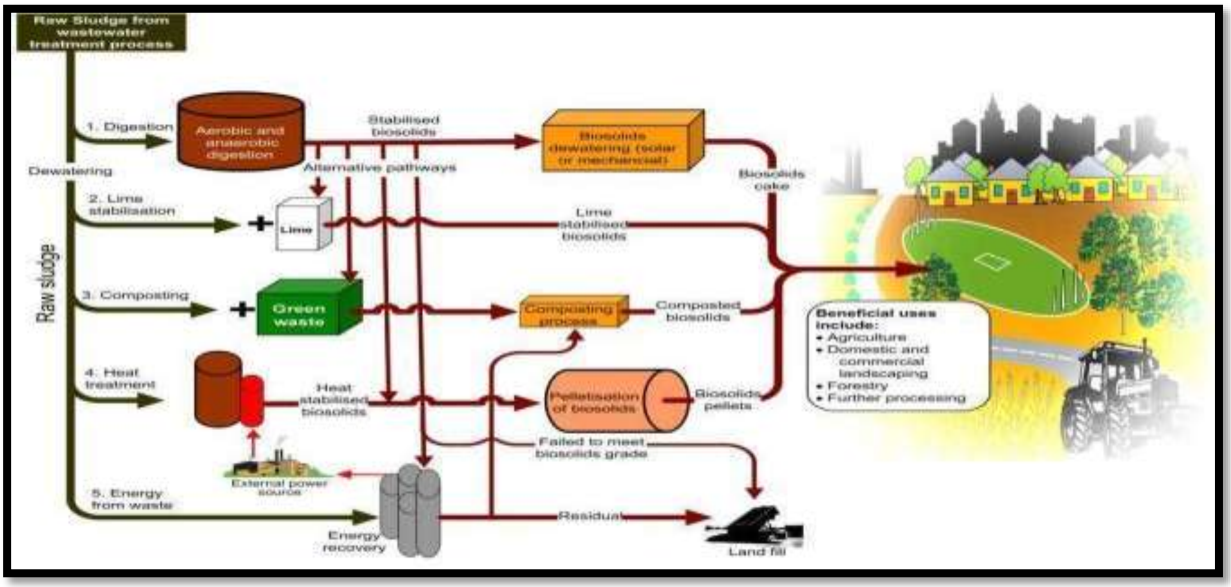


Fig. 1.2 Schematic shows Biosolids from raw sewage sludge (Sharma, 2008)

1.3 Biosolids Historical Background

Before the era of wastewater treatment, municipal wastewater was untreated and biosolids did not exist. As population grew, there is sharp surge in the quantity of waste production hence biosolids came into existence, which are an end product of the municipal wastewater treatment, largely composed of organic matter and nutrient-laden organic solids, and its consistency can range in form from slurry to dry solids, depending on the type of treatment.

As a result of above, EPA first developed biosolids management regulations under the 1972 Federal Water Pollution Control Act to prevent biosolids-borne constituents from entering the nation's navigable waters. EPA publication 943, Guidelines for Environmental Management: Biosolids land application, provides a framework for achieving safe and sustainable land application of biosolids. These Guidelines are focused on achieving safe and sustainable use of biosolids as a geotechnical fill required for construction projects such as in roadways, roadway embankments or building pads. To qualify for beneficial reuse, the biosolids will need to meet geotechnical standards required by the end user (EPA Victoria, 2009).

1.4 Identification of Problem

Arulrajah et al. (2013), Disfani et al. (2011) and Hoyos et al. (2011) reported that prior to 1998; sewage sludge or biosolids was primarily disposed into seawaters or was either used as a fertilizer on agricultural land. But at present due to enhancement in efficiency of modern wastewater treatment operations, it has led to the production of larger quantities of residuals, or biosolids. Thus, the sustainable usage of Biosolids in geotechnical engineering applications has considerable social and the economic benefits to industrialized and developing nations. Simultaneously, shortage of natural resources, lack of available land space and the increasing waste disposal costs, has placed higher urgency and pressure on recycling solid waste. Gomez et al. (2010) also reported that the production of dry biosolids ranges from 20 to 32.85 kg per person per year. During the last couple of decades there has been a major changes regarding the disposal of treated sewage sludge.

Arulrajah et al. (2013) reported that approximately 10 million dry tons of biosolids were stockpiled in Australia, and these stockpiles were increasing nationwide at a rate of approximately 0.4 million dry tons per annum. In the state of Victoria alone, 67000 dry tones of biosolids were produced annually and stockpiled in various wastewater treatment plants and were increasing annually with the population growth. So, reuse of waste materials in civil engineering application such as in road, pavements and footpaths offers a solution that can reduce the demand for scarce virgin natural resources and simultaneously reduce the quantity of waste materials which are destined for landfills. One of the surveys which have been carried out nationally on biosolids end use in Australia for year 2015 is presented in the chart as shown in Fig. 1.3. It was observed that there has been a decrease in stockpiling of biosolids down from 23% in 2010 and 20% in 2013 to 9% and a marginal drop in other unspecified and landfill end use of biosolids. There has been an increase in biosolids used for land rehabilitation (unmeasured in 2010 and up from 4% in 2013 to 16%) as well as an increase in biosolids used for agriculture (up from 55% in 2010 and 59% in 2013 to 64%). This indicates a significant shift towards greater beneficial use of biosolids in Australia.

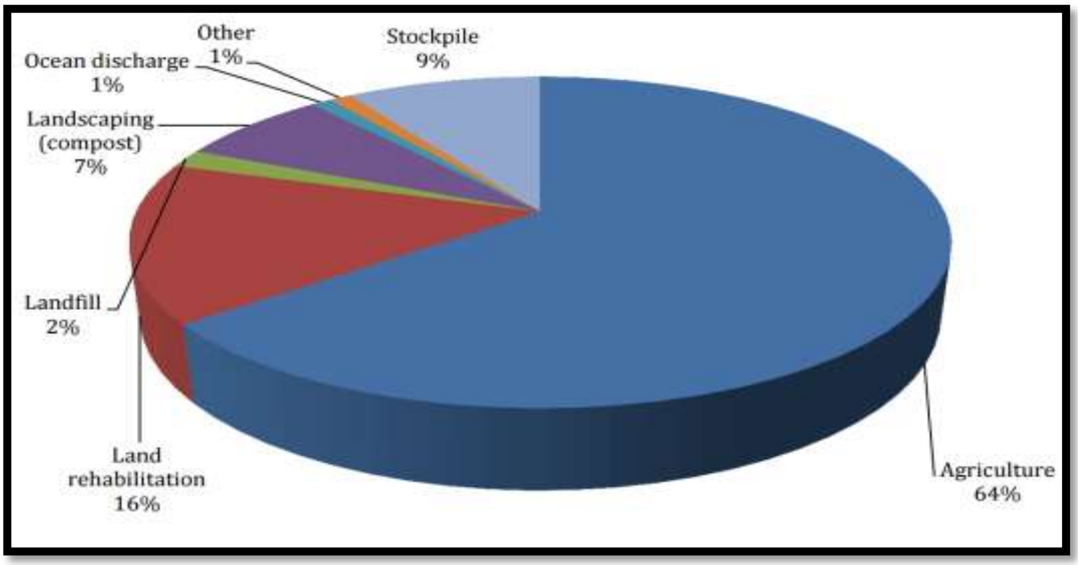


Fig. 1.3 Biosolids End Use in Australia

(Source: Australian Water Association, 2015)

In one of the few available studies on biosolids Hundal et al. (2005), Suthagaran et al. (2007), Suthagaran et al. (2008) and Suthagaran et al. (2010) assessed the geotechnical and geoenvironmental characteristics of untreated and stabilised biosolids with certain percentage of cement and lime, resulted in high shear strength and dry density to enable it to be considered as an engineering fill material in road embankment. In Victoria, to overcome the deficiencies of recycled glass and biosolids when used on their own and to enhance the strength properties of them, the innovative idea of mixing these two materials and their geotechnical properties were studied by (Disfani et al. 2009; Disfani et al. 2011; Disfani et al. 2012) and concluded that the mixture of biosolids and recycled glass showed satisfactory shear strength characteristics, thereby indicating the excellent potential of these mixtures to be used as an embankment fill material for roads. A study by Disfani et al. (2013) quantified the settlement characteristics of aged wastewater biosolids to facilitate its long-term biodegradation settlement prediction when used as fill material in road embankment applications. In this research a sensitivity analyses method was adopted to predict the biodegradation settlement of biosloids and analyze the factors which affecting the biodegradation process and proposed a framework to provide a guidelines for future end-users to calculate the total settlement of biosloids layers in embankment fill.

1.5 Organization of this report

This report is organized in fix chapters. The Chapter 1 of thesis provides a brief introduction of problem investigated and production and uses of biosolids. This chapter also provides an overview of historical background of biosolids.

In Chapter 2, a thorough literature review is conducted on the topic covered by this thesis and summarizes the objectives of the research conducted to address it. The literature review incorporated a review of existing publications of biosolids and also incorporated international experiences of work with biosolids as an engineered fill materials used in engineered fills.

This is followed by Chapter 3 which provides a description of the field site from where biosolids is procured. This chapter also discusses the methodology of conducting the extensive suite of laboratory test on untreated biosolids followed by theoretical modeling for the prediction of long term settlement due to biodegradation in an embankment using biosolids.

The chapter 4 emphasizes on the results obtained from the laboratory testing and theoretical modeling. This chapter also deals with the validation of results.

Finally, Chapter 5 summarizes the conclusions of this research and provides recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter provides a review of existing publications as well as important literature pertaining to the history and theory of biosolids used in engineered fills. A review of geotechnical, chemical and biological characteristics of biosolids is provided. The review includes a description of biodegradation settlement of an embankment using aged waste water biosolids as well as the analytical model to study the rate of biodegradation induced settlement. The chapter also includes the materials which are used for the improvement of mechanical behavior of biosolids for potential use in road fills and provides a framework for waste water biosolids settlement prediction. The review incorporated international experiences of work with biosolids as an engineered fill.

2.2 Geotechnical Characteristics of Biosolids

A review of past studies indicates that there are to date limited studies on the geotechnical aspects of biosolids have been published internationally but most reported investigative studies have been carried out in Australia. On the other hand the geotechnical aspects of sewage sludge have been extensively reported in various countries such as Hong Kong, Singapore, Turkey, the U.K., and the United States.

Koenig et al. (1996) presented the shear strength, hydraulic characteristics and consolidation properties of sewage sludge with the aim of predicting its behavior when applied in landfills. In addition, an attempt is made to establish a predictive relationship between various sludge characteristics.In this study they have found that consolidation behavior of sewage sludge follows conventional consolidation theory with higher values of compression index and compressibility factor in comparison with those for soils. The vane shear strength of the dewatered sludge from the different plants varied between 0.69 and 12.96 kN/m^2 for total solids (TS) contents of 13.05 to 22.90%. Permeability and intrinsic resistance are separately related to applied stress by a logarithmic relationship involving the compressibility coefficient.

Stone et al. (1998) studied the engineering and physical properties of sewage sludge which were collected from different sewage treatment plants in Trinidad were measured in the laboratory. The properties assessed were dry bulk density, porosity, water content, solids content, Atterberg limits, hydraulic conductivity, density-water relations, shear strength and compressibility. The finding of their research suggests that organic matter contained in sewage sludge can improve the physical properties of soil such as aggregate stability, water retention and infiltration and to reduce soil compactibility. The compressibility of the sludges defined in terms of a compression index increased from 0.50 to 1.02. The sewage sludge were found to display engineering behavior similar to mineral soils, differing only in the magnitude of the examined parameters.

Klein and Sarsby, (2000) carried out experimentation study which include consolidation and shear strength tests, in order to determine the geotechnical engineering and consolidation behavior of wastewater sludges and found that there is certain similarity in mechanical behavior of biosolids to that of highly organic clays in that biosolids possess high potential for excessive deformation. Klein and Sarsby (2000) concluded that once the sludge placed in landfills, it can be considered as geotechnical material similar to that normally consolidated cohesive material with high organic content.

Lo et al. (2002) studied the geotechnical properties of dewatered sewage sludge generated from Stonecutters Island treatment plant in Hong Kong. Compaction, consolidation, hydraulic conductivity and direct shear tests were carried out on the sludge mixtures. Results of compaction test indicate that dewatered sewage sludge exhibit compaction characteristics similar to that of clay soil. The consolidation behavior of sewage sludge does not follow the conventional Terzaghi's theory. Under an overburden pressure higher than 24 kPa, the relationship between the logarithm of the hydraulic conductivity and the void ratio is linear. Results from direct shear tests reveal that, for sewage sludge, slopes of 20° can probably be constructed during the landfill operation without causing sliding problems. Lo et al. (2002) confirmed the findings of Klein and Sarsby (2000**)** that sludge once placed in landfills can be considered as geotechnical material similar to that normally consolidated cohesive material with high organic content.

Reinhart et al. (2003) carried out the laboratory testing, geotechnical stability modeling of waste and economic analysis. The shear strength and compressibility properties of the municipal solid waste mixed with biosolids and lime sludge were determined. The large scale direct shear test and modified compaction test were conducted to determine the compressibility and strength characteristics of both municipal solid waste and the mixture of solid waste with biosolids and lime sludge. The laboratory tests showed that, the lime sludge had more inherent shear strength than biosolids where as geotechnical stability modeling showed that the addition of biosolids and lime sludge reduces the strength of the waste in the landfill. The stability of the landfill is adversely affected when the sludges are placed as discrete layers compared to their being placed as pockets. The economic analysis showed that landfilling of biosolids is less expensive than treating biosolids to Class A standards and land applying and nearly equal in cost to aerobic digestion of biosolids at 6% solids and land applying and lime stabilization of biosolids at 1.5% dry solids. The economics will improve if landfill owners reduce the tipping fees for biosolids, keeping in mind the fact that the savings due to the use of biosolids as a moisture source could offset the reduced tipping fee.

O'Kelly (2004) studied the various geotechnical characteristics of sludge collected from Tullamore wastewater treatment plant in the United Kingdome. The properties including compaction, compressibility, strength and other geotechnical properties and stated that the sludge material in various treatment plants can have different engineering properties due to different input levels of domestic and industrial wastewater. These properties were determined to assess its suitability as landfill material. In this study, sludge was dewatered to optimum moisture content for compaction, placed in landfill in layers and compacted to the maximum dry unit weight, thereby maximizing the operational life of the landfill site. The geometry of the landfill is of utmost important in terms of its suitability, therefore, effective-stress strength properties were used to determine the factor of safety (FOS) against the slope stability of the landfill.

Vajirkar (2004) has reported on the strength characteristics of biosolids mixed with municipal solid waste based on cone penetration test which was carried out in Florida, USA. The shear strength parameters obtained from the CPT data are then used to study the stability

of different slope configurations of the landfill. Based on the field investigations, the angle of internal friction was found to be about 29°and the determination of any cohesion was not possible. From the slope stability study, it was found that the factor of safety reduces significantly with the introduction of biosolids due to a reduction in shear strength and increase in the overall moisture content. From a parametric study, the stability of a 1:2 side slope with an angle of friction lower than about 20° was found to be less than the safe limit of 1.5. In addition, the factors of safety for landfills with trenches extending close to the edges of the slopes were also found to be unsafe and this situation needs to be avoided in practice.

O'Kelly (2005) investigates the consolidation properties of a dewatered municipal sewage sludge using the oedometer, hydraulic consolidation cell and Triaxial apparatus. Stabilized test specimens of dried-compacted material and slurry material at different states of biodegradation were consolidated under applied stresses of (3–400) kPa. The oedometer test indicates that the primary consolidation was dominant during the early compression of the slurry with a coefficient of permeability value of the order of (10–9) m/s and became more difficult progressively. Below about 650% water content, the sludge material became impermeable for practical purposes, with secondary compression due to creep deformation and biodegradation of the solid organic particles dominant. However, the material was extremely compressible with C_{sec} = 0.02–0.08 from multiple-increment oedometer tests (σ_a = 3–400 kPa).

Chu et al. (2005) has reported on the consolidation properties of cement-treated anaerobically digested sewage sludge in the Republic of Singapore with the use of prefabricated vertical drains. Chu et al. (2005) have reported on the geotechnical properties of sewage sludge in Singapore and proposed the option of using cement-treated sewage sludge as a fill material for land reclamation activities in Singapore. Pore pressure dissipation of the sewage sludge was measured during the consolidation process in a large-consolidometer to enable the consolidation around prefabricated vertical drain to be studied. Ordinary Portland cement and hydrated lime were used as binder materials for the consolidation test using an initial sample height of 450 mm. A settlement of 298 mm was measured using the large consolidometer for the test that lasted 550 hours.

Hundal et al. (2005) studied the geotechnical parameters of untreated biosolids which was collected from municipal wastewater treatment plant in Chicago in terms of their strength, compressibility, consolidation and physical properties. Bearing capacity of biosolids was determined by Illinois bearing ratio (IBR) test which varied from 1.6 to 4.8 and concluded that the biosolids are suitable fill material for embankment construction and their bearing capacity can be increased by blending them with top soil or other waste material.

Golder Associates (2006) reported that, clay-rich biosolids samples were collected from the Eastern Treatment plant (ETP), Victoria and the samples were used for various testing purposes. Bulk sample were collected from the top, middle and bottom of the each stockpile by digging test pits with excavators. The laboratory results of these tests indicate that the moisture content of many of the samples recovered from the stockpiles in the Eastern Treatment Plant (ETP), Victoria were above optimum moisture content and suggested that the addition of lime is most effective where the moisture content is close to optimum moisture content (dry biosolids material). The difference between average and optimum moisture content of dry sample is 12.5% for 0% lime addition and the moisture content reduces to 8.7% for 5% lime addition. The addition of lime to wet biosolids material was reported to be ineffectual in reducing the moisture content. The difference between average and optimum moisture content of wet sample is 21.8% for 0% lime addition and 19.0% for 5% lime addition. Similarly, the unconfined compressive strength (UCS) of the modified biosolids increases with the percentage of the cement.

Hyun et al. (2007) analyzed the long term settlement of the municipal solid waste landfill by various settlement estimation methods. Their research was based on the fact that in municipal solid waste landfill, settlement caused by the decomposition of biodegradable solid waste takes place over a long period, and this settlement contributes to the total settlement. The findings of their research suggested that the fill age of a municipal solid waste landfill is a critical factor for evaluating the long term settlement caused by decomposition. Their research showed that for the fresh municipal solid waste landfill (fill age less than 5 years) all methods predicted that the long term settlement potentials are (20 to 60) % of the thickness of the landfill. However, the long term settlement potential rapidly decreased for the intermediately old sites (fill age around 8 years old) and this decreased long term settlement potential is more noticeable in the old sites. Therefore, it was shown that fresh municipal solid waste landfill had more potential of long term settlement caused by the decomposition of biodegradable organic solids. For the sites with fill age of 25 years, the possible long term settlement was estimated to be less than 5% of the fill thickness.

Puppala et al. (2007) presented the physical and engineering properties of cohesive soil supplemented with biosolids and dairy manure and concluded that the biosolids and the dairy manure compost could provide the engineering benefits to control soil, because the physical and engineering properties are directly related to the amount of organic matter present in the biosolids and dairy manure.

Suthagaran et al. (2008a) this study was conducted in order to evaluate the potential use of biosolids as fill material in road embankment. Laboratory and field tests were conducted in this study in order to evaluate the geotechnical properties of biosolids samples obtained from a waste water treatment plant in Victoria. Based on field tests the consistency of biosolids in the stockpiles was found to vary from firm to very stiff and considered a fairly consistent material in geotechnical terms. CBR results for untreated biosolids as well stabilised with 1%, 3% and 5% of cement was found to vary between (0.8 to 1.1)% and (1.7 to 2.0) %which was obtained from standard laboratory CBR test. The results indicates that stabilised biosolids with 3% and 5% cement satisfy the VicRoads requirement for Type B fill material which indicates the potential for reuse of biosolids as a construction material for embankment fill.

Suthagaran et al. (2008b) assessed the geotechnical characteristics of untreated and stabilised biosolids with certain percentage of cement. In this study In-situ CBR values were obtained from the dynamic cone penetration test and results ranged between (2 to 19) % for the biosolids in the stockpiles. Laboratory CBR values for treated biosolids with 5% cement showed values of between (3.8 to 4.6)% using the standard CBR test and it was found that treated biosolids with 5% cement would meet the requirements of the local roadwork specifications. The laboratory and field testing results both indicate the potential for reuse of biosolids as a construction material for embankment fill.

Asakura et al. (2009) studied the geotechnical properties of sewage sludge and the sludge blended with other waste materials in order to determine the allowable ratio of sludge required to ensure an aerobic zone in the landfills in Japan. The geotechnical properties of sludge include moisture content, loss on ignition, bulk density, particle density, particle size distribution, OMC , MDU were determined. In this study they developed a method to improve sludge permeability, by adding slag, C&D waste to sludge. In regard to Slag and construction and demolition, when volumetric Slag or C&D content mixed with Sludge was increased from 62% to 75% whereas saturated hydraulic conductivity and gas permeability were increased by approximately 10 (construction and demolition) and 200 (Slag) times and by more than 100 (C&D) and 400 (Slag) times, respectively.

Disfani, M.M. et al. (2009) has given the innovative idea of mixing the recycled glass and biosolids in various ratios in order to overcome the deficiencies of recycled glass and biosolids when used on their own and to enhance the strength properties of them in Victoria. The findings of their research suggested that the mixture of biosolids and recycled glass showed satisfactory shear strength characteristics, thereby indicating the excellent potential of these mixtures to be used as an embankment fill material for roads.

Arulrajah et al. (2011) assessed the geotechnical properties of biosolids obtained from wastewater treatment plant in Melbourne, Australia. The laboratory test results indicate that the wastewater biosolids show high moisture content, liquid limit and plasticity indices comparable to common organic soils. The biosolids samples were found to be classified as OH according to USCS. The specific gravity of biosolids found to be lower than that of natural inorganic soils. Compaction tests results indicate that MDD varied only slightly with the OMC changes. The MDD of biosolids is half and the OMC is (2-3) times that of other natural inorganic soils. The consolidation characteristics of biosolids indicate that biosolids have similar behavior to organic clays but with higher consolidation potential.

Wanigaratne and Udamulla, (2012) A series of laboratory tests including index properties, particle size distribution tests, compaction tests and CBR tests were conducted on biosolids to assess whether it could be used in embankment fill material. The geotechnical tests on untreated biosolids showed that the dry density requirement was not satisfied although the rest of the geotechnical properties were at acceptable level. Therefore, in the second phase of their study the biosolids were stabilised with crushed bricks and revealed that chemically and mechanically stabilized bio-solids have improved physical properties than untreated bio-solids. The addition of 30% crushed bricks can be used in Type I and Type II embankment fill material by applying an effort of 3929kN/m^3 according to the Sri Lanka RDA (Road Development Authority) specification indicating the potential for reuse of bio-solids.

Arulrajah et al. (2013) investigated the geotechnical and geoenvironmental parameters of wastewater biosolids in road embankment which were collected from wastewater treatment plant in the state of Victoria in Australia. Classification, compressibility, shear strength, and contaminant concentration tests were undertaken on several specimens from various stockpiles. The test results suggested that even though compacted biosolids specimens show high shear strength properties, the main issue would be the high potential of untreated biosolids to deform (settle) under the applied loads in both the short term and long term. This high potential to deform makes biosolids, in its untreated form, unviable for road work applications such as embankment fills. Biosolids as such will have to be stabilised with an additive or blended with a high quality material to enhance its geotechnical properties to enable it to be considered as an engineering fill material. The test results indicated that the biosolids samples collected from the wastewater treatment plant were classified as equivalent to organic fine-grained soils of medium to high plasticity with a group symbol of OH according to USCS. The biosolids samples were found to have high moisture content, liquid limit, and plasticity indices which are comparable to commonly found organic soils in nature. The specific gravity of biosolids was found to be substantially less than that of natural inorganic soils. The compaction tests results indicated that MDD varied only slightly with the moisture content changes. The dry unit weight of the compacted material was low in comparison with inorganic soils but was in line with the low particle density of biosolids. The consolidation tests indicate that biosolids have similar consolidation characteristics to organic soils with higher values for compression index as compared to naturally occurring soils, which suggests the high potential for deformation under applied loads for untreated biosolids. The low CBR test results indicate high deformation potential settlement of biosolids samples, which emphasizes the need to stabilize untreated biosolids prior to their usage in road embankment fills. Shear strength tests indicate that biosolids have shear properties similar to medium to high over consolidated clays. In regards to the environmental characteristics of biosolids, the heavy metals and other prime contaminants as well as the biological contaminants were found to be within the safe limits specified by EPAVictoria (2009) for usage in geotechnical fills. With regards to contaminants containing nitrogen, phosphorus, and total organic carbon, biosolids require special protection in the event there is potential leaching flow to adjoining water bodies

Disfani, M.M. et al. (2013) quantified the settlement characteristics of aged wastewater biosolids to facilitate its long-term settlement prediction when used as fill material in road embankment applications. The findings of their research showed that the time taken for the fully biodegradation process of a 0.5m biosolids layer in a 5m embankment fill clearly indicates sensitivity of pH value in the biodegradation process. The maximum rate of biodegradation process is expected at a pH value of 7(neutral). Increasing values of moisture content and temperature accelerate the biodegradation process while not affecting the attained biodegradation settlement after 100 and 160 years respectively. In this research a sensitivity analyses method was adopted to predict the biodegradation settlement of biosloids and analyze the factors which affecting the biodegradation process and proposed a framework to provide a guidelines for future end-users to calculate the total settlement of biosloids layers in embankment fill.

Disfani, M.M. et al. (2014) biosolids samples were collected from the stockpiles at the western wastewater treatment plant in Melbourne, Australia, were tested to determine their geotechnical characteristics in both untreated and stabilised conditions. Different proportion of fly ash and Bauxsol blended with biosolids and geotechnical tests were undertaken on the blended materials and results from laboratory tests were compared with local roadwork specification for embankment fill. The laboratory results indicate that the maximum dry density of biosolids increase with increasing the proportion of bauxsol and fly ash while subsequently decreasing the optimum moisture content of the stabilised biosolids compared with the untreated biosolids. The stabilisation of biosolids with additives significantly increases the CBR value of the biosolids specimens to the extent where they meet local road authorities' requirement for type B of fill material for road embankments. Reduction in the coefficient of consolidation and secondary compression values were noticed when additives were added to biosolids. In CU Triaxial tests, the shear strength of untreated biosolids was significantly improved by adding fly ash up to 10% content, while adding bauxsol was found to have negative effect on the shear strength.

Kayser et al. (2015) this study reports on the shear strength, settlement, leachate volume and composition of biosolids amended with fly ash (FA), KOBM, lime kiln dust (LKD) and smelter slag (WD) with and without addition of lime. The biosolids samples used in this study originated from a local wastewater treatment plant (WWTP) in Auckland, New Zealand. Experimental equipment involved specially developed bio rigs simulating different overburden pressures which are followed by a pilot scale study and the field tests to investigate time and scaling effects. Results of their study showed that the alkaline additives can enhance the shear strength and stiffness of biosolids but result in a more compressible material (larger settlements resulting in larger disposable volume of material). Strength measurements showed that independent of the testing method (unconsolidated undrained Triaxial or hand shear vane), FA and Lime mixtures (20% lime) showed the highest strength increase, followed by WD + L and KOBM mixtures (10% lime), with WD and LKD mixtures (0% lime) exhibiting the lowest increase. For FA and Lime mixtures, strength increase was mainly related to the formation of $CaCO_3$ which was favored under higher overburden pressure and drained conditions. Mixtures with a clear increase in strength with time, after the addition of additive, lead to a positive correlation between solid content and strength. While solids content may be positively correlated with the strength that it cannot be used solely for strength characterization of all biosolids, either amended or unamended, since the change in strength is highly depend upon the resulting chemical reactions involving a particular additive.

Ukwatta and Mohajerani, (2016) this paper deals with the geotechnical properties of samples of biosolids, which were collected at ETP-SP No.22 and WTP-SP No.10 in Melbourne. Various geotechnical tests including liquid limit, plastic limit, particle density, particle size distribution, organic content, and linear shrinkage were undertaken. The laboratory test showed that the ETP and WTP biosolids can be classified as silty sand (SM) and well-graded sand to silty sand (SW-SM), according to the Australian Standard. The organic contents of the ETP and WTP biosolids were 7% and 22.1%, respectively. Both the ETP and WTP biosolids samples as well as the soil sample are basically formed by silica, alumina, and ferric oxide. However, WTP biosolids contain a relatively higher percentage of

CaO and P_2O_5 compared to the ETP biosolids and the soil. The results of compaction test indicated that OMC and MDU of the ETP biosolids were linearly proportional to the organic content present in the biosolids-soil mixture. The OMC increased and the MDU decreased, as the percentage of the organic content increased in the mixture. Therefore, it can be concluded that the organic content and particle size distribution of the tested biosolids - soil mixtures had a considerable influence on their compaction characteristics.

2.3 Chemical Characteristics of Biosolids

Arulrajah et al. (2011) studied the chemical characteristics of biosolids collected from the western treatment plant in Melbourne, Australia. Results of comprehensive set of chemical experimentation indicate that the heavy metals and other prime contaminants were found to be within the safe limits specified by (EPA Victoria, 2009). Biosolids contaminants were classified based on BCC as either Grade C_1 limit or Grade C_2 therefore, these are deemed safe if BCC is below C_1 limit and can be used without any restrictions or unsafe if BCC is above C_2 limit. Biosolids within C_1 and C_2 limits can be used subject to specified guidelines (EPA Victoria, 2004).

Arulrajah et al. (2013) investigate the chemical characteristics of biosolids samples which were collected from the stockpiles in Australia, for the purpose of chemical testing. Samples were tested for different types of heavy metals, different forms of nitrogen, phosphorus, total organic carbon, DDT and its derivatives, and organochlorine pesticides. Chemical assessment tests indicated that heavy metals, dichloro diphenyl trichloroethane (DDT) and organochlorine pesticides concentration results were within acceptable limits specified by EPAVictoria (2009) for usage in geotechnical applications. With regards to contaminants containing nitrogen, phosphorus, and total organic carbon, the biosolids were found to require special protection in the event there is potential leaching flow to adjoining water bodies.

Kayser et al. (2015) residuals from wastewater treatment operations (biosolids) were mixed with lime, fly ash, lime kiln dust, or two smelter slags to assess their efficiency as potential stabilisation agents by assessing their effects on the shear strength, compressibility, and solids content of mixtures. In addition, the minerals formed and leachate produced during stabilisation was determined. Tests were performed to explore the change of the geoenvironmental properties of the amended biosolids, while under pressure, at different scales using laboratory, pilot and field scale tests. The biosolids samples used in this study originated from a local wastewater treatment plant (WWTP) in Auckland, New Zealand. Leachate volume, concentrations of DOC, calcium, copper, nickel and zinc were determined for the biorig and pilot scale experiments. Overall, Lime mixtures showed the largest production of leachate, followed by FA mixtures, with WD + L and LKD mixtures having the lowest rate of production. Leachate analyses showed that a lower mobility of Ca^{2+} can be related to higher strength readings, depending on the total amount of CaO available. Leachability of Ca^{2+} was also the main source of increase in leachate pH and DOC, which further related to increased solubility of Cu^{2+}, $Zn^{2+}$and Ni^{2+}. Nonetheless, concentrations were within the New Zealand regulatory limits for Class A landfills.

Ukwatta and Mohajerani, (2016) this paper presents some of the chemical properties of two samples of biosolids collected from Melbourne Water's Eastern Wastewater Treatment Plant (ETP) stockpile No. 22 and the Western Wastewater Treatment Plant (WTP) stockpile No. 10. Chemical tests comprising leachate analysis for heavy metals and chemical composition were conducted on the samples of biosolids. From an environmental perspective, all the samples of biosolids were found to be safe in terms of leaching for use as a landfill application material.

Wanigaratne and Udamulla, (2012) studied the chemical properties of biosolids collected at Biyagama Export Processing Zone in Sri Lanka. To be acceptable for geotechnical reuse, bio-solids must meet the heavy metal contaminant concentration. Bio-solids that exceed any of the contaminant listed are not permitted for geotechnical reuse in accordance with the Australian Environment Protection Authority (2009) guidelines. Heavy metal levels of the biosolids collected at Biyagama Export Processing Zone in Sri Lanka are lower than the Australian Guidelines for environmental management to be used as a geotechnical fill and therefore it is safe to use as a fill material.

2.4 Biological Characteristics of Biosolids

Arulrajah et al. (2011) assessed the biological characteristics of the biosolids collected from the western treatment plant in Melbourne, Australia. In regards to the biological contaminants, the biosolids tested were found to be within safe limit as prescribed by EPA Victoria (2004).

Arulrajah et al. (2013) environmental assessment tests indicated that the concentration of pathogens (bacteria, viruses, or parasites) results were within the highest treatment grade, which indicates that the biosolids were within acceptable limits specified by EPAVictoria (2009) for usage in geotechnical applications.

Wanigaratne and Udamulla, (2012) investigate the pathogen levels of BEPZ biosolids which showed that concentration of pathogens in biosolids are lower than that of USEPA standards and therefore it is safe to use as a fill material. It was seen that the after 40 days of drying period the fecal coliform content decreased to (1.1 X 10^3 MPN/g) which is within the limit of USEPA class B bio-solids (2 X 10^6 MPN/g). After 50days of drying period the fecal coliform content decreased to 7 X 10^2 MPN/g which is within the limit value of USEPA class (A) bio-solids (less than 1000MPN/g). These values ensure that pathogens have been reduced to levels that are unlikely to pose a threat to public health and environment under the specific use conditions. It is also revealed that salmonella was absent in bio-solids analyzed. Even though bio-solids satisfy the environmental standards, it is recommended to use adequate clay lining to reduce the heavy metals and pathogens leaching to environment.

2.5 Summary of Literature Review

The literature survey on biosolids as fill material reveals that very few studies are presently available. The current knowledge of the engineering properties of human waste biosolids is relatively limited or unknown, while several studies on engineering properties of sewage sludge are available. From the literature review in this chapter, it can be concluded that the compacted biosolids show high shear strength and poor drainage characteristics, makes it enable to be used as fill material in road embankments. Similarly, the consolidation characteristics of biosolids indicate that biosolids have a similar behavior to organic soils, but with a higher compression potential.

It can further be concluded that the biosolids stabilized with an additive or blended with a high quality material can enhance its geotechnical properties as well as reduce the possibility of untreated biosolids to deform (settle) under applied loads in both the short term and long term. In regards to the environmental and chemical characteristics of biosolids, the heavy metals and other prime contaminants as well as biological contaminants were found to be within the safe limits for usage in geotechnical fills. Hence it is concluded that before using the untreated as well stabilized biosolids in embankment fills, their geotechnical, and chemical and environmental characteristics must be investigated.

2.6 Objectives

Based on literature review, the following objectives were determined

1) Study of geotechnical properties of biosolids.
2) Study the chemical properties of biosolids.
3) Prediction of Long term biodegradation settlement of the wastewater biosolids in road embankment by applying an analytical model.
4) 4) Assess the viability of biosolids as fill material in road embankment.

CHAPTER 3

METHODOLOGY

3.1 General

This chapter discusses the methodology followed in conducting the laboratory tests on untreated biosolids samples to determine the geotechnical and chemical properties followed by the theoretical modeling for long term settlement prediction for wastewater biosolids in road embankment. Laboratory tests were performed according to the Indian Standards (IS: 2720) methods of testing soil for engineering purposes. The geotechnical laboratory tests were conducted at Jaypee University, Waknaghat, Solan. Fig. 3.1 shows the flow diagram of research methodology adopted in this report in order to accomplish the project.

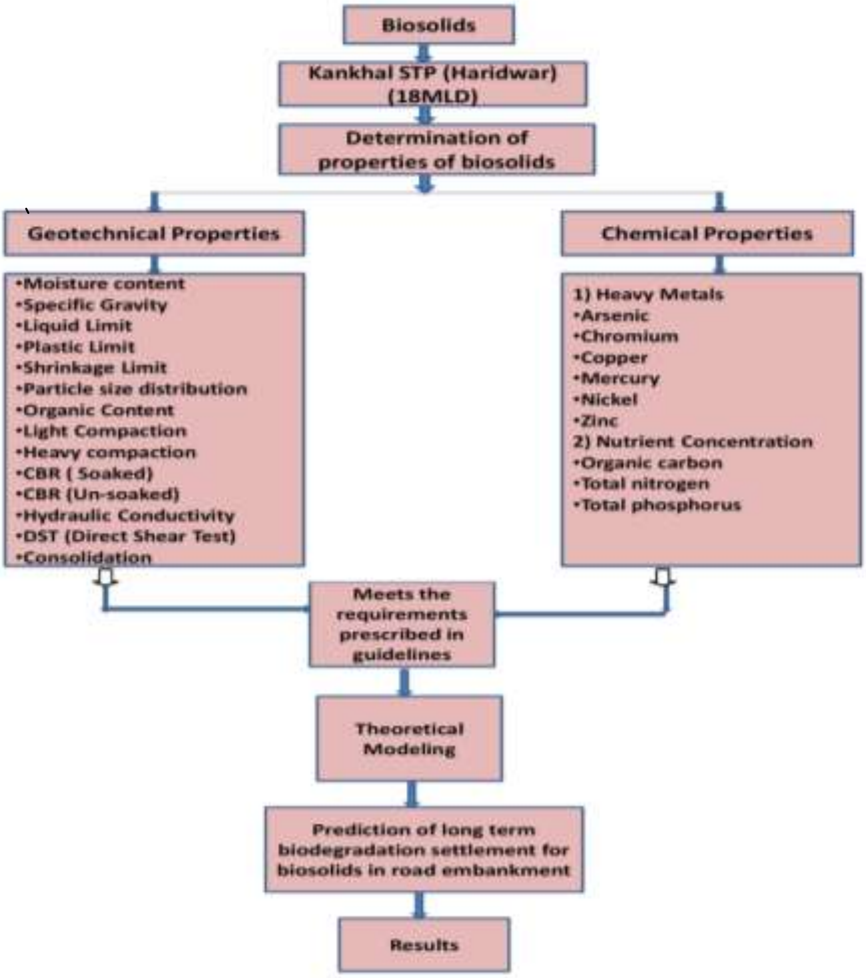


Fig. 3.1 Flow diagram showing research methodology

3.2 Procurement of Biosolids

The Biosolids Stockpile Area is located at the Kankhal Sewage Treatment Plant in Haridwar, Uttarakhand. The capacity of STP is 18 MLD and it is based on the Activated Sludge Process which is adjacent to capacity of STP 27 MLD based on Cyclic Activated Sludge Process (i.e. advanced SBR). The Biosolids Stockpile Area as shown in Fig. 3.3 is approximately 168 m^2 in size and is located on both sides of the Sludge Drying Pans (SDP) 1-12. Fig. 3.2 shows the location of wastewater treatment plant in Haridwar, India.

Fig. 3.2 Location of the Wastewater Treatment Plant (Source: Google Map)

Following the construction, approximately 1900 m^3 of biosolids were harvested from (12) existing Sludge Drying Pans per year and stockpiled in the Biosolids Stockpile Area. The biosolids originating from the existing Sludge Drying Pans (1-12) shown in Fig. 3.4 was used in this research project. The biosolids were stockpiled in the Biosolids Stockpile Area for approximately three months prior to sampling. The Biosolids Stockpile Area was constructed with provision for the stockpiling up to 2 rows of biosolids stockpiles in 6 meters high and separated by access roads. Fig. 3.2 shows the location of wastewater treatment plant in Haridwar, India.

Fig. 3.3 Biosolids stockpiles **Fig. 3.4 Sludge Drying Pans**

3.3 Laboratory Testing Methodology

This section discusses the methodology of conducting the extensive suite of laboratory test which includes geotechnical, chemical and physicochemical tests on untreated biosolids.

3.3.1 Geotechnical Characteristics of Biosolids

Properties of biosolids are somewhat unique as an engineering material. Some of the engineering properties of biosolids that are of particular interest when it is used as a highway embankment or fill material are its moisture density relationship, particle size distribution, shear strength, compressibility and permeability. As embankment fill is typically an earthen material which is used to create a strong and stable base and are usually constructed by compacting earthen materials. Therefore, compaction and permeability are very important for good performance of the embankment. The following sections describe the geotechnical properties comprises index and engineering properties of biosolids which are determined using standard methods on a laboratory scale.

3.3.1.1 Moisture Content

The moisture content (or water content) is the ratio of the mass of water to the mass of the biosolids sample. The moisture content of the biosolids was determined using IS: 2720 (Part II)-1973 “Determination of the moisture content of a soils – Oven dried method”. The oven drying method is a standard and very accurate laboratory method for the determination of moisture content. In this method, the biosolids sample was taken in a non-corrodible container as shown in Fig. 3.5. The mass of the sample and that of the container were obtained using an accurate weighing balance shown in Fig. 3.6. The biosolids sample in the container is then dried in an oven shown in Fig. 3.7 at a temperature of 60°C instead of the standard drying temperature of 105°C for a period longer than 24 hours because higher temperature is not suitable for biosolids as it contains significant amount of organic matter. At higher temperature, organic matter tends to decompose and get oxidized or this was to prevent drying and charring of the organic matter in the biosolids. When the biosolids has dried, it is then removed along with container from the oven and its weight was measured shown in Fig. 3.8. The observation table for moisture content of biosolids is given in Appendix (A.1).

Fig. 3.5 Empty Container

Fig. 3.6 Container + Wet Biosolids

Fig. 3.7 Oven

Fig. 3.8 Container + Dry Biosolid

Moisture content of the sample is calculated using equation (1)

$$\text{Moisture Content (\%)} = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \qquad \dots (1)$$

W_1= Weight of container (g)

W_2=Weight of container and wet biosolid (g)

W_3=Weight of container and dry biosolid (g)

3.3.1.2 Specific Gravity

Specific gravity is the ratio of the density of solid particles to the density of water. Particle Density can be measured by using any other liquid such as kerosene for soluble solid material. Kerosene was used to determine the specific gravity of biosolids, because it was identified as a partly soluble material in water. The specific gravity of the biosolids was determined using IS: 2720 (Part III/Sec1 & Sec 2)-1980 "Determination of the Specific Gravity– Fine grained soil (Density Bottle Method)" and "Determination of the Specific Gravity– Fine medium and coarse grained soil (Pycnometer Method)". The specific gravity of biosolids was measured using the small Pycnometer method as well as density bottle method. In density bottle as well as in Pycnometer method, the specific gravity of kerosene was first determined at 27^{o}C because it acts as a better wetting agent than water in case of organic soil and it was obtained from both density bottle and Pycnometer method and found to be 0.78. The observation table of specific gravity of biosolids and kerosene is reported in Appendix (A.2).

<u>Density Bottle Method</u>

In this method the density bottle of 50 ml and 25 ml was taken and were cleaned and dried. The mass of the bottle, including that of stopper, was taken. Take 10 g of oven dried biosolids in bottle and weigh shown in Fig. 3.9. The sample should be passed through 2mm IS sieve before use. Kerosene was then added to cover the sample. The sample was allowed to soak kerosene for about 2 hours until there is no further loss of air. Keep the bottle without stopper. More kerosene was added to the bottle to make it fill and then stopper was inserted in the bottle and its mass is taken as shown in Fig. 3.10. Now make the bottle empty, rinse thoroughly, fill it with kerosene and weigh its mass as shown in Fig. 3.11.

Fig. 3.9 Density Bottle +Biosolid

Fig. 3.10 Density Bottle +Kerosene +Biosolid

Fig. 3.11 Density Bottle+ Kerosene

The specific gravity of biosolid is then calculated using equation (2)

Specific Gravity of Biosloids (G_k) (at room temperature) = $\frac{W_3}{W_3+W_1-W_2}$ … (2)

W_1=Weight of (DB +Kerosene) (g)

W_2=Weight of (DB +Kerosene+BS) (g)

W_3=Weight of (BS) (g)

G_{BS} = Specific gravity of biosolids

DB = Density Bottle

BS = Biosolids

G_w = Specific gravity of water

This test gives the specific gravity of biosolids at temperature at which the test was conducted. Generally the specific gravity is reported at 27°C and 4°C (IS: 2720 Part-II). So, the specific gravity of biosolids at 27°C was determined using equation (3).

(G_k) at 27°C = $\frac{G_w \text{at (room temprature)}}{G_w \text{at (27°C)}}$ X G_k at (room temerature) ... (3)

<u>Pycnometer Method</u>

The procedure for the determination of specific gravity of biosolids using Pycnometer is similar to the density bottle method except that an oven dried biosolids approximately 200 g was taken as the capacity of Pycnometer is large. The process flow for the determination of specific gravity using Pycnometer method is shown in Fig. 3.12, 3.13, 3.14 and 3.15.

Fig. 3.12 Empty Pycnometer

Fig. 3.13 Pycnometer + Biosolid

Fig. 3.14 Pycnometer + Biosolid + Kerosene

Fig. 3.15 Pycnometer + Kerosene

The specific gravity of biosolid is then calculated using equation (4).

Specific Gravity of Biosolids (G_{BS}) at 27°C = $\frac{(W_2 - W_1)}{(W_2 - W_1) - (W_3 - W_4)}$ X G_k at 27°C … (4)

W1=Weight of empty Pycnometer (P) (g)

W2=Weight of (P+BS) (g)

W3=Weight of (P+ BS+ Kerosene) (g)

W4=Weight of (P +Kerosene) (g)

P = Pycnometer

BS = Biosolids

3.3.1.3 Grain Size Analysis

Particle size analysis consists of sieve analysis. Sieve analysis is used to determine the distribution of coarse fraction (>0.075mm) of biosolids. The coarse and fine fractions of biosolids were determined from particle size distribution curves. Sieve analysis was performed using IS: 2720 (Part IV) -1985, "Grain size analysis". In this method wet sieving of biosolids is carried out. About 200 g of air dried biosolid sample was taken passing through

4.75mm IS sieve. Submerge this biosolid sample in a mixture which contains 2 g of Sodium hexametaphosphate and 1 g of Sodium carbonate in one liter of water as shown in Fig. 3.16.

Fig. 3.16 Biosolids mixed with deflocculating agent

Mix should be thoroughly stirred with glass rod and left for submergence for about 2 hours. After sufficient period of submergence wash this sample on 75 µ IS sieve until the water passing the sieve is clear. Now take the fraction which is retained on 75 µ sieve and dry it in an oven at 60^{o}C for 24 hours. The portion which passes from sieve was allowed in the bucket to settle for 24 hours as shown in Fig. 3.17. After 24 hours of suspension remove the clear water gently so that the biosolids particle settled in the bucket does not flow with water. Now dry this portion of sample in an oven and kept it for hydrometer analysis. The fraction retained on75 µ sieve was then passes through the set of fine sieves. A set of fine sieves, consisting of the sieves of size 4.75 mm, 2mm, 1.18 mm, 425 µ, 300 µ, 150 µ, 75µ were used. The sample of biosolids was placed in the top sieve and the set of sieves was kept on a mechanical shaker as shown in Fig. 3.18. After starting the machine, about 15 minutes of shaking was done. After shaking the biosolid on sieve shaker, biosolids retained on each sieve was weighed. After getting the values, percentage finer was determined and results were plotted on the semi log graph sheet between particle size (mm) and percentage finer by weight (%) (N). The particle size distribution tests were performed on three different biosolids samples. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) values were determined and the average values are reported in Appendix (A.3).

Fig. 3.17 Arrangement for settlement of biosolids

Fig. 3.18 Mechanical shaker with set of sieve

C_u and C_c value can be calculated by using equation (5) and (6).

1) Coefficient of Uniformity (C_u) = $\frac{D_{60}}{D_{10}}$ … (5)

2) Coefficient of Curvature (C_c) = $\frac{D_{30}^2}{D_{60} \text{ X } D_{10}}$ … (6)

Where D_{60} = Particle size (i.e. 60% of the biosolids is finer than this size)

D_{10} = Particle size (i.e. 10% of the biosolids is finer than this size)

3.3.1.4 Atterberg Limit Test

Atterberg limits are used to define the consistency of biosolids and it comprises of liquid limit (LL) and plastic limit (PL). Liquid limit is defined as the threshold water content at which soil changes from the plastic state to the liquid state where as plastic limit is defined as the threshold water content at which a soil changes from the semi plastic state to plastic state. The Plasticity index (PI) is the difference between the liquid limit and plastic limit. Liquid limit was determined using IS: 2720 (Part-V) 1985, "Determination of the liquid– one point method (Casagrande apparatus) and plastic limit".

Liquid Limit of Biosolids

In this method about 120 g air dried biosolid sample was taken which was passed through 425µ IS sieve, thoroughly mixed with distilled water in an evaporating dish to form a uniform paste. A portion of the paste was then placed in the cup of the liquid limit device, and the surface was smoothened and levelled with a spatula to have a maximum depth 1cm. A groove was cut through the sample along the symmetrical axis of the cup in one stroke, using a Casagrande grooving tool. When biosolids pat has been cut, the handle was turned at a rate of 2 revolutions per second until the two parts of the biosolids sample come into contact at the bottom of the groove. Some amount of biosolids sample was taken near the closed grooved for water content determination, which was kept for 26 hours in an oven at 60^{o}C temperature. After the determination of water content, liquid limit was determined by plotting the graph on semi-logarithmic graph between the number of blows (N) as abscissa on a logarithmic scale and the corresponding water content as ordinate on linear scale. The water content corresponding to 25 blows show the value of liquid limit. The liquid limit test was performed on three samples of biosolids and the average value are reported in Appendix (A.4).

Plastic Limit of biosolids

For the determination of the plastic limit of biosolids, an air dried biosolids sample was taken which was passed through a 425µ IS sieve. About 30g of biosolid was taken in an evaporating dish and thoroughly mixed with distilled water till it becomes plastic and can be easily moulded with fingers. About 10 g of plastic biosolid mass was taken in one hand and a ball was formed. The ball was rolled with fingers on a glass plate to form a thread of uniform diameter of about 3mm, without crack formation. When the diameter of 3mm is reached, the biosolids was again remoulded into a ball. This process of rolling and remoulding was repeated until the thread starts just crumbled at a diameter of 3mm. The crumbled threads were kept for water content determination. The value of water content will gives the value of plastic limit. This test was repeated with two more samples. The plastic limit was then taken as the average of the three water content values. The observations and calculation of plastic limits of biosolids on three samples is given in Appendix (A.5).

3.3.1.5 Shrinkage Limit

A shrinkage limit test gives a quantitative indication of how much moisture can change before any significant volume change. Large changes in soil volume are important considerations for soils to be used as fill material for highways and railroads, or for soils that are to support structural foundations. Uneven settlement or lifting resulting from volume changes can result in cracks in structures or uneven roadbeds. Shrinkage parameters of untreated biosolids were determined according to IS: 2720 (Part -VI) – 1972, “Determination of shrinkage factors”. In this method about 30 g of biosolid sample was taken in an evaporating dish and mixed with distilled water somewhat greater than the liquid limit, to make a paste which can be placed in the shrinkage dish without any air voids. Take the shrinkage dish and measure its weight. Coat the inside of the shrinkage dish with a thin layer of Vaseline and place the biosolid specimen in the dish in three equal layers about one third the capacity of the dish at a time. Tap the dish until the biosolid is thoroughly compacted and add more biosolid sample and continue the tapping till the shrinkage dish is completely filled, and excess paste projects out about its edges. Weigh the dish with full wet sample and placed it in an oven at 60^0C for 24 hours. After sufficient drying period remove the dish from oven and measure its weight as shown in Fig. 3.19. Remove the dry pat from dish and determine its empty weight. Immerse the dry pat in the glass cup full of mercury and press it with prongs on the top of the cup as shown in Fig. 3.20. The observations and calculation of shrinkage limits of biosolids on three samples is given in Appendix (A.6).

Fig. 3.19 Weight of (SD + Dry BS)

Fig. 3.20 Dry BS pat immersed in glass of full mercury

Now transfer the mercury displaced by the dry pat to the mercury weighing dish and measure its weight which will give the volume of the dry pat i.e. mass of the mercury divided by the specific gravity of mercury as shown in Fig. 3.21. Take the shrinkage dish and fill it with mercury. Remove the excess mercury by pressing the plain glass plate firmly over the top of the shrinkage dish as shown in Fig. 3.22. Now transfer the mercury of the shrinkage dish to the mercury weighing dish and measure its mass which will give the volume of the shrinkage dish i.e. the mass of mercury in grams divided by the specific gravity of mercury.

Fig. 3.21 Weight of mercury displaced **Fig. 3.22 Shrinkage dish fill with mercury**

Shrinkage parameter of biosolids is then calculated by using equations 7, 8, 9 and 10.

1) Shrinkage limit of biosolids, SL = $\frac{(M_1 - M_s) - (V_1 - V_2)\rho_w}{M_s}$ … (7)

2) Shrinkage Ratio, SR (%) = $\frac{M_s}{V_2 \text{ X } \rho_w}$ … (8)

3) Volumetric Shrinkage, VS (%) = $\left(\frac{V_1 - V_2}{V_2} \right)$ X 100 … (9)

4) Linear Shrinkage, SL = 100 [1- $\left(\frac{100}{VS+100} \right)^{1/3}$] … (10)

M_1 = Initial wet mass of biosolids (g)

M_s = Mass of dry biosolids (g)

V_1 = Initial volume (cc)

V_2 = Volume after drying (cc)

P_w = Density of water (g/cc)

VS= Volumetric shrinkage (%)

3.3.1.6 Standard Compaction Test (Light Compaction)

Compaction refers to the removal of air voids from material by the application of mechanical energy. Basically there are two types of compaction methods available in engineering practices which are the standard and modified compaction. The compaction method is selected according to the engineering application of the material. The optimum moisture content (OMC) is the moisture content at which maximum dry density (MDD) will develop and this can be determined from compaction tests. The OMC and MDD are used to express compaction criteria for a material. Moisture–density relationships for biosolids were determined using standard proctor testing procedure in accordance with IS: 2720(Part-VII) 1980, “Determination of water content - dry density relation using light compaction”. In this method about 2 kg of air dried biosolids sample was taken and mixed with water in order to bring its water content to about 12%. The biosolids was thoroughly mixed and left for maturing for about 15 to 30 minutes. The mould for light compaction was dried, cleaned and greased lightly. The mass of empty mould with the base plate, but without collar, was taken as shown in Fig. 3.23. The collar was then fitted to the mould and mould was placed on a solid base and filled with fully matured biosolids to about one-third of its height. The biosolids was compacted by 25 blows of the rammer, with free fall of 310mm. The blows were evenly distributed over the surface. After completing the blow, the mould was again filled to about two-third height with the biosolids and it again compacted by 25 blows. Likewise, the third layer was placed and compacted in the same manner. After compaction the collar was rotated to break the bond between the biosolids in the mould and that in collar. The collar was then removed, and the biosolids was trimmed off with the top of the mould. The mass of mould, base plate and the compacted biosolids was taken as shown in Fig. 3.24, and thus the mass of compacted biosolids was determined.

Fig. 3.23 Empty mould +Base plate **Fig. 3.24 Mould +compacted BS +Base Plate**

The bulk density of the biosolids was computed from the mass of the compacted biosolids and the volume of the mould. Representative biosolid sample were taken from the bottom, middle and top of the mould for the determination of the water content. The biosolids removed from the mould was broken with hand and more water was added to the biosolids with 6% increment in water. When the water content of biosolids was obtained, the dry density was computed from the bulk density and the water content. After getting the values of dry density and water content, compaction curve is plotted between them and the value of MDD and OMC was determined form the curve. The observations and calculation for the determination of MDD and OMC of biosolids on three samples is given in Appendix (A.7).

The bulk mass density and dry density is then calculated using equation (11) and (12).

$$\text{Bulk Mass Density (g/cc)} = \frac{\mathrm{M}}{\mathrm{V}} \quad \ldots (11)$$

$$\text{Dry Density (g/cc)} = \frac{\text{Bulk Mass Density}}{1+\mathrm{w}} \quad \ldots (12)$$

Whereas, M= Mass of compacted biosolids (g)

V= Volume of mould (cc)

w = water content

3.3.1.7 Modified Compaction Test (Heavy Compaction)

Moisture–density relationships for biosolids were determined using standard proctor testing procedure in accordance with IS: 2720(Part-VIII) 1983, "Determination of water content - dry density relation using heavy compaction". In this method about 3 kg of air dried biosolids sample was taken and mixed with water in order to bring its water content to about 12%. The biosolids was thoroughly mixed and left for maturing for about 15 to 30 minutes. The mould for heavy compaction was dried, cleaned and greased lightly. The mass of empty mould with the base plate, but without collar, was taken as shown in Fig. 3.25. The collar was then fitted to the mould and mould was placed on a solid base and filled with fully matured biosolids. The biosolids was compacted by 56 blows of the rammer, with free fall of 450 mm. The blows were evenly distributed over the surface. After completing the blow, the mould was again filled with the biosolids and it again compacted by 56 blows. Likewise, the third, fourth and fifth layer was placed and compacted in the same manner. After compaction the collar was rotated to break the bond between the biosolids in the mould and that in collar. The collar was then removed, and the biosolids was trimmed off with the top of the mould. The mass of mould, base plate and the compacted biosolids was taken as shown in Fig. 3.26, and thus the mass of compacted biosolids was determined. The bulk density of the biosolids was computed from the mass of the compacted biosolids and the volume of the mould.

Representative biosolid sample were taken from the bottom, middle and top of the mould for the determination of the water content. The biosolids removed from the mould was broken with hand and more water was added to the biosolids with 6% increment in water. When the water content of biosolids was obtained, the dry density was computed from the bulk density and the water content. After getting the values of dry density and water content, compaction curve is plotted between them and the value of MDD and OMC was determined form the curve.

Fig. 3.25 Empty mould +Base plate **Fig.3. 26 Mould +compacted BS +Base Plate**

The bulk mass density and dry density is then calculated using equation (13) and (14).

Bulk Mass Density (g/cc) = $\frac{M}{V}$ … (13)

Dry Density (g/cc) = $\frac{\text{Bulk Mass Density}}{1+w}$ … (14)

Whereas, M= Mass of compacted biosolids (g)

V= Volume of mould (cc)

w = water content

3.3.1.8 Hydraulic Conductivity Test (Variable Head Permeameter)

Permeability is the ease with which water can flow through the medium. Knowledge of permeability is essential in respect of stability and settlement of structure. Thus, biosolids to be used as fill material in road embankment it becomes an important parameter to be determined as it affects the embankment construction and its performance quality. Falling head permeability test were undertaken on untreated biosolids samples according to IS: 2720

(Part-17)-1986, "Determination of permeability of a soil specimen by the variable head permeameter". In this method about 2 kg of biosolid sample was taken, mixed with quantity of water to achieve optimum moisture content. Place the sample into the permeameter mould and Compact it in three equal layers by giving 25 blows with 2.6 kg rammer on each layer. After completion of compaction measure the weight of mould and compacted biosolid as shown in Fig. 3.27. Place the porous stone on the drainage base and keep a filter paper on it. Now place the mould with compacted biosolid on the drainage base and attach the cap having saturated porous stone. Connect the reservoir to the outlet at the base and allow the water to flow upwards till it has saturated the sample .Disconnect the reservoir from the outlet at the bottom. Now connect the stand pipe to the inlet at the top and fill it with water. Open the stop cock at the top and allow the water to flow out till all the air in the mould is removed. After about 5 min close the stop cock and allow the water through the biosolid specimen as shown in Fig. 3.28. Select the heights h_1 and h_2 i.e. 10 cm and 40 cm measure above the centre of the outlet. Now open the valve and start the stop watch and record the time interval for the head to fall down from 10 cm to $\sqrt{10\ X\ 40}$ and also from $\sqrt{10\ X\ 40}$ to 40 cm. Repeat this step and note down the time interval for different heights. Stop the flow and disconnect the assembly.

Fig. 3.27 Weight of mould +BS

Fig. 3.28 Variable head permeameter assembly

The permeability of biosolid is then calculated using equation (15).

Permeability, k (cm) = $\frac{2.303\ a\ L}{A\ .t}\ \log_{10}(h_1/h_2)$ … (15)

Whereas, a = area of specimen (cm^2)

L = Length of standpipe (cm)

A = area of specimen (cm^2)

t = time (sec)

h_1 and h_2 = height (cm)

3.3.1.9 California Bearing Ratio Test (for soaked condition)

CBR test were conducted on untreated biosolids for four days soaked in water using standard compaction energy according to IS: 2720 (Part-16) -1986," Laboratory determination of California bearing ratio (CBR)- for soaked specimen". In this method take about 3kg of biosolid sample passing 20 mm IS sieve but retained on 4.75 mm sieve and compact it at optimum water content and the corresponding dry density as found by standard compaction test (light compaction). Fix the base plate to the bottom of mould and extension collar to the top. Now insert the spacer disc over the base with the central hole of the disc at the lower face. Place the filter paper on the top of the disc. Take biosolid sample in the mould and compact it using rammer having weight 2.6 kg in three equal layers, each layer is given 56 blows with drop of 310mm. After compaction remove the extension collar, base plate and spacer disc and measure the weight of the mould and compacted biosolid sample. Now place the filter paper on the base plate and invert the mould with the compacted sample as shown in Fig. 3.29. Apply a surcharge in multiples of 2.5 kg. The minimum surcharge applied was 5 kg as shown in Fig. 3.30. Now fill the tank with water in order to immerse the mould, test specimen and surcharge masses as shown in Fig. 3.31. Keep the mould in the tank undisturbed for 4 days. Maintain the water level constant in tank.

After 4 days take out the mould from the tank and allow the specimen to drain off for 15 minutes. Now place the mould containing specimen with the base plate on the lower plate of the loading machine as shown in Fig. 3.32. Place the 5 kg surcharge mass on the top of the soaked specimen. Now set the load dial gauge and the displacement dial gauge to zero. The initial load already applied to the plunger considered as zero. Now record the load corresponding to penetration of 0.0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, and 11.5mm. At the end of the test raise the plunger and remove the mould from the loading machine. The CBR values are usually calculated for penetration of 2.5mm and 5mm. So note down the penetration value corresponding to 2.5 and 5 mm. The observations and calculation of CBR test on three biosolid samples is given in Appendix (A.8).

Fig. 3.29 Base plate + Inverted mould with compacted biosolids

Fig. 3.30 Base plate + Inverted mould with compacted biosolids + Surcharge weight

Fig. 3.31 Soaking of specimen

Fig. 3.32 Schematic of CBR test

The CBR is then determined using equation 16 and 17.

$$1)\ \text{CBR (2.5mm) (\%)} = \frac{\text{Obsereved test load corresponding to 2.5mm}}{\text{Standard load for 2.5mm penetration}} \text{ X } 100 \qquad \ldots (16)$$

$$2)\ \text{CBR (5mm) (\%)} = \frac{\text{Obsereved test load corresponding to 5mm}}{\text{Standard load for 5mm penetration}} \text{ X } 100 \qquad \ldots (17)$$

Whereas, Standard load for 2.5mm penetration depth is equal to 1370 kg and for 5 mm it is equal to 2055 kg.

3.3.1.10 California Bearing Ratio Test (for unsoaked condition)

California Bearing Ratio is an indirect measure of shear strength. It is a penetration test meant for the evaluation of sub-grade strength of roads and pavements and useful to evaluate the suitability of biosolids as engineered fill material.CBR test were conducted on untreated biosolids on unsoaked specimen using standard compaction energy according to IS: 2720 (Part-16) -1986," Laboratory determination of California bearing ratio (CBR)- for unsoaked specimen". In this method take about 3kg of biosolid sample passing 20 mm IS sieve but retained on 4.75 mm sieve and compact it at optimum water content and the corresponding dry density as found by standard compaction test (light compaction). Fix the base plate to the bottom of mould and extension collar to the top. Now insert the spacer disc over the base with the central hole of the disc at the lower face. Place the filter paper on the top of the disc. Take biosolid sample in the mould and compact it using rammer having weight 2.6 kg in three equal layers, each layer is given 56 blows with drop of 310mm. After compaction remove the extension collar, base plate and spacer disc and measure the weight of the mould and compacted biosolid sample. Now place the filter paper on the base plate and invert the mould with the compacted sample as shown in Fig. 3.33.

Apply a surcharge in multiples of 2.5 kg. The minimum surcharge applied was 5 kg as shown in Fig. 3.34. Now place the mould containing specimen with the base plate on the lower plate of the loading machine as shown in Fig. 3.35. Place the 5 kg surcharge mass on the top of the unsoaked specimen. Now set the load dial gauge and the displacement dial gauge to zero. The initial load already applied to the plunger considered as zero. Now record the load corresponding to penetration of 0.0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, and 11.5mm. At the end of the test raise the plunger and remove the mould from the loading machine. Now draw the load penetration curve between load (kg) and penetration (mm) and determined the CBR values for penetration of 2.5mm and 5mm. The CBR values are usually calculated for penetration of 2.5mm and 5mm. The observations and calculation of CBR test on three biosolid samples is given in Appendix (A.9).

The CBR is then determined using equation 18 and 19.

1) CBR (2.5mm) (%) = $\frac{\text{Obsereved test load corresponding to 2.5mm}}{\text{Standard load for 2.5mm penetration}}$ X 100 … (18)

2) CBR (5mm) (%) = $\frac{\text{Obsereved test load corresponding to 5mm}}{\text{Standard load for 5mm penetration}}$ X 100 … (19)

Whereas, Standard load for 2.5mm penetration depth is equal to 1370 kg and for 5 mm it is equal to 2055 kg.

Fig. 3.33 Base plate + Inverted mould with compacted biosolids

Fig. 3.34 Base plate + Inverted mould with compacted biosolids + Surcharge weight

Fig. 3.35 Schematic of CBR test

3.3.1.11 Consolidation Test

Consolidation is the process of compression by gradual reduction of pores under a steady applied pressure. The main objective of consolidation test is to predict and estimate the rate and amount of settlement of embankment. The rate of settlement of biosolids depends on the rate of dissipation of pore water pressure created by the increased loading. One dimensional consolidation test was undertaken to evaluate the consolidation properties of the biosolids. One dimensional consolidation characteristics of biosolids were determined according to IS: 2720 (Part.15)-1986, "Determination of one dimensional consolidation properties of a soil". In this method dynamically compacted biosolids specimen was taken in which biosolids was compacted at optimum water content and the corresponding dry density as found by standard compaction test (light compaction) as shown in Fig. 3.36. Take the metal ring and measured its diameter, height and mass. Now press the ring into the compacted biosolids specimen with hands. Remove the biosolids around as well as top and bottom of the ring and measures the weight of ring and compacted biosolids as shown in Fig. 3.37

Fig. 3.36 Dynamically compacted specimen **Fig. 3.37 Weight of Ring + Compacted BS**

Saturate the porous stone, filter paper in distilled water for about 15-20 minutes as shown in Fig. 3.38. Assemble the consolidometer by placing the bottom porous stone, bottom filter paper, biosolid sample, top filter paper and top porous stone one by one as shown in Fig. 3.39.

Fig. 3.38 Saturated porous stone and filter paper

Fig. 3.39 Floating ring consolidation cell

Place the whole arrangement properly in position in the loading device. Level the loading beam as well as set the dial gauge in position. Now connect the mould assembly to the water reservoir for saturating the soil specimen. Apply an initial setting load of 5 kN/m^2 to the assembly. Allow the setting load to stand to attain an almost constant dial gauge reading as shown in Fig. 3.40. Apply the first load increment of 20 kN/m^2 and start the stop watch. Record the dial gauge reading at 0, 0.25, 1.0, 2.25, 4, 6.25, 9, 12.25, 16, 20.25, 25, 36, 49, 64, 100,144, 196, 225, 256 and 1440 minutes. After taking readings increase the load to apply a pressure of 40, 80, 160, 320 and 640 kN/m^2. After the last load increment decrease the load to ¼ of the last load and allow it to stand for 24 hours and take the dial gauge reading. Repeat the procedure until the load is reduced to the initial setting load and keep it for 24 hours and finally take the dial gauge reading. After completing dial gauge observations dismantle the assembly and take the ring with specimen and measure its weight. Now draw the (e-log $\bar{\sigma}$) curve between void ratio (e) on arithmetic scale and pressure ($\bar{\sigma}$) (kN/m^2) on log scale as well as between $\sqrt{t}$ and dial gauge reading and ($\bar{\sigma}$)and void ratio (e). Determine the consolidation parameter form the curve.

Fig. 3.40 Consolidometer + Loading assembly

Consolidation parameter is then calculated using equation 20, 21 and 22.

1) Compression Index (C_c) = $\frac{e_i - e_f}{\log_{10}(\frac{\sigma_f}{\sigma_i})}$ … 20

2) Coefficient of Consolidation (C_v) (m^2/sec) = 0.848 $\frac{d^2}{t_{90}}$ … 21

3) Coefficient of volume change (m_V) (m^2/kN) = $\frac{\Delta H}{H_i} \cdot \frac{1}{\Delta\sigma}$ … 22

Whereas, e_i = Initial void ratio read from e-log p curve

e_f = Void ratio at final pressure

σ_f = Final pressure (kN/m^2)

σ_i = Initial pressure (kN/m^2)

ΔH = Change in thickness (m)

d^2 = drainage path (m)

$\Delta\sigma$ = Increment of pressure (kN/m^2)

H_i = Initial thickness of the sample (m)

3.3.1.12 Direct Shear Test (DST)

Shear strength of biosolids was determined according to IS: 2720 (Part-13) - 1986," Determination of shear strength parameters (Direct Shear Test)". Shear strength of any material is its maximum resistance to shear stresses just before the failure. In this method, sample was prepared by compacting the biosolids inside the compaction mould at optimum water content by using standard proctor energy. Now the biosolid specimen of size 60 X 60 X 25 mm were extracted from the compacted samples and placed inside the shear box. Attach the base plate to the lower half of the box and place the porous stone in the box. For drained test perforated grids were used. Now measure the weight of the base plate, porous stone and grid. Place the upper grid, porous stone and pressure pad on the specimen and mounted on the loading frame. The upper half is brought in contact with the proving ring. Fill the container with water in order to saturate the sample. Fit the dial gauge to the container to give shear displacement and other dial gauge was fitted on the recording yoke to record the vertical movement. Now slightly raised the upper box with the help of spacing screws and adjust the space between the two halves.

Place the loading yoke to apply normal stress of 25kN/m^2 and allow the sample to consolidate under the applied normal stress. Note the reading of the vertical displacement dial gauge. Remove the spacing screws and adjust the dial gauges and proving to read zero. Now apply the horizontal shear load and record the readings of the proving ring, horizontal displacement and vertical displacement dial gauge at regular time intervals. Continue the test till the specimen fails. Now repeat the test under normal stresses of 50, 100, 200, 400 kN/m^2. Now plot the graph between shear stress and normal stress in order to determine the shear parameters i.e. (c and φ').

3.3.2 Chemical Test

Biosolids samples collected from stockpiles were tested for different types of heavy metals and nutrients concentration. To be acceptable for geotechnical reuse, heavy metals present in biosolids must meet the contaminant concentration criteria as given by EPA Victoria (2009).

3.3.2.1 Heavy Metals

Biosolids samples were analyzed for 6 heavy metals (Arsenic, Chromium, Copper, Mercury, Nickel and Zinc) contents which may contains organic and inorganic compounds of heavy metals using atomic absorption spectrometer. To measure total metals, the biosolid sample was digested with strong acid which helps in converting any organic compounds to inorganic compounds. By digestion, that will dissolve almost all elements that could become environmentally available. For the digestion of the sample one gram (on dry basis) sample is digested with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2).

All dried biosolid samples (1.0+0.05 g) were ignited in a porcelain crucible at 400 °C in muffle furnace for 4 to5 hour. Then, the ignited samples were treated with 10 mL of HCl for one hour at 60 to 80 °C. The residues were digested with strong acids (HNO_3 and H_2O_2) using the Method (3050B) given by USEPA (1996). The final digested solutions were combined with the acid extract for high alkaline earth metals and diluted with de-ionized water. The diluted solution was filtered through glass fiber filter (0.45 μm) and is taken to atomic absorption spectrometer system where the concentration of heavy metals in biosolids is determined.

3.3.3 Physicochemical Test

The presence of the certain chemicals constituents which is in excess of permissible limits cause the deleterious effect on the foundation and damage caused by them may be visible even after decades when it may become irreparable. Therefore, it is necessary to estimate the chemical constituents expected in the soil mass existing within the vicinity of foundation so that protective measures may be adopted. Biosolids which is used as fill material in road embankment tested for pH value, organic content and electrical conductivity tests.

3.3.3.1 pH value of Biosolids

The hydrogen ion concentration is designated as its pH value. The pH value of a solution indicates its acidic or alkaline nature. The pH value of biosolids was determined by electrometric methods. This method is based on the principal that the solution to be tested can be considered as an electrolyte of a voltaic cell. In this method take about 40 g oven dried biosolids sample passing through 425µ sieve in a flask as shown in Fig. 3.41 and add 100ml of distilled water shown in Fig. 3.42. Now stir the solution carefully and allow it to stand overnight. Calibrate the pH meter using standard buffer solution as shown in Fig. 3.43. Wash the electrodes by distilled water and then gently immerse them in the beaker containing biosolids suspension. Three readings of the pH value were taken as shown in Fig. 3.44. After taking observations take both the electrodes out of the suspension and wash with distilled water.

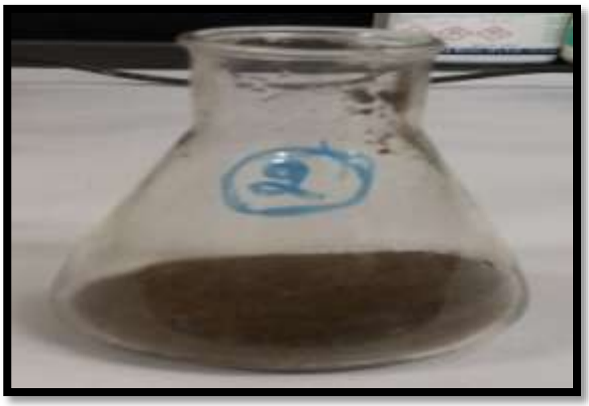


Fig. 3.41 Conical flask + Biosolids **Fig. 3.42 Conical flask + BS + Distilled water**

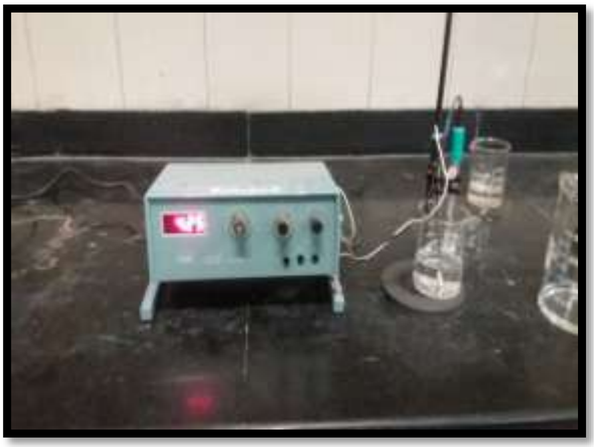


Fig. 3.43 Calibration of pH meter **Fig. 3.44 pH value of biosolids suspension**

3.3.3.2 Organic Content Test (Loss on Ignition)

The organic content is used as criteria for acceptability of materials for construction of road base and structural fills because it degrades over time results in production of gasses and settlement. Therefore, the organic content in biosolids was measured by LOI (loss on ignition) method by igniting dry powdered biosolids material in a muffle furnace at a temperature of 440^0C using (ASTM C- 2974) test method. In this method, about 10 g of the oven-dried moisture content specimen was taken in the porcelain crucible as shown in Fig. 3.45. The mass of crucible and biosolids sample is taken shown in Fig. 3.46. Now place the crucible and biosolids in a muffle furnace shown in Fig. 3.47. Bring the muffle furnace temperature up to 440^oC. Hold the furnace at this temperature until there is no change in mass, which usually takes 4 to 5 hours. Now remove the crucible from furnace and place it in a dessicator to cool shown in Fig. 3.48. After sufficient period of cooling measure the weight of crucible and biosolid ash. Place the crucible back in the muffle furnace for a period of at least one hour and measure the weight of crucible again. Repeat this step until there is no change in mass from the previous measurement. Now record the final weight of the crucible and ash.

Fig. 3.45 Weight of empty crucible

Fig. 3.46 Weight of (crucible + Biosolid)

Fig. 3.47 Muffle furnace

Fig. 3.48 Dessicator

The organic content of biosolids is determined using equation 23 and 24.

1) Ash content, AC (%) = $\frac{M_{ac}-M_c}{M_{bsc}-M_c}$ X 100 … (23)

2) Organic Content = 100-AC … (24)

Whereas, M_{ac} = Mass of crucible and ash (g)

M_{bsc} = Mass of crucible and biosolid (g)

M_c = Mass of crucible (g)

3.3.3.3 Electrical Conductivity

Electrical Conductivity of biosolids is a measurement which correlates several physical and chemical properties of biosolids such as soil texture, cation exchange capacity, drainage conditions, organic matter level, salinity etc. Electrical Conductivity is the ability of a material to conduct electric current through it. It is commonly expressed in milli Siemens per meter (milli S/m). In this method take about 10 g of air dried biosolids sample and add 50mL of deionised water as shown in Fig. 3.49. Now shake the solution atleast for 1 hour in order to dissolve the soluble salts. Calibrate the conductivity meter using KCl solution. Rinse the cell thoroughly and add the solution into the conductivity cell. Record the value indicated on the conductivity meter as shown in Fig. 3.50. Now rinse the cell with deionised water between samples.

Fig. 3.49 Flask + BS + Deionised water

Fig. 3.50 Conductivity meter

3.4 Theoretical Modeling

This section discusses the methodology and analysis of the long term biodegradation settlement prediction for wastewater biosolids when used as fill material in road embankment applications. Biodegradation of organic matter in biosolids results in increase in the void ratio and reduction in the structural strength of road embankment leading to a substantial loss of volume and settlement. The understanding of mechanism governing biodegradation settlement and the development of means to accurately predict the rate and the magnitude of settlement is an essential element in the design of road embankment using untreated biosolids.

3.4.1 Methodology

Prediction of settlement due to biodegradation is an important issue in order to evaluate its performance in various geotechnical applications and guarantee the integrity of load bearing structures such as fill material under pavements. A review of past studies indicates that there are to date limited studies on long term settlement prediction for wastewater biosolids in road embankments. Disfani et al. (2013) analyzed the biodegradation induced settlement of a road embankment built with aged biosolids by applying a mathematical model proposed by Chakma and Mathur (2007) used for municipal solid waste landfills.

However, for MSW landfills various estimation methods have been proposed to predict its long-term biodegradation settlement which was based on different theoretical and empirical models. Amongst the many empirical models available, an empirical model which is based on field data (Sower, 1973), a logarithmic function model (Yen and Scanlon, 1975), and a one dimensional consolidation model proposed by (Oweis and Khera, 1986) are some of the early models adopted by researchers to the MSW landfills settlement. Later, in the nineties, more empirical models such as a rheological model for the long-term compression in peat (Edil et al. 1990), a biologic model based on the Terzaghi's consolidation theory (Edgers et al. 1993), a hyperbolic function model (Ling et al. 1998) and a mathematical model proposed by (Park and Lee 1997, 2002) that considers the compression because of the decomposition of biodegradable organic solids have been developed. But it was observed that the existing models did not incorporate the effect of several parameters such as moisture content, bulk density, pH, and temperature for predicting settlement due to biodegradation. Thus, Chakma and Mathur (2007) proposed a mathematical model which incorporates the above mentioned parameters.

In this study, the long term settlement due to biodegradation for wastewater biosolids in road embankment was analyzed by adopting the Chakma and Mathur (2007) proposed mathematical model as well as model developed by Hettiarachchi et al. (2009). The results obtained from Chakma and Mathur (2007) developed model is then compared with the model proposed by Hettiarachchi et al. (2009). Chakma and Mathur (2007) modified model is presented in equation (25).

$$\frac{d(M_{si})}{dt} = [-\ k_j x\ \xi\ (T, pH, \theta) x M_{si}], \qquad (j=1, 2, 3, 4; i=1, 2, 3, 4) \qquad \dots (25)$$

Where (ξ) is the function of Temperature (T), pH and moisture content (θ) in fraction as defined by Chakma and Mathur (2007) and is presented in equation (26).

$$\xi\,(T, pH, \theta) = \frac{T \, X \, \theta \, X \exp\left(-0.288\,(pH-7)^2\right)}{1+\exp(0.25T-18)} \qquad \ldots(26)$$

whereas, M_{si} are the masses of different components of waste such as non- biodegradable (M_{S1}), slowly biodegradable (M_{S2}), moderately biodegradable (M_{S3}), and rapidly biodegradable (M_{S4}), with their respective rate constants k_1, $k_{2,}$ $k_{3,}$ k_4 .The decay rate of biodegradable waste (k) for non-biodegradable, slowly biodegradable, moderately biodegradable and rapidly biodegradable waste are categorized as 0.00 day^{-1}, 0.00001 day^{-1}, 0.0001 day^{-1} and 0.001 day^{-1}. The volume of waste (V_s) at time (t) can be calculated using equation (27) proposed by Chakma and Mathur (2007).

$$V_{s\,(t)} = \sum_{j=1}^{j=4} \frac{f_i \, X \, M_{si} \, X \exp\left[-\; k_j x \, t \, x \, \xi\,(T,ph,\theta)\right]}{\rho_j} \qquad \ldots(27)$$

Whereas, ρ_j = Density of waste material

f_i = Percentage of waste under different categories

M_{si} = Masses of different components of waste

Now the strain (ε_b) due to biodegradation is estimated by using equation (28) developed by Chakma and Mathur (2007).

$$\varepsilon_b\,(t) = \frac{V_i - V_s(t)}{V_i} \qquad \ldots(28)$$

Whereas, V_i = Initial volume of waste layer

Finally, the settlement at any time (t) due to biodegradation is then computed by equation (29)

$$S_b\,(t) = H_i \, x \, \varepsilon_b\,(t) \qquad \ldots(29)$$

where (H_i) is the initial thickness of waste layer

Hettiarachchi et al. (2009) proposed a model which can predict settlement at variable moisture and pressure conditions as encountered in bioreactor landfills. In this model mechanical compression of municipal solid waste was computed with the help of laboratory compression tests and the settlement due to biodegradation of MSW can be estimated by first order kinetics and is presented in equation (30).

$$(\Delta H)_b = \frac{M_{sj}}{\rho_w} \sum_{j=1}^{j=4} \frac{f_{sj}}{G_{sj}} \left(1\text{-}\exp^{-\lambda_j t}\right) \qquad \ldots(30)$$

where, $(\Delta H)_b$ = Change in height due to biodegradation (m)

M_{sj} = Masses of different components of waste (kg)

ρ_W = Density of water (kg/m^3)

f_{sj} = Solid fraction for each waste material group

G_{sj} = Specific gravity of different groups of waste material

λ_j = First order constant (decay constant) of each category of waste material (day^{-1})

t = time (days)

3.4.2 Analysis of biodegradation settlement

In road embankment using untreated biosolids, settlement will takes place over a long period because of the volume reduction due to the decomposition of organic solids present in the biosolids, and this settlement considerably contributes to the total settlement. Total settlement of biosolids in embankment fill applications comprises four components: immediate settlement, consolidation settlement, creep settlement and biodegradation-induced settlement. In the analysis of biodegradation settlement of untreated biosolids, four assumptions were made.

1) In the analysis of biodegradation settlement, biosolids taken in this study is considered as rapidly biodegradable as samples used in this research work were more than 5 months old which is believed to be under transitional and active biodegradation phase.

2) It is assumed that the percentage of biodegradable material in the biosolids layer is equal to the average organic content value as determined on a laboratory scale.

3) When the embankment construction is completed it is assumed that the biodegradation will occur concurrently with consolidation.

A typical road embankment using untreated biosolids geometry of 3m height has been considered and is shown in Fig. 51. Based on the guidelines specified by (VicRoads, 2007) the maximum allowable thickness of usage of biosolids in road embankment only (0.5-1) m, which is to be placed above design flood levels and above 1m of the subgrade level. In order to determine the biodegradation settlement of an embankment using untreated biosolids the thickness of biosolids layer is taken as 0.8m.

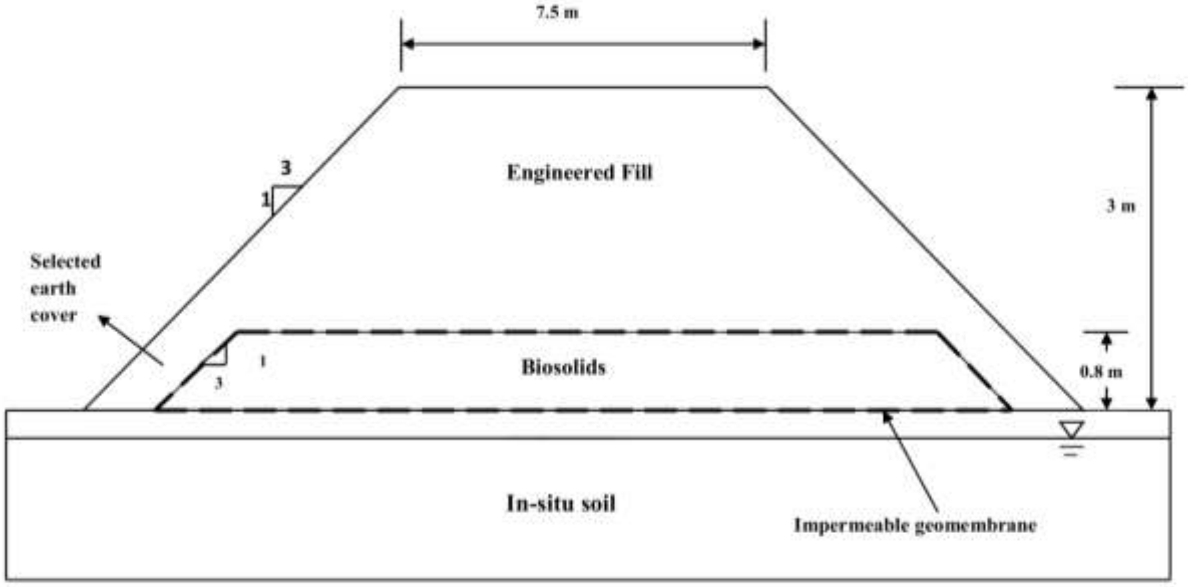


Fig. 3.51 Typical geometry of road embankment using biosolids for settlement analysis

The geometry of road embankment is based on guidelines specified by local road authority for the construction of earth embankment for road works. The embankment is to be built to side slope of 3H: 1V. This slope is recommended mainly from the consideration of safety of traffic. The top width of the embankment i.e. width of pavement is taken as 7.5m for two lanes as recommended by IRC. In view of environmental concern impermeable clay liner or geotextile separator is provided in order to prevent the groundwater as well as fill material due to the leaching or seepage of biosolids. The side cover is provided to prevent the erosion of biosolids particles. The thickness of earth cover depends upon the height of embankment i.e. upto 3m height of an embankment the thickness on the side slope should be about 1m. The sensitivity of biodegradation settlement of an embankment using biosolids with varying pH, moisture content (θ) and temperature (T) is carried out as well as the total settlement of biosolids layer due to primary, secondary consolidation and biodegradation is also computed.

3.4.3 Input Parameters of Model

Chakma and Mathur (2007) proposed a modified model which takes into consideration of pH, moisture content and temperature. These input parameters needs to be determined as biodegradation settlement of biosolids in road embankment mainly dependent on these factors. Along with these parameters organic content and electrical conductivity of untreated biosolids were determined in accordance with the Indian Standards on three samples of untreated biosolids which are explained in section 3.3.3 and are summarized in Table 3.1.

Table 3.1 Temperature, pH and electrical conductivity of biosolids

Untreated Biosolid Sample	Temperature (^{0}C)	pH	Organic Content (%)	Electrical conductivity (μS/cm)
BS-Sample 1	14.2	4.22	43.38	3510
BS-Sample 2	14.3	4.24	40.7	3550
BS-Sample 3	14.5	4.25	39.39	3530
Average	14.33	4.23	41.15	3530

For Chakma and Mathur (2007) modified model input parameters are taken as:

Temperature (T) = 14.33^{o}C

Moisture Content (θ) = 102 %~1.02

pH = 4.23

Initial Volume (V_i) = 16.88 m^3

Density of Biosolid (ρ_j) = 14.66 kN/m^3

Mass of Biosolid (M_{si}) = 247.46 kN

Percentage of biodegradable waste (f_j) = 41.15 %

Initial thickness of Biosolid layer (H_i) = 0.8m

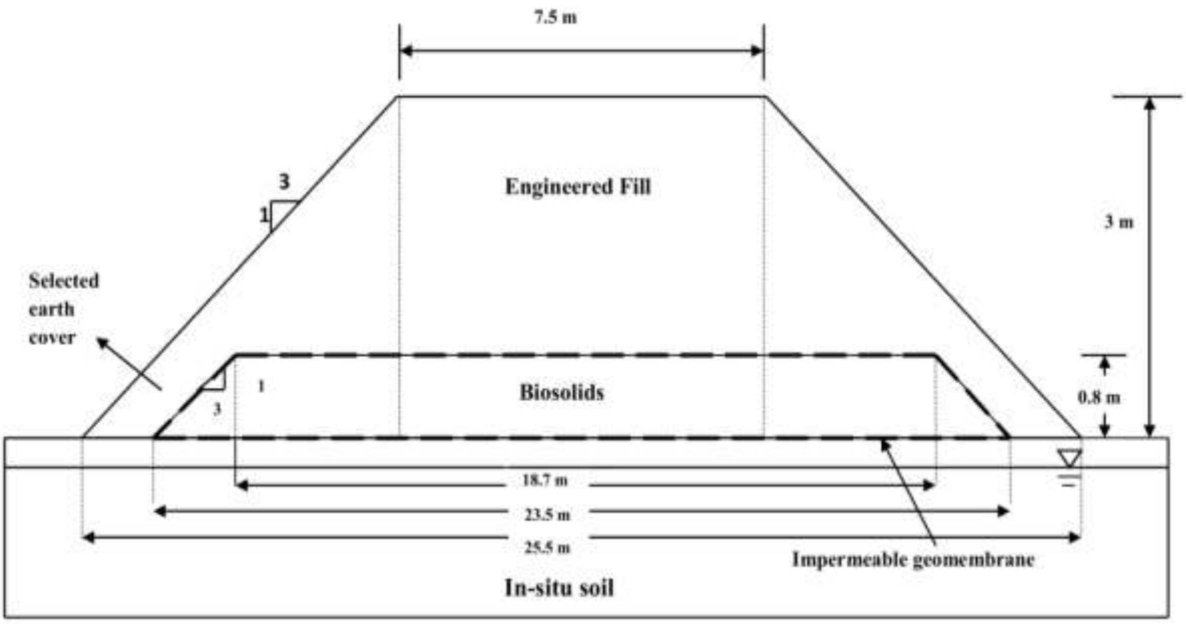


Fig. 3.52 Geometry of road embankment for settlement analysis

For Hettiarachchi et al. (2009) modified model input parameters are taken as:

Mass of biosolid (M_{si}) = 247.46 kN

Density of water (f_w) = 9.81kN/m^3

Specific gravity of biosolid (G_{sj}) = 1.35

Initial solid fraction for highly degradable waste (f_{si}) = 0.41

First order kinetic constant (decay constant) (λ_j) = 0.001 day^{-1}

CHAPTER-4

RESULTS AND DISCUSSION

4.1 General

Biosolids samples obtained from stockpiles at Biosolids Stockpile Area, Kankhal Wastewater Treatment Plant were tested to investigate the geotechnical, chemical characteristics of untreated biosolids and the suitability of biosolids as stabilised fill material. The biodegradation induced settlement of road embankment built with untreated biosolids is also analyzed by applying an analytical method. As per described methodologies the geotechnical and chemical test results are discussed as follows:

4.2 Geotechnical characteristics of Biosolids

4.2.1 Moisture Content

The natural moisture content of biosolids was found to vary between 100% and 105%. The observation and calculations of moisture content of biosolids is presented in Table 4.1. The moisture content was determined on the basis of the oven dry mass corresponding to a drying temperature of 60^{o}C instead of the standard drying temperature of 105^{o}C as prescribed in IS: 2720 (Part-II) -1973. This was to prevent drying and charring of the organic matter in the biosolids.

Based on the results the moisture content of biosolids was found to be very high due to their fibrous structure results in large voids and the high cation exchange capacity which increase the attraction of water molecules. Nature of the organic matter (humification) also leads to the high water content. The more humified the Biosolids, the smaller the water content or in other words the water content decreases with degree of humification (decomposition). The biosolids samples used in this research work were more than 5 months old, which means the biosolids are less decomposed leads to high water content.

Observations and Calculations

Temperature maintained in oven =60°C

Drying Period = 26 to 27 hours

Table 4.1 Moisture content of biosolids (Oven-drying Method)

Sample No	Moisture Content (%)
BS-1	103-105
BS-2	101-103
BS-3	100-102
Result	**100-105**

4.2.2 Specific Gravity

The specific gravity of biosolids was measured using density bottle as well as pycnometer method and was found to vary between (1.77-1.81) and (1.33-1.37). In this research work the value of specific gravity of biosolids obtained from Pycnometer method is taken because the density bottle method is suitable for fine-grained soils, with more than 90% passing 2mm-IS sieve whereas pycnometer method is used for medium-grained soils, with more than 90% passing 20mm-IS sieve. It was found during experiment that more than 90% of biosolids passed through 20mm IS-sieve and also pycnometer method was adopted in all previous research work done on the same topic. Kerosene was used instead of distilled water as the density fluid in the Pycnometer to prevent the dissolving of biosolids during the test. The observation and calculation of specific gravity of biosolids by Pycnometer method is given in Table 4.2.

Table 4.2 Specific Gravity of biosolids (Pycnometer Method)

Parameter	Sample 1	Sample 2
Weight of Pycnometer (W_1) (gm)	460.8	462.1
Weight of (P + BS) (W_2) (gm)	661.4	660.3
Weight of (P+ Kerosene+ BS) (W_3) (gm)	1109.3	1116.7
Weight of (P+ Kerosene) (W_4) (gm)	1026.2	1030.6
Sp. Gravity of BS (G_{bs}) at 27°C	**1.33**	**1.37**

The specific gravity of biosolids obtained is considerably lower than that of inorganic soil. Humification(decomposition) of organic content in the biosolids is the reason for lower specific gravity of biosolids which means fresh biosolids are less decomposed, contains high organic content will have low specific gravity and vice-versa. As biosolids studied in this research was fresh sample are less humified leads to lower specific gravity.

4.2.3 Grain size analysis

The size of individual particles has an important influence on the behavior of engineering properties. The particle distribution tests comprised of wet sieve analysis performed on three samples of biosolids using IS: 2720 (Part-IV)-1985 test method. Based on the gradation curve as shown in Fig. 4.1, the particle size distribution contents of the biosolids samples along with their coefficients of uniformity and curvature were calculated.

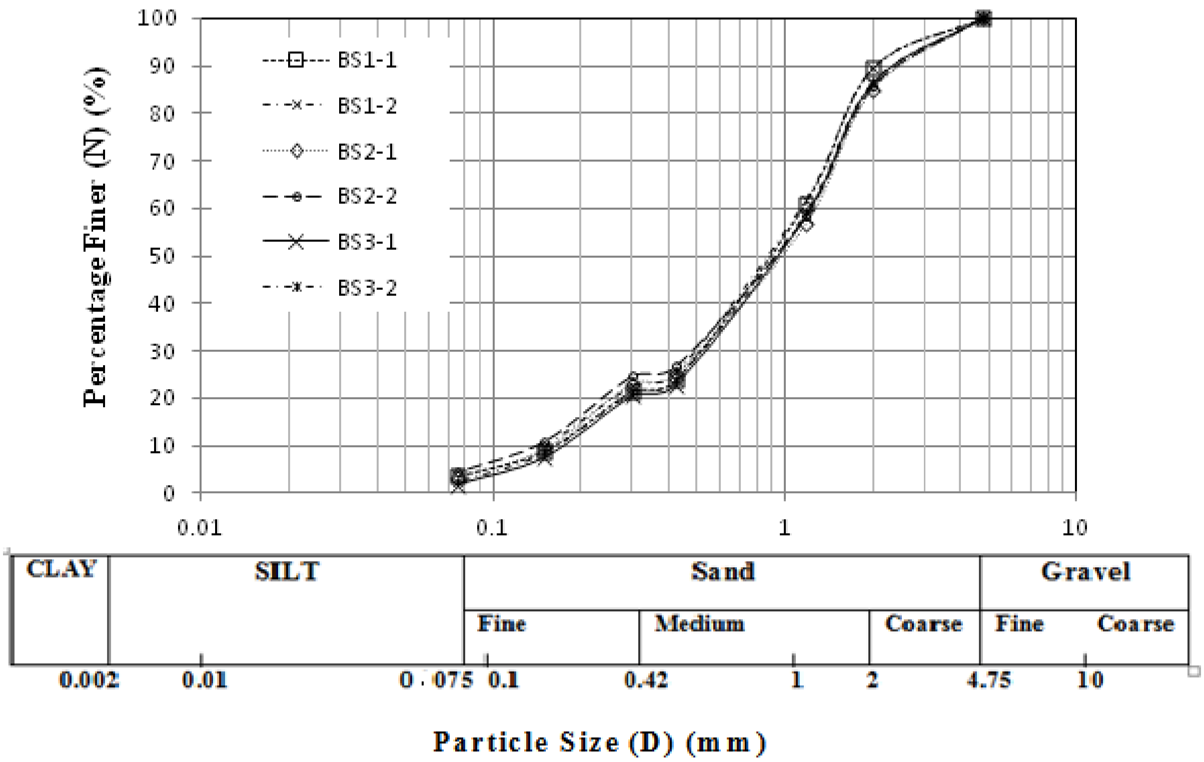


Fig. 4.1 Particle Size Distribution of Biosolids

The average value and range of coefficients of uniformity (C_u) and curvature (C_c) values are reported in Table 4.3. The higher value of the coefficients of uniformity shows the larger range of particle size in the biosolids.

Table 4.3 (C_c) and (C_u) values of biosolids

Sample No.	C_u	C_c
BS1-1	7.03	1.24
BS1-2	7.64	1.06
BS2-1	7.87	1.08
BS2-2	9.21	1.12
BS3-1	7.32	1.27
BS3-2	7.9	1.11
Range	(7.03-9.21)	(1.06-1.27)

The results indicate that around 85% of particles are coarse particles (between 0.075mm to 2 mm in size) are summarized in Table 4.4. Although these particles are categorized as coarse particles; in reality they are smaller organic-silt sized particles that have adhered and attached together during the stockpiling of biosolids as biosolids collected were more than 5 month old. Organic compounds present in biosolids are based on rings and chains of carbon atoms. When carbon atoms form bond to each other and other atom, will form a new molecular orbital which creates a force of attraction between the two atoms known as a covalent bond. Due to this an adhesive force is created which leads to binding of biosolids particle together during the stockpiling of biosolids.

Table 4.4 Range of particle size

	BS-1-1	**BS-1-2**	**BS-2-1**	**BS-2-2**	**BS-3-1**	**BS-3-2**	**Range**
Particle size > 2 mm (%)	10.5	10	14.9	14.3	13.7	13	(10 to 14.9)
Particle size between (0.075 and 2 mm) (%)	85.8	85	81.9	81.2	84.6	84	(81.2 to 85.8)
Particle size between (<0.075mm) (%)	3.7	5	3.2	4.4	1.7	2	(1.7 to 5)

4.2.4 Atterberg Limit Test

Atterberg limit test is carried out on air-dried biosolids in order to determine their plasticity characteristics. The Atterberg limit tests were performed on three samples of biosolids using IS: 2720 (Part-V)-1985 test method. For all Sample flow curve is plotted between number of blows (N) and moisture content (%) on semi-logarithmic graph as shown in Fig. 4.2, 4.3 and 4.4), water content corresponding to 25 blows is determined which gives the value of liquid limit. The LL of biosolids found to vary between (127% and 138%) while plastic limit ranged between (94% to 101%).The average value of LL, PL and PI is presented in Table 4.5 along with their classification according to ISC.

Table 4.5 ISC classification of biosolids

Sample No.	Liquid Limit	Plastic Limit	Plasticity Index	ISC Classification
1	127	94	33	OH
2	138	95	43	OH
3	138	101	37	OH
Average (%)	133.7 ~134	96	37	-
Range (%)	(127 to 138)	(94 to101)	(33 to 41)	-

As per ISC (Indian Standard Classification) in terms of compressibility all biosolids samples exhibit high compressibility. The plasticity index values of the samples indicate that the soil samples in general exhibit high plasticity characteristics. So based on the test results it was concluded that the fine fraction of biosolids material largely comprises of organic silt-size particles of medium to high plasticity and are presented with a group symbol of ‘OH’ as per Indian Standard Classification (ISC). The higher value of LL shows the high water adsorption capacity of biosolids.

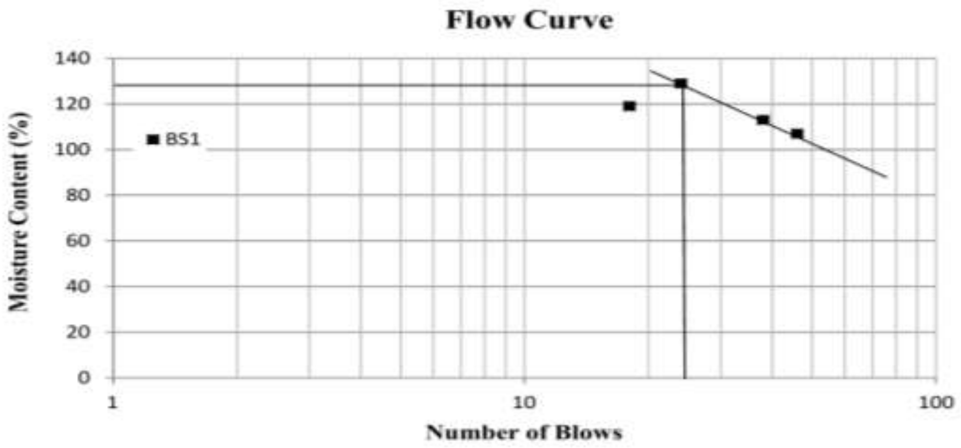


Fig. 4.2 Flow curve for Biosolid sample (1)

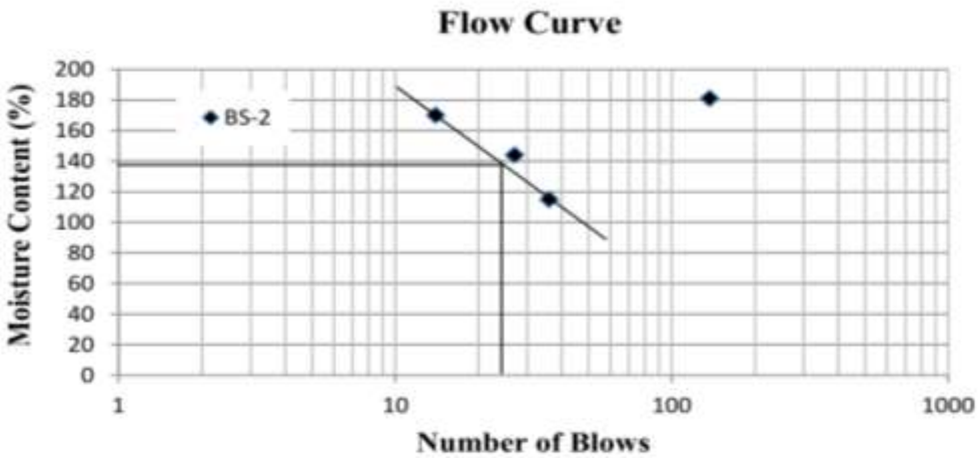


Fig. 4.3 Flow curve for Biosolid sample (2)

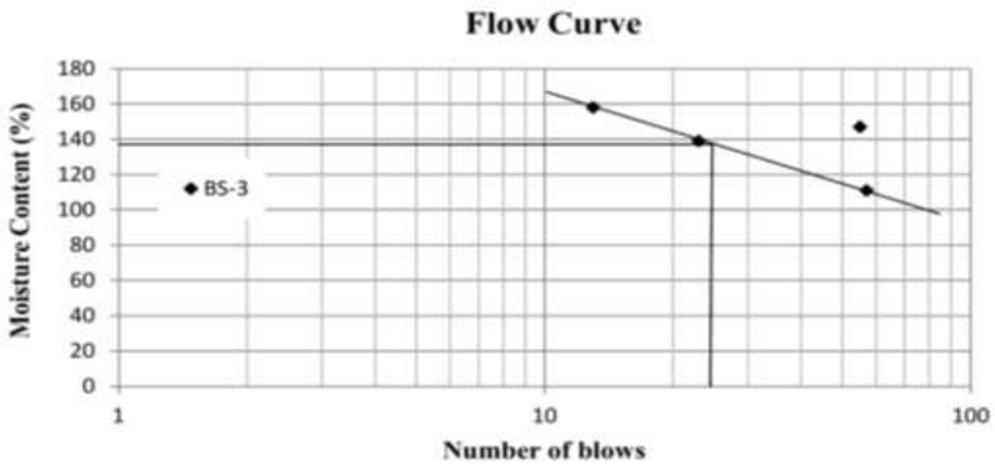


Fig. 4.4 Flow curve for Biosolid sample (3)

The plasticity index (PI) was found to vary between (33 and 41) %. The plasticity chart of biosolids is presented in Fig. 4.5, which suggests that the LL of biosolids exceeds those of highly plastic clays or other organic materials. The higher value of LL and PL may due to the higher amount of organic content in biosolids. Bush and Keller (1981) reported that the liquid limit and plastic limit of soil will increase with the addition of organic matter content in the soil. Extensive research work which has been carried out by Huang et al. (2009) shown that with increasing amount of organic content increase both upper and lower plastic limits. The higher water adsorption of the organic matter increases the limits, but the tendency of organic matter to aggregate the soil mineral fraction tends to reduce the limits. In general both liquid and plastic limits increase with organic content.

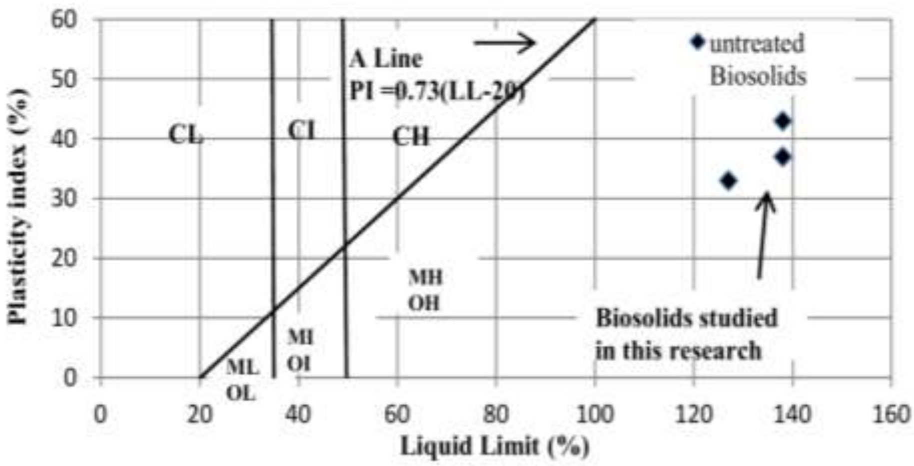


Fig. 4.5 Plasticity chart for biosolids

From the plasticity chart it is seen that all the biosolids samples studied in this research lie below the A-line and falls under (OH) classification i.e. (organic silt-size particles of medium to high plasticity) as per Bureau of Indian Standard Classification System (ISC). So, based on the Atterberg limit test results and also the behavior of material during plastic limit and liquid limit tests, it is concluded that the fine fraction of biosolids material largely comprises of organic silt-size particles.

4.2.5 Shrinkage Limit

A shrinkage limit test gives a quantitative indication of how much moisture can change before any significant volume change. Large changes in soil volume are important considerations for soils to be used as fill material for highways and railroads, or for soils that are to support structural foundations. Uneven settlement or lifting resulting from volume changes can result in cracks in structures or uneven roadbeds. Shrinkage parameters of untreated biosolids were determined according to IS: 2720 (Part-6) – 1972 and are summarized in Table 4.6.

Table 4.6 Observations and calculation for Shrinkage Limit Test

Biosolids Sample No. / **Parameter**	**1**	**2**	**3**
Weight of Shrinkage Dish (g)	34.2	31.8	24.3
Weight of (Shrinkage dish + wet soil) (g)	61.1	56.6	52.9
Weight of wet soil (g) (M_1)	26.9	24.8	28.6
Weight of (Shrinkage dish + dry soil) (g)	45.5	42	36.3
Weight of dry soil (g) (M_s)	11.3	10.2	12
Weight of empty Mercury dish (g)	308.8	308.8	308.8
Weight of (mercury dish+ mercury displaced) (g)	513.5	526.8	540
Weight of mercury displaced (g)	204.7	218	231.2
Volume of dry pat (V_2) (ml) (mass/density)	15	16	17
Volume of shrinkage dish (V_1) (ml)	25	24	24

Results of shrinkage parameters of biosolids are given in Table 4.7. The shrinkage limit and shrinkage ratio of biosolids varied from (51 to 80) % and (0.64 to 0.75) which indicates the expansiveness of biosolids with change in water content where as the linear shrinkage ranges between (10.9 and 15.5) % indicates very high swell potential of biosolids.

Table 4.7 Results of shrinkage parameters of biosolids

Shrinkage Parameters	Results
Shrinkage limit, SL (%)	51-80
Shrinkage Ratio, SR (%)	0.64-0.75
Volumetric Shrinkage, VS (%)	41.2-65.5
Linear Shrinkage, SL (%)	10.9-15.5

4.2.6 Hydraulic Conductivity Test (Variable Head Permeameter)

Falling head permeability test were undertaken on untreated biosolids samples according to IS: 2720 (Part-17)-1986, which were mixed to the optimum water content and compacted under standard compaction effort prior to test. The hydraulic conductivity of biosolids found to vary between ($5.5 x 10^{-3}$ and $6.1 x 10^{-3}$) cm/sec, which is slightly higher than those of natural occurring silts. This is due the fact that, with increase in the degree of decomposition tends to increase the specific surface with increasing fines content, which generates more resistance to water flow through voids between particles. The test result indicates that biosolids have fair drainage characteristics and are classified as semipervious according to USBR (United States Bureau of Reclamation) recommendations.

4.2.7 Compaction Test Results

Knowledge of compaction characteristics of biosolids used as fill material is important as the construction of embankments and structural fills using soil or biosolids involves compaction as well as some of the engineering properties of the fill material can be modified by the compaction process. Proper compaction is critical to the performance of conventional soil embankment or structural fill and may be even more, when recycled materials such as biosolids are used in such construction. It is commonly assumed that if the dry density is within acceptable limits, the performance of the fill will be satisfactory.

The quality control of fill at site is always based on density measurements in laboratory and field, which are expressed in terms of relative compaction. Compaction tests were undertaken on air dried biosolids samples using standard and modified proctor compactive effort. Results of standard proctor compaction (light compaction) and Modified proctor test (heavy compaction) on air-dried biosolids material are summarized in Table 4.8 and 4.9.

Table 4.8 Average value and Range of MDD and OMC of biosolids for light compaction

Sample No	**Sample No (1)**	**Sample No (2)**	**Sample No (3)**
MDD (kg/m^3)	760	731	734
OMC (%)	67.8	71	66.20
Average value of MDD (kg/m^3)	742	-	-
Average value of OMC (%)	68	-	-
Range (MDD)	(731 to 760) kg/m^3	(7.2-7.4)kN/m^3	(0.73-0.76)gm/cc
Range (OMC) (%)	(66 to 71)	-	-

Table 4.9 Average value of MDD and OMC of biosolids for heavy compaction

Sample No	**Sample No (1)**	**Sample No (2)**	**Sample No (3)**
MDD (kg/m^3)	840	860	850
OMC (%)	53	52	55
Average value of MDD (kg/m^3)	850	-	-
Average value of OMC (%)	53	-	-
Range (MDD)	(840 to 860) kg/m^3	(8.23-8.43)kN/m^3	(0.84-0.86)gm/cc
Range (OMC) (%)	(52 to 55)	-	-

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) results obtained from the standard compaction test results of biosolids ranges between (7.2 and 7.4 kN/m^3) and (8.23 and 8.43 kN/m^3) while OMC of biosolids ranges between (66% and 71%) and (52 to 55%). The variation of dry unit weight of biosolids with the water content for the standard compaction energy is given in Fig. 4.6. The compaction method is selected according to the engineering application of the material. The standard compaction method was selected to compact the biosolids material as per the IRC (Indian Road Congress) requirement for rural roads. Similarly, modified compaction method was selected to compact the biosolids material for NH/SH/MDR roads.

Based on the test results it was found that the maximum dry density of biosolids under standard and modified compaction effort, is lower than that of conventional earth fill compacted at same effort, where as the optimum moisture content was found to be very high. This property of biosolids was believed to be due to the presence of high organic content in biosolids which decreases maximum dry density and increases optimum moisture content due their high water absorption capacity.

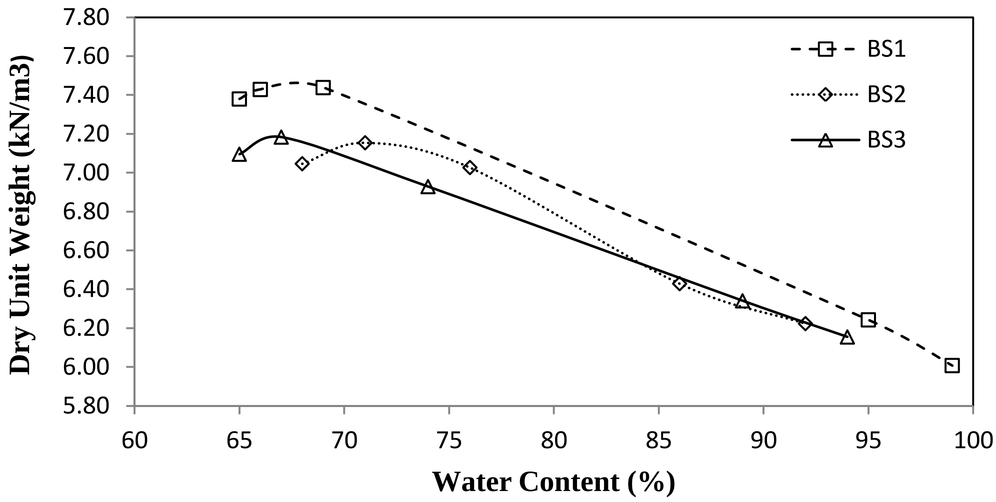


Fig. 4.6 Compaction curve of biosolids from standard compaction tests

The compaction tests results indicated that maximum dry unit weight varied only slightly with the moisture content changes. The dry unit weight of the compacted material was low in comparison with inorganic soils. The dry density is then compared with existing local road authority i.e. IRC (Indian Road Specification) for fill material. The specification for fill material is given in Table 4.10. The value of MDD of biosolids for light compaction is found to be very low (0.73 to 0.76 gm/cc) when compared with the density requirements for embankment fill as given in specification. Biosolids as such will have to be stabilised with an additive or blended with a high-quality material in order to enhance its density.

Table 4.10 Density requirement of Embankment / Sub grade for rural roads (IRC: 36-2010)

Type of work	For NH/SH/MDR Maximum laboratory dry density when tested as per IS: 2720 (Part 8) (For heavy compaction)	For rural roads Maximum laboratory dry density when tested as per IS: 2720 (Part 7) (For light compaction)
Embankments up to 3 meters height, not subjected to extensive flooding	Not less than 15.2 kN/m^3	Not less than 14.4 kN/m^3
Embankments exceeding 3 meters height or embankments of any height subject to long periods of inundation	Not less than 16 kN/m^3	Not less than 15.2 kN/m^3
Sub grade and earthen shoulders/ backfill	Not less than 17.5 kN/m^3	Not less than 16.5 kN/m^3

4.2.8 California Bearing Ratio Test (for soaked condition)

California Bearing Ratio is an indirect measure of shear strength. It is a penetration test meant for the evaluation of sub-grade strength of roads and pavements and useful to evaluate the suitability of biosolids as engineered fill material.CBR test were conducted on untreated biosolids for four days soaked in water and on un-soaked samples using standard compaction energy (IS:2720 (Part-16) -1986 test method). The samples were prepared at the optimum moisture content which was obtained from the standard compaction test. Standard compaction effort was applied to the sample to measure the suitability of biosolids as fill material in accordance with the IRC specification. The load and penetration value of untreated biosolids on three samples are summarized in Table 4.11.

Table 4.11 CBR test results of untreated biosolids (for soaked condition)

S.No.	Penetration (mm)	Load (kg) For sample-1	Load (kg) For sample-2	Load (kg) For sample-3
1	0	0	0	0
2	0.5	31.992	39.99	34.658
3	1	53.32	55.986	53.32
4	1.5	69.316	79.98	74.648
5	2	87.978	109.306	98.642
6	2.5	106.64	135.966	127.968
7	3	130.634	162.626	146.63
8	3.5	146.63	189.286	175.956
9	4	165.292	213.28	189.286
10	4.5	178.622	237.274	213.28
11	5	197.284	258.602	234.608
12	5.5	213.28	279.93	250.604
13	6	229.276	317.254	269.266
14	6.5	247.938	343.914	301.258
15	7	263.934	367.908	343.914
16	7.5	274.598	391.902	359.91
17	8	293.26	413.23	378.572
18	8.5	306.59	429.226	415.896
19	9	327.918	450.554	429.226
20	9.5	341.248	469.216	458.552
21	10	357.244	503.874	482.546
22	10.5	367.908	525.202	503.874
23	11	378.572	546.53	527.868
24	11.5	389.236	565.192	543.864

From the observation table load penetration curve is plotted as shown in Fig. 4.7. The CBR value for penetration 2.5mm and 5mm were calculated and greater value of CBR corresponding to a penetration taken for design purpose. The CBR test results of untreated biosolids in soaked condition showed CBR value vary from (10 to 13) %.

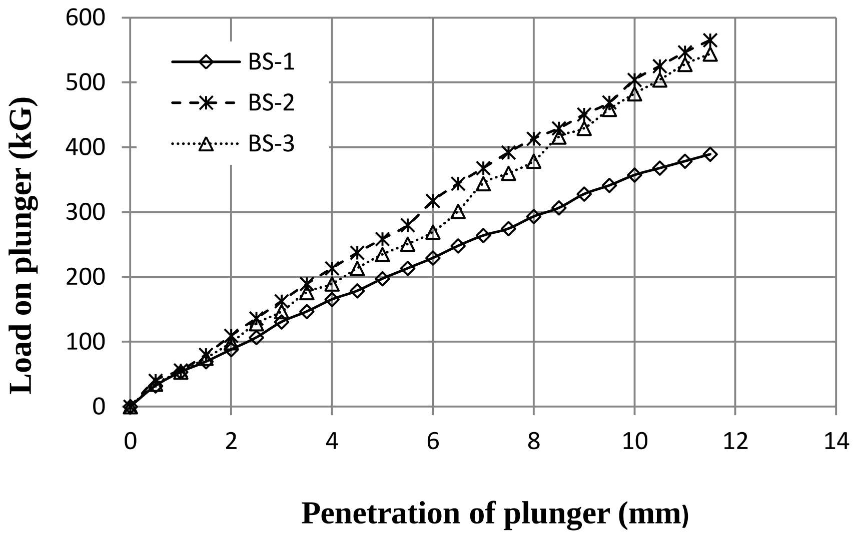


Fig. 4.7 Load penetration curve for untreated biosolids (for soaked condition)

According to the specification given in IRC: 37-2012, the sub grade should have a minimum CBR (for soaked condition) of 8 % for roads having traffic of 450 commercial vehicles per day or higher. So from the results shown in Fig. 4.7 it is apparent that the CBR value of biosolids for soaked condition satisfy the requirements given by Indian Road Congress (IRC). The CBR results of untreated biosolids for soaked condition with minimum recommended value given by IRC is shown in Fig. 4.8.

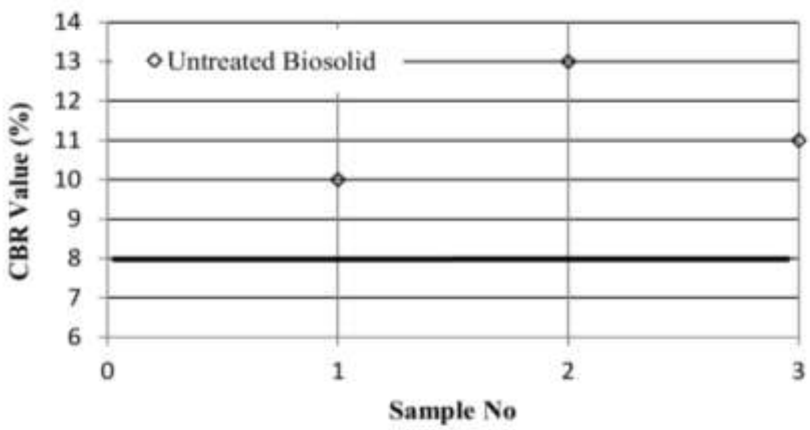


Fig. 4.8 CBR results of untreated biosolids with minimum recommended value given by Indian Road Congress (IRC)

Similarly the test observations of load and penetration of untreated biosolids are recorded in Table 4.12.

Table 4.12 CBR test results of untreated biosolids (for un-soaked condition)

S.No.	Penetration (mm)	Load (kg) For sample-1	Load (kg) For sample-2	Load (kg) For sample-3
1	0	0	0	0
2	0.5	66.65	74.65	82.65
3	1	106.64	103.97	125.30
4	1.5	133.3	127.97	154.63
5	2	159.96	157.29	175.95
6	2.5	186.62	178.62	199.95
7	3	213.28	207.95	231.94
8	3.5	239.94	231.94	253.27
9	4	266.6	261.26	285.26
10	4.5	295.92	285.26	319.92
11	5	319.92	314.58	357.24
12	5.5	346.58	335.92	373.24
13	6	359.91	354.58	389.24
14	6.5	375.91	373.24	402.56
15	7	399.9	391.90	423.89
16	7.5	418.56	415.89	439.89
17	8	437.23	426.56	445.22
18	8.5	453.22	447.88	463.88
19	9	479.88	463.88	479.88
20	9.5	490.54	479.88	501.21
21	10	506.54	495.87	519.87
22	10.5	514.54	506.54	535.86
23	11	530.53	522.54	557.19
24	11.5	538.53	535.86	575.85

The load penetration curve of untreated biosolid for un-soaked condition was plotted as shown in Fig. 4.9. From the curve CBR value corresponding to 2.5 and 5 mm were calculated and higher value corresponding to a penetration were taken which was found to vary from (15 to 17) %.

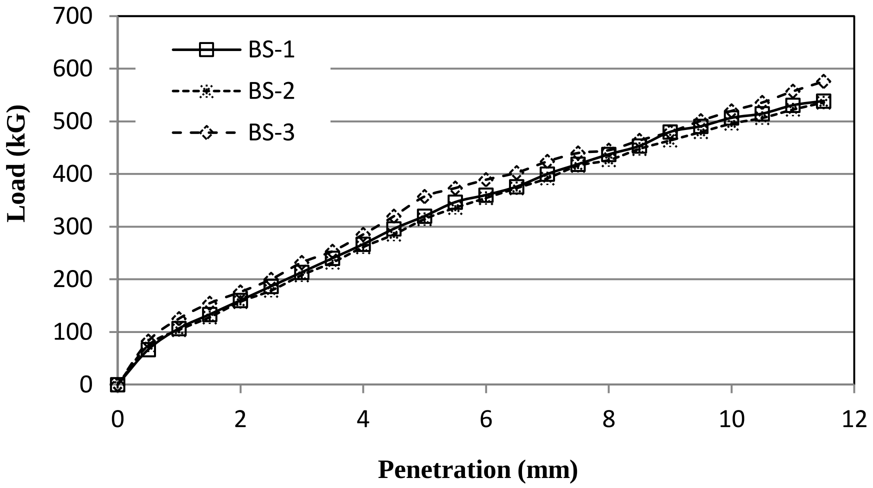


Fig. 4.9 Load penetration curve for untreated biosolids (for un-soaked condition)

The CBR results of untreated biosolids for soaked as well as for un-soaked condition shows high CBR value than the values specified by IRC. Hence, high CBR results of the biosolids studied in this research indicate the untreated biosolids have sufficient bearing capacity to be used without stabilization in an engineered fill application.

4.2.9 Direct Shear Test

Consolidation parameters of untreated biosolids were determined by conducting the one dimensional oedometer test on biosolids samples. The graph between normal stress versus shear stress is shown in Fig. 4.10 and values are summarised in Table 4.13.

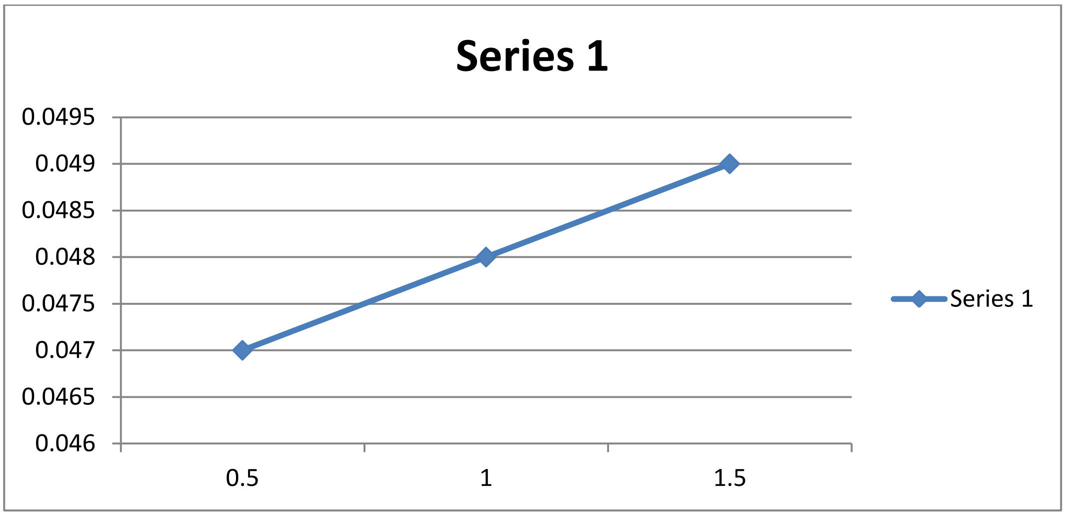


Fig. 4.10 Direct shear test results for untreated biosolids (Shear test versus Normal stress)

Table 4.13 Direct shear test results

Biosolid Sample No -1		**Biosolid Sample No-2**	
Normal Stress (kg/cm^2)	**Shear Stress (kg/cm^2)**	**Normal Stress (kg/cm^2)**	**Shear Stress (kg/cm^2)**
0.5	0.047	1	0.67
1	0.048	2	1.10
1.5	0.049	3	1.53

4.2.10 Consolidation Test

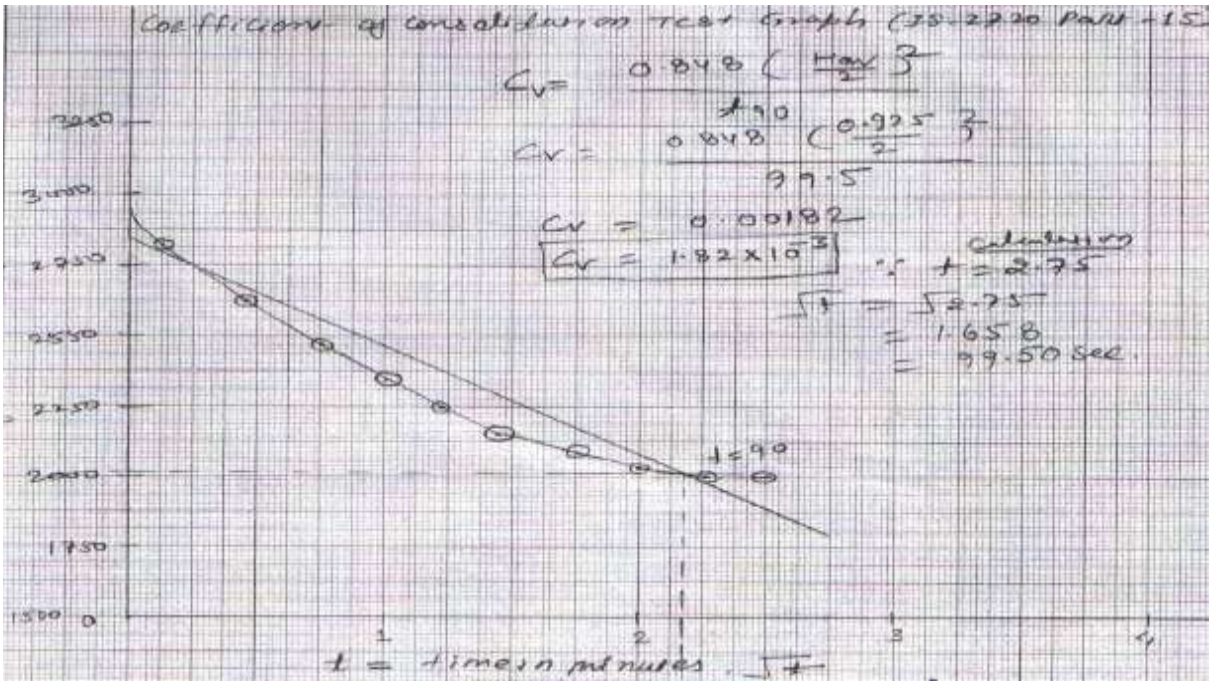


Fig. 4. 11 Coefiicient of Consolidation graph ($\sqrt{t}$ versus dial gauge reading)

4.3 Chemical characteristics of Biosolids

Biosolids samples collected from stockpiles were tested for different types of heavy metals and nutrients concentration. To be acceptable for geotechnical reuse, heavy metals present in biosolids must meet the contaminant concentration criteria as listed in Table 4.13 in order to ensure that there are no detrimental impacts to surface waters or ground water due to contaminants leaching or eroding from the geotechnical fill. If any of the contaminant concentration in biosolids as listed in Table 4.13 exceeds, are not permitted for geotechnical reuse in accordance with the Australian Environment Protection Authority (2009) guidelines. Test results of collected sample indicate that heavy metals found to be within the safe limits as specified by EPA Victoria (2009). Therefore, the heavy metals do not limit the employment of biosolids as a geotechnical fill material.

Table 4.13 Chemical Contaminants Test Results

S.No.	Contaminant	Units	Heavy Metals concentration in biosolids	Australian standards for maximum contaminant heavy metal (EPA 2009)
1	Arsenic	mg/kg	180	500
2	Chromium	mg/kg	90	500
3	Copper	mg/kg	11	5,000
4	Mercury	mg/kg	-	75
5	Nickel	mg/kg	60	3,000
6	Zinc	mg/kg	220	35,000

A summary of reported concentrations of the selected contaminants examined here is presented in Fig. 4.10. The concentrations are presented on a logarithmic scale in the form of biosolids contaminant concentration (BCC) along with safe and unsafe limits defined by the Victorian Environmental Protection Authority (EPA Victoria 2009).

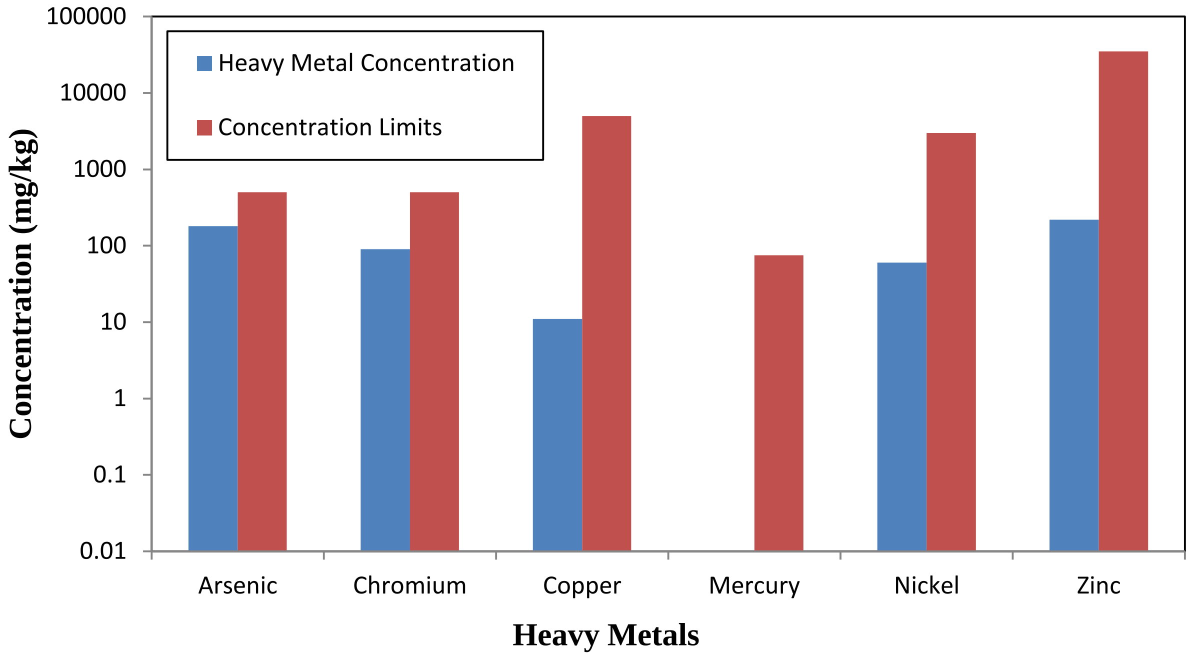


Fig. 4.10Typical concentrations of selected chemical contaminants in biosolids

In regards to biosolids nutrients concentration such as nitrogen, phosphorus and total organic carbon do not need to meet classification criteria for use as geotechnical fill. However, the concentration of these nutrients must be measured because they are expected to be high in biosolids. Table 4.14 presents the test results for the concentration of nitrogen, phosphorus and total organic carbon.

Table 4.14 Nitrogen, Phosphorus and Organic Carbon Contaminants Test Results

S.No.	Contaminant	Units	Contaminant Concentration
1	Total Nitrogen as N	mg/kg	90
2	Total Phosphorus as P	mg/kg	<10
3	Total organic carbon	mg/kg	1100

4.4 Theoretical Modeling

The long term settlement due to biodegradation is computed using equation (5) which was given by Chakma and Mathur (2007) and equation (6) which has been developed by Hettiarachchi et al. (2009).

4.4.1 Analysis of biodegradation settlement by Chakma and Mathur (2007) model

In the analysis of biodegradation settlement of road embankment using biosolids, the sensitivity of a biodegradation settlement with varying pH, moisture content (θ) and temperature (T) values over a long span of time is carried out.

a) <u>Effect of changing pH values on biodegradation settlement of biosolids</u>

With varying pH values the biodegradation settlement is calculated using equation (7) and the results obtained from the proposed model is shown in Fig. 11 and are summarized in Appendix (A.10).

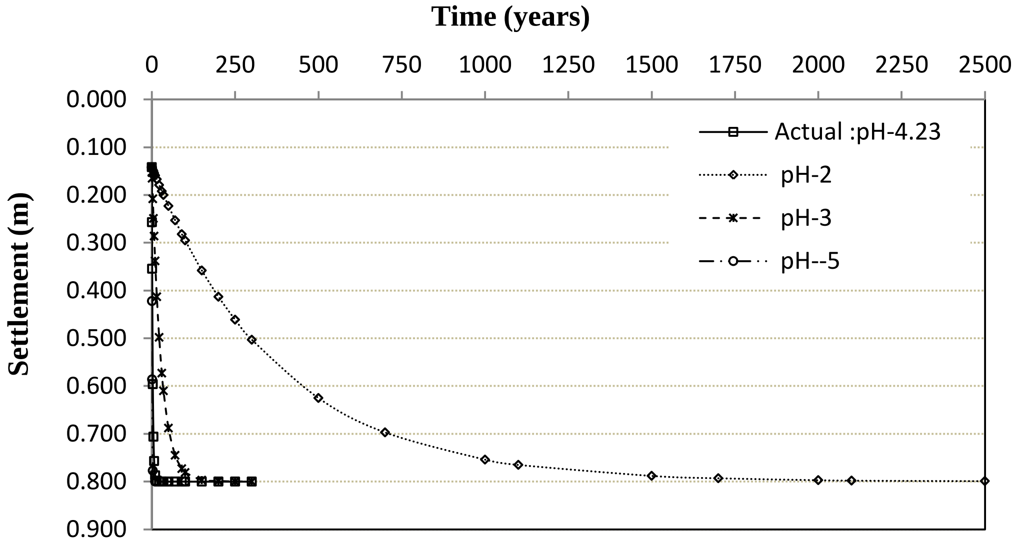


Fig. 4.11 Biodegradation settlement of road embankment with varying pH values

Fig. 4.11 shows the effect of pH values on biodegradation induced settlement using untreated biosolids by reducing the pH to 2 and 3 and increasing it to 5 and 6. The results show that 10 years after the construction biodegradation settlement was found to be 787mm for actual pH value of 4.23. The biodegradation settlement was reduced to 338 mm and 159 mm with reduced pH values of 3 and 2 respectively while it increases to 800 mm with the increased pH value of 5. Fig. 4.11 also suggests that for pH values of 4.23 and 5 it takes between 7 to 22 years to reach the maximum biodegradation settlement while for pH value of 2 and 3 it will take 250 to more than 2500 years. With varying pH values of biosolids the time taken for fully biodegradation process is presented in Fig. 4.12 and is summarized n Table 4.15.

Table 4.15 Time taken for fully biodegradation process with varying pH values

Time	**pH**
2500	2
250	3
22	4.23
30	4
7	5
3	6
3	7
3	8
7	9
30	10
250	11
2500	12

Fig. 4.12 implies that pH value of biosolids between 2 and 6 i.e. acidic range the biodegradation process decreases dramatically and then increases exponentially with pH value of biosolids between 8 and 12 i.e. alkaline range.

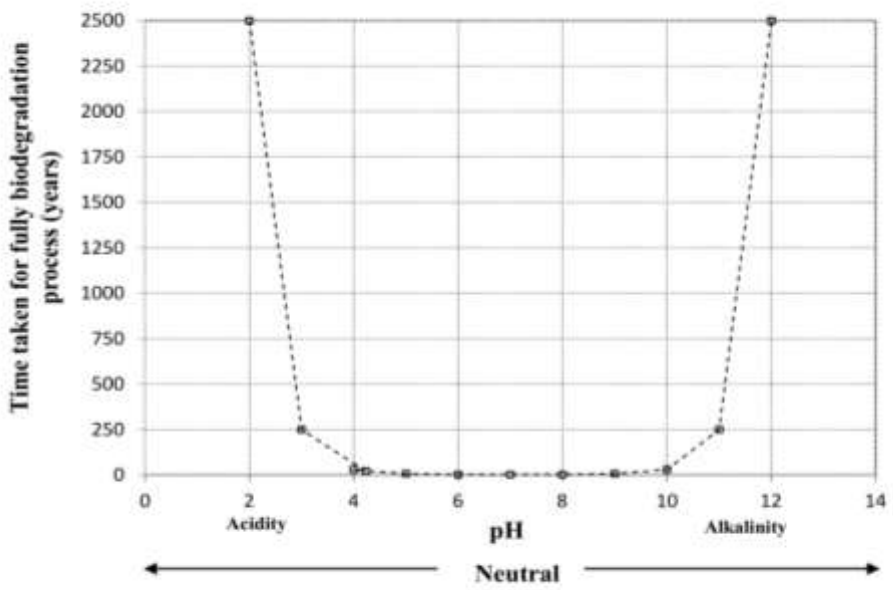


Fig. 4.12 pH values versus time taken for full biodegradation process

For full biodegradation of biosolids with pH value of 2 will take 2500 years which reduces to 7 years with pH value of 5, which implies that for full biodegradation process untreated biosolids with more acidity takes a longer time than the biosolids with less acidity. Similarly for biosolids with more alkalinity (i.e. ph value of more than 12) takes a longer time than the biosloids with less alkalinity for full biodegradation process.

b) <u>Effect of changing moisture content values on biodegradation settlement of biosolids</u>

The biodegradation settlement with varying moisture content (θ) values of untreated biosolids layer is depicted in Fig. 4.13 and is summarized in Table 4.16. The biodegradation settlement of biosolids layer for actual moisture content (i.e. optimum moisture content) and for higher and lower moisture contents are shown in Fig. 4.13 which suggests that after 30 years of construction there will be no effect of moisture content on amount of biodegradation settlement.

Table 4.16 Biodegradation settlement with varying moisture content

	θ = 28%	**θ =38%**	**θ =48%**	**θ =58%**	**θ =68%**	**θ =78%**	**θ =88%**
Time (years)	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**
0	0.142	0.142	0.142	0.142	0.142	0.142	0.142
0.5	0.192	0.209	0.225	0.241	0.257	0.272	0.287
1	0.239	0.271	0.3	0.328	0.354	0.379	0.403
3	0.393	0.458	0.512	0.557	0.596	0.628	0.655
5	0.505	0.579	0.634	0.675	0.706	0.73	0.747
7	0.586	0.657	0.704	0.736	0.757	0.791	0.781
10	0.668	0.726	0.758	0.776	0.787	0.793	0.796
15	0.741	0.775	0.789	0.796	0.798	0.799	0.8
22	0.781	0.795	0.798	0.8	0.8	0.8	0.8
30	0.795	0.799	0.8	0.8	0.8	0.8	0.8
35	0.798	0.8	0.8	0.8	0.8	0.8	0.8
50	0.8	0.8	0.8	0.8	0.8	0.8	0.8

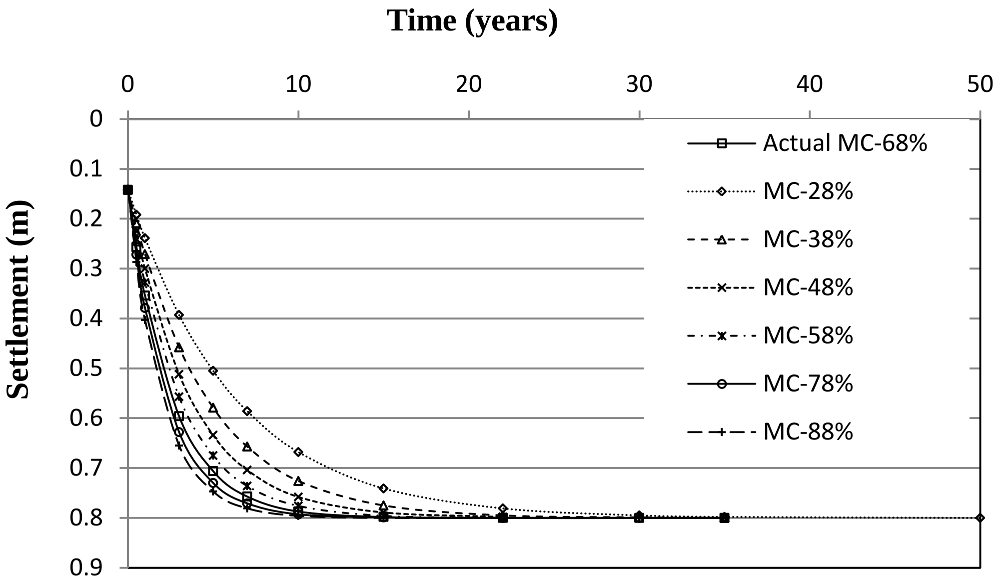


Fig. 4.13 Biodegradation settlement of embankment using untreated biosolids with changing moisture content (θ)

The time taken to reach the maximum settlement with varying moisture content values of biosolids is presented in Fig. 4.14 which implies that with higher moisture content value of untreated biosolids reach the maximum settlement at a faster rate.

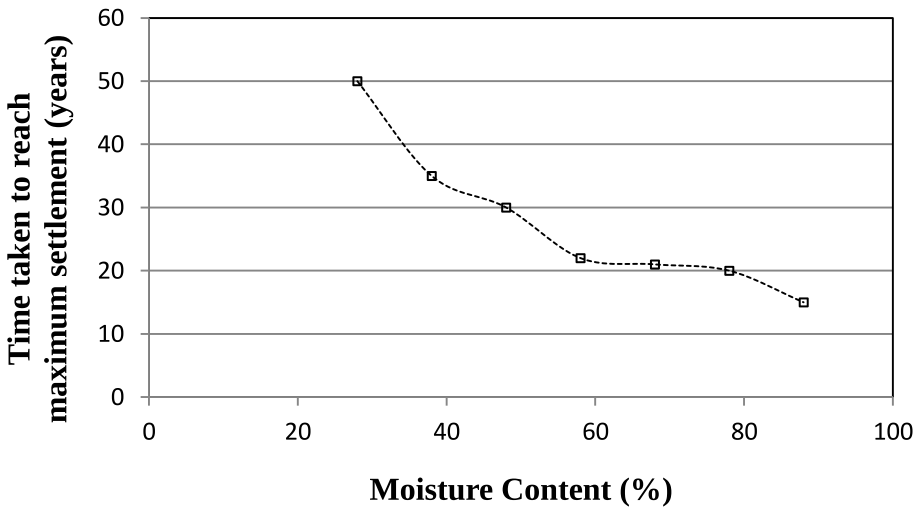


Fig. 4.14 Moisture content versus time taken to reach maximum settlement

Fig. 4.14 suggests that the biosolids with moisture content value of 88% will take 15 years to reach the maximum settlement while for moisture content value of 28%, it will take 50 years.

c) Effect of changing temperature values on biodegradation settlement of biosolids

The effect of changing temperature on biodegradation induced settlement is shown in Fig. 4.15 which suggests that biosolid layer with higher value of temperature reach the maximum settlement at a faster rate i.e. increasing temperature will accelerate the biodegradation process significantly.

Table 4.17 Biodegradation settlement with varying Temperature

	T=5	**T=10**	**T=14.33**	**T=20**	**T=25**	**T=30**	**T=35**	**T=40**
Time (years)	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**	**S_b (m)**
0	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142
0.5	0.184	0.224	0.257	0.297	0.329	0.36	0.389	0.415
1	0.225	0.299	0.354	0.418	0.467	0.509	0.546	0.578
3	0.362	0.509	0.596	0.672	0.715	0.743	0.762	0.775
5	0.467	0.631	0.706	0.757	0.778	0.789	0.794	0.797
7	0.546	0.702	0.757	0.785	0.794	0.798	0.799	0.8
10	0.631	0.757	0.787	0.797	0.799	0.8	0.8	0.8
15	0.715	0.789	0.798	0.8	0.8	0.8	0.8	0.8
22	0.767	0.798	0.8	0.8	0.8	0.8	0.8	0.8
30	0.789	0.8	0.8	0.8	0.8	0.8	0.8	0.8
35	0.794	0.8	0.8	0.8	0.8	0.8	0.8	0.8
50	0.799	0.8	0.8	0.8	0.8	0.8	0.8	0.8
70	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

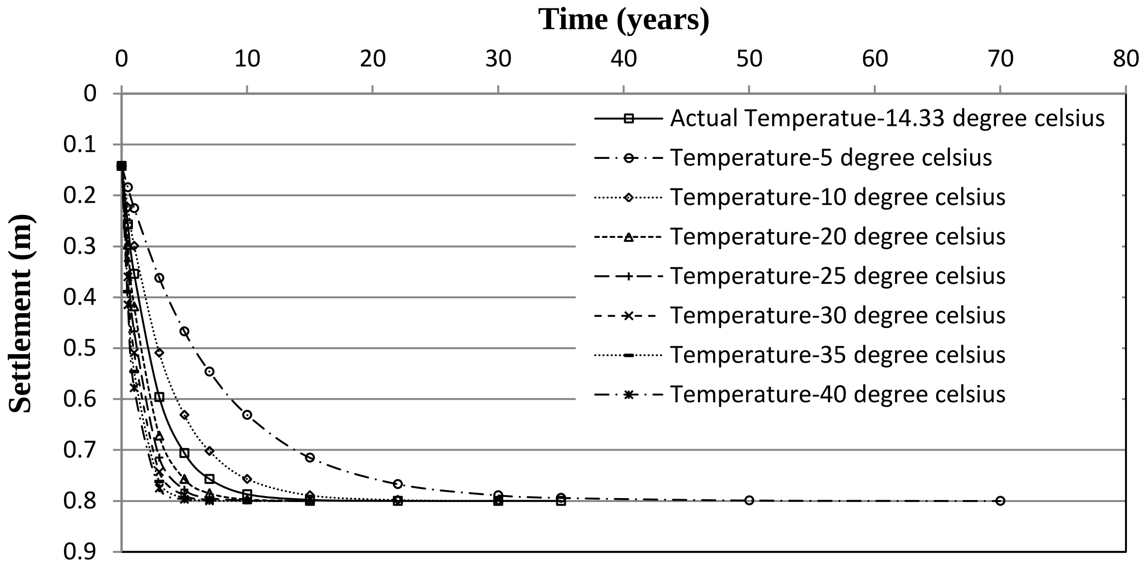


Fig. 4.15 Biodegradation settlement of embankment using untreated biosolids with changing Temperature (T)

Fig. 4.15 also implies that after 50 years of the construction the biodegradation settlement is the same for all possible scenarios.

4.4.2 Analysis of biodegradation settlement by Hettiarachchi et al. (2009) model

Hettiarachchi et al. (2009) model did not incorporate the effect of various parameters such as moisture content, bulk density, pH, and temperature while computing settlement of road embankment using untreated biosolids.

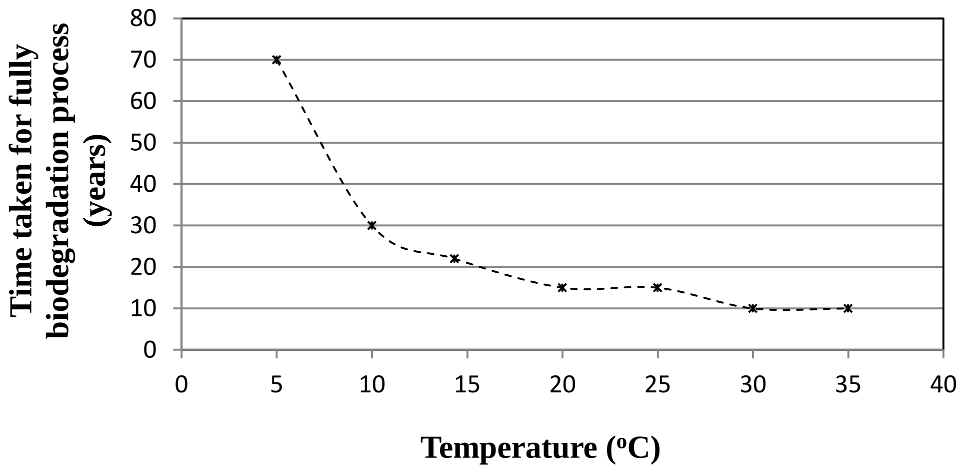


Fig. 4.16 Biodegradation settlement of 3m high embankment using untreated biosolids

Fig. 4.16 suggests that the settlement at the end of 30 years is found to be 456mm for a 3m high embankment using untreated biosolids. The Fig. 4.16 depicts that the rate of settlement increases for the first 30 years but remains same throughout the remaining years.

4.4.3 Comparison between Chakma and Mathur (2007) model and Hettiarachchi et al. (2009) model

The preliminary results obtained from Chakma and Mathur (2007) model and Hettiarachchi et al. (2009) model is shown in Fig. 4.17 and is summarized in Table 4.18.

Table 4.18 Results obtained from Chakma and Mathur (2007) model and Hettiarachchi et al. (2009) model

Settlement / Time	Chakma and Mathur (2007)	Hettiarachchi et al. (2009) model
Time (years)	**Settlement (m)**	**Settlement (m)**
0	0.142	0
0.5	0.257	0.075
1	0.354	0.139
3	0.596	0.303
5	0.706	0.382
7	0.757	0.420
10	0.787	0.444
15	0.798	0.454
22	0.8	0.455
30	0.8	0.456
35	0.8	0.456
50	0.8	0.456
70	0.8	0.456

The results suggests that in Chakma and Mathur’s (2007) model, the biodegradation settlement of the embankment will take 22 years to reach the maximum biodegradation settlement while in the Hettiarachchi et al. (2009) model, it will take 30 years to reach the maximum biodegradation settlement. The difference arises since various factors like pH, temperature and moisture content were not incorporated in Hettiarachchi et al. (2009) model whereas the Chakma and Mathur’s (2007) model consider all parameters on the basis of degree of degradation that predicts a more realistic value of long term settlement due to biodegradation.

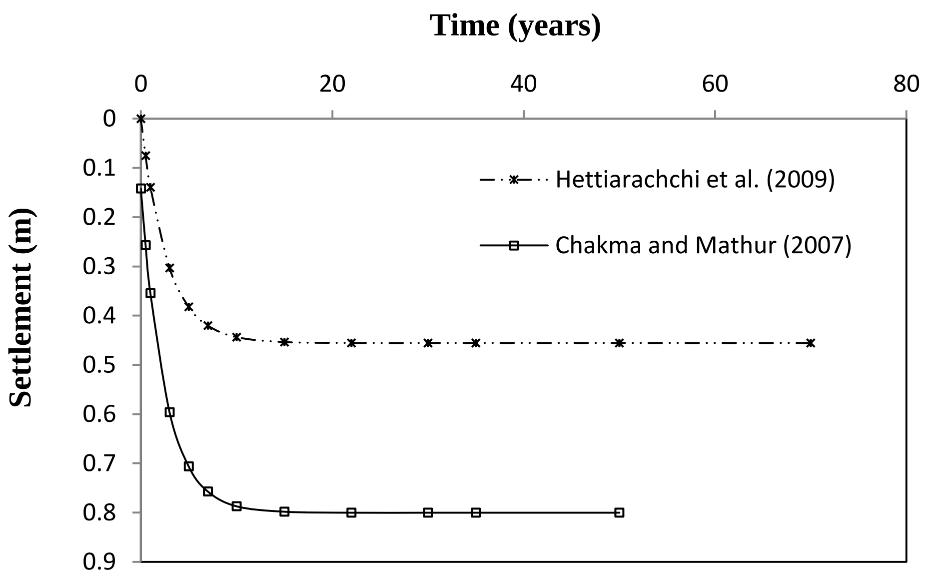


Fig. 4.17 Variation of settlement for Chakma and Mathur (2007) model and Hettiarachchi et al. (2009) model

4.5 Validation of Results

To understand the limitation and relative accuracy of the procedure used to determine the geotechnical and chemical characteristics of untreated biosolids, the experimental results is compared with the data in literature. In this section the output results obtained from theoretical analysis of biodegradation settlement of an embankment using untreated biosolids is also compared with the data in literature.

4.5.1 Geotechnical Characteristics of Biosolids

4.5.1.1 Moisture Content and Specific Gravity

The experimental results of index properties i.e. moisture content, specific gravity and organic content of biosolids are compared with the results in literature as shown in Table 4.19.

Table 4.19 Moisture Content and Specific Gravity and Organic Content Test Results

S.No.	Properties	Units	Results	Author
1)	Moisture Content	%	100-105	Present study
		%	46.8-57	Arulrajah et al. (2011); Arulrajah et al. (2011); Disfani et al.(2013); Suthagaran et al. (2008); Suthagaran et al. (2010)
		%	68.79	Wanigaratne and Udamulla, (2012)
2)	Specific Gravity		1.33-1.37	Present study
			1.75-1.79	Arulrajah et al. (2011); Arulrajah et al. (2011); Disfani et al.(2013); Suthagaran et al. (2008); Suthagaran et al. (2010)
			1.93	Wanigaratne and Udamulla, (2012)
3)	Organic Content	%	39.3-43.3	Present study
		%	24.4-38.5	Arulrajah et al. (2011); Arulrajah et al. (2011); Disfani et al.(2013); Suthagaran et al. (2008); Suthagaran et al. (2010)
		%	25.5	Wanigaratne and Udamulla, (2012)

The results show that moisture content and organic content of biosolids for the present study is found to be very high as compared to results obtained from literature as shown in Table 4.19. The higher value of moisture content of biosolids resulted from nature of the organic matter i.e. humification which means less decomposed the biosolids, more will be the moisture content. As biosolids used in the present work are more than 5 months old having organic content ranges from (39.3 to 43.3 %), which signifies that it is fresh (new) as compared to the biosolids studied in literature which were more than 20 years old (aged biosolids). Similarly, the specific gravity of biosolids also depends upon the degree of decomposition of organic matter in biosolids i.e. fresh biosolids are less decomposed, contains high organic content will have low specific gravity and vice-versa.

4.5.1.2 Atterberg Limits

Table 4.20 Atterberg Limit Test Results

S.No.	Properties	Units	Results	Author
1)	Liquid Limit	%	127-138	Present study
		%	100-110	Arulrajah et al. (2011); Arulrajah et al. (2011); Disfani et al.(2013); Suthagaran et al. (2008); Suthagaran et al. (2010)
		%	79.80	Wanigaratne and Udamulla, (2012).
2)	Plastic Limit	%	94-101	Present study
		%	79-83	Arulrajah et al. (2011); Arulrajah et al. (2011); Disfani et al.(2013); Suthagaran et al. (2008); Suthagaran et al. (2010)
		%	NP	Wanigaratne and Udamulla, (2012).
3)	Plasticity Index	%	33-41	Present study
		%	21-27	Arulrajah et al. (2011); Arulrajah et al. (2011); Disfani et al.(2013); Suthagaran et al. (2008); Suthagaran et al. (2010)

The test results for Atterberg limits of biosolids for present and past studies reported in Table 4.20. The biosolids samples for present study found to have high liquid limit, plastic limit and plasticity indices that are comparable to commonly found organic soils. This is due the fact that biosolids procured are fresh in nature containing (39.93 to 43.3 %) of organic content. The high percentage of organic matter in biosolids contributes to the water held at the liquid limit leads to increase the upper and lower limits. However, liquid limit and plasticity indices of biosolids studied in literature also found to be high due to high water adsorption of organic matter which increases the limits. Thus, from the behavior of biosolids during liquid and plastic limit tests it can be inferred that the fine fraction of biosolids largely comprises of organic clay to silt sized particles.

4.5.1.3 Particle Size Distribution

Table 4.21 Particle Size Distribution Contents

S.No.	**Particle size**				C_u	C_c	**Authors**
	> 2.36 mm (%)	**2.36 and 0.075 mm (%)**	**0.075 and 0.002 mm (%)**	**< 0.002 mm (%)**			
1	10-14.9	81-86	1.7-5	-	7.03-9.21	1.06-1.27	Present study
2	4-16	40-44	22-33	18-23	100-360	0.3-0.4	Arulrajah et al. (2011); Disfani et al.(2013)
3	3.4-3.6	44-50	44-50	2	17-26	0.5-1.3	Arulrajah et al. (2013)
4	2-4	44-58	34-51	1-4	11.7-25.0	0.46-2.92	Suthagaran et al. (2008); Suthagaran et al. (2010)

Based on the gradation curve, the particle size distribution contents of untreated biosolids along with their (Cu) and (Cc) values were calculated and are reported in Table 4.21. The results from literature indicate that particles size in biosolids although categorized as coarse particles but in reality they are smaller silt-sized particles. This is due to the fact that the biosolids studied in literature are more than 20 years old and due to such long term stockpiling they are adhered and attached together. Whereas, biosolids for present study also categorized as coarse particles as organic compound present in biosolids depend on rings and chains of carbon atoms which create a force of attraction leads to binding of biosolids particle together during the stockpiling of biosolids.

4.5.1.4 Hydraulic Conductivity

Arulrajah et al. (2011), Arulrajah et al. (2013), Disfani et al. (2013), Disfani et al. (2014), Suthagaran et al. (2008) and Suthagaran et al. (2010) carried out the test on untreated biosolids and reported an average hydraulic conductivity value of (1.24-1.60) $x10^{-7}$ m/s while the permeability of biosolids studied in this research found to vary between ($5.5x10^{-5}$ and $6.1x10^{-5}$) m/sec. This is due the fact that, with increase in the degree of decomposition resulted in decrease in porosity and considerable decrease in the effective diameter of pores.

4.5.1.5 Compaction Characteristics

Standard compaction test results i.e. optimum moisture content and maximum dry density obtained from literature and present studies are shown in Fig. 4.18 and Fig. 4.19. The result indicates that the OMC of biosolids is higher than that of natural clay soils due to their high water absorption capacity.

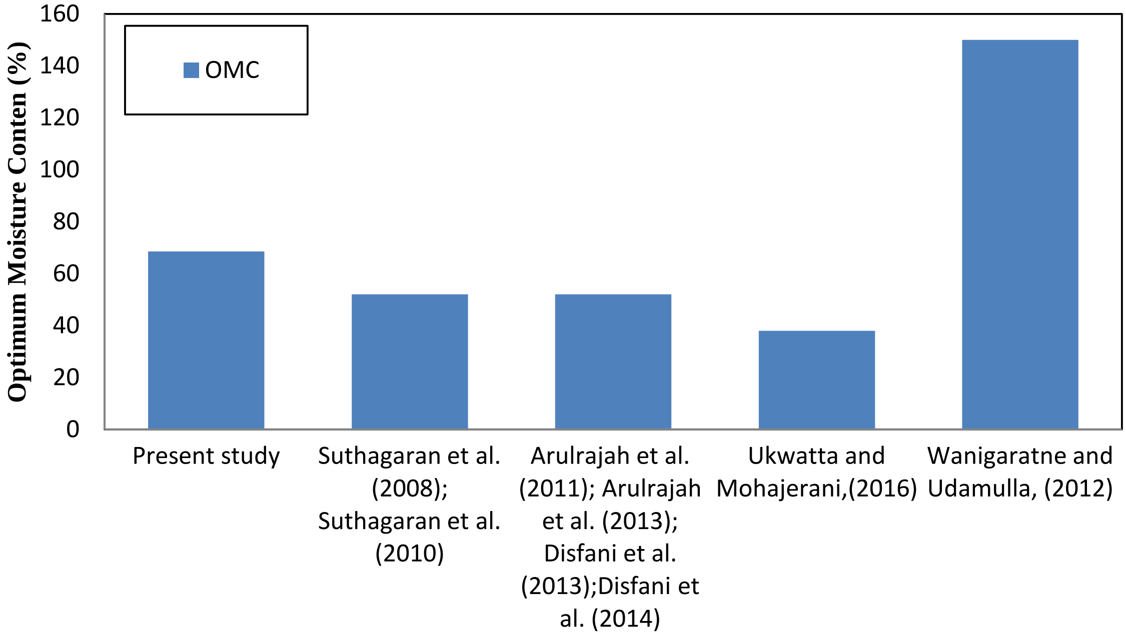


Fig. 4.18 Calculated and Measured values of OMC for Biosolids

Maximum dry density (MDD) of biosolids found to be low as compared to that of typical compacted clays which is believed to be the function of organic content present in biosolids. As higher percentage of organic content in biosolids leads to decrease in the maximum dry density and increase in the optimum moisture content.

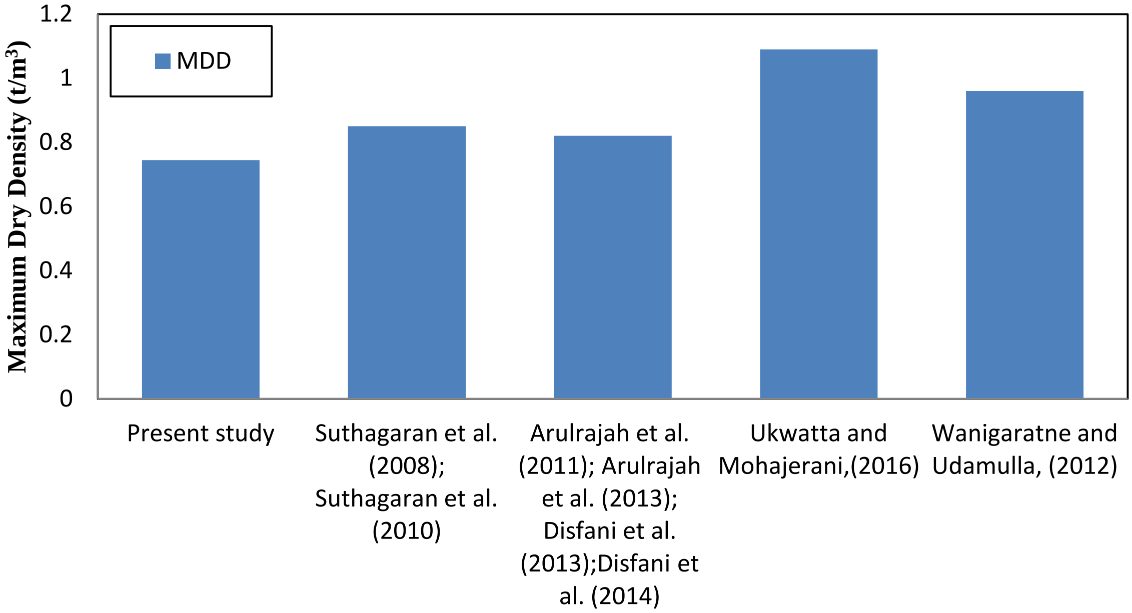


Fig. 4.19 Calculated and Measured values of MDD for Biosolids

4.5.1.6 California Bearing Ratio (CBR)

CBR values reported in literature and found in present study are summarized in Table 4.22. The results of CBR from literature indicates the high deformation potential settlement of biosolids samples which accentuates the need to stabilize untreated biosolids prior to their usage in road embankment fills with additive materials. However, the CBR results of biosolids reported in present study satisfy the requirements given by local road authorities.

Table 4.22 CBR values of biosolids

S.No.	Properties		Units	Result	Authors
1)	CBR				
		a)	%	10-13	Present study
		b)	%	0.8-1.1	Suthagaran et al. (2008) Suthagaran et al. (2010)
		c)	%	0.8-1.1	Arulrajah et al. (2011); Arulrajah et al. (2013); Disfani et al. (2013); Disfani et al. (2014)
		d)	%	2.92	Wanigaratne and Udamulla, (2012)

4.5.2 Theoretical Modeling

In order to predict the long term biodegradation settlement of biosolids when used as fill material in road embankment applications, an innovative research study was undertaken on aged biosolids by Disfani et al. (2013). In this study an analytical model was used which is proposed by Chakma and Mathur (2007) to analyze the biodegradation settlement of road embankment by using aged biosolids. proposed by Chakma and Mathur (2007) whereas in present study biodegradation settlement of road embankment is predicted by using fresh biosolids. Typical road embankment geometry for settlement analysis used by Disfani et al. (2013) and in present study is shown in Fig. 4.20 and Fig. 4.21.

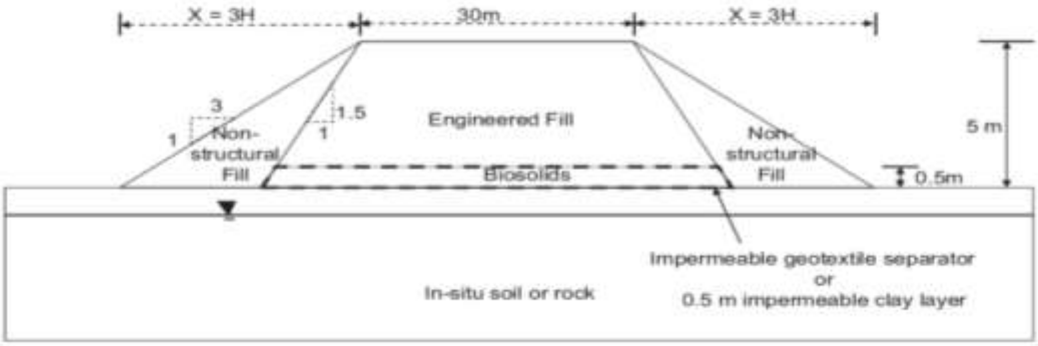


Fig. 4.20 Geometry of road embankment for settlement analysis (Disfani et al. (2013).

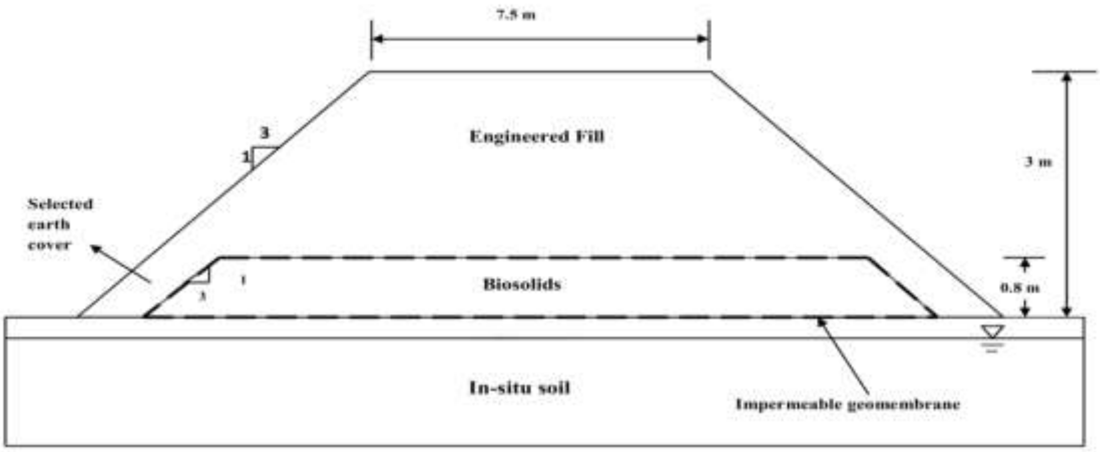


Fig. 4.21 Geometry of road embankment for settlement analysis (Present Study).

Time taken for full biodegradation process with varying pH values of biosolids were analyzed and is presented in Fig. 4.22. The analysis of biodegradation settlement studied by Disfani et al. (2013) indicates that the biosolids with low pH values (pH less than 3) and high value (pH more than 11) will take longer time (more than 1000 years) for full biodegradation of aged biosolids in road embankment whereas in present study the time taken for full biodegradation process of fresh biosolids will take more than 2500 years which clearly shows the sensitivity of pH value in the biodegradation process.

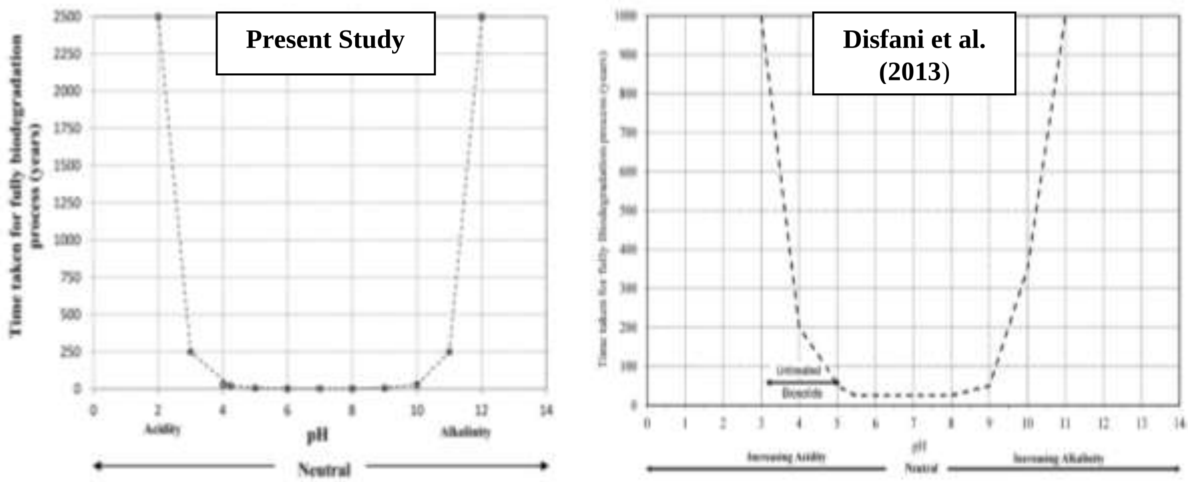


Fig. 4.22 pH values versus time taken for full biodegradation process

Similarly, variation of temperature and moisture content of biosolids also affect the biodegradation process. The results of past study indicates that increasing temperature and moisture content of aged biosolids will accelerate the biodegradation process while not affecting the attained biodegradation settlement after 160 and 100 years respectively.

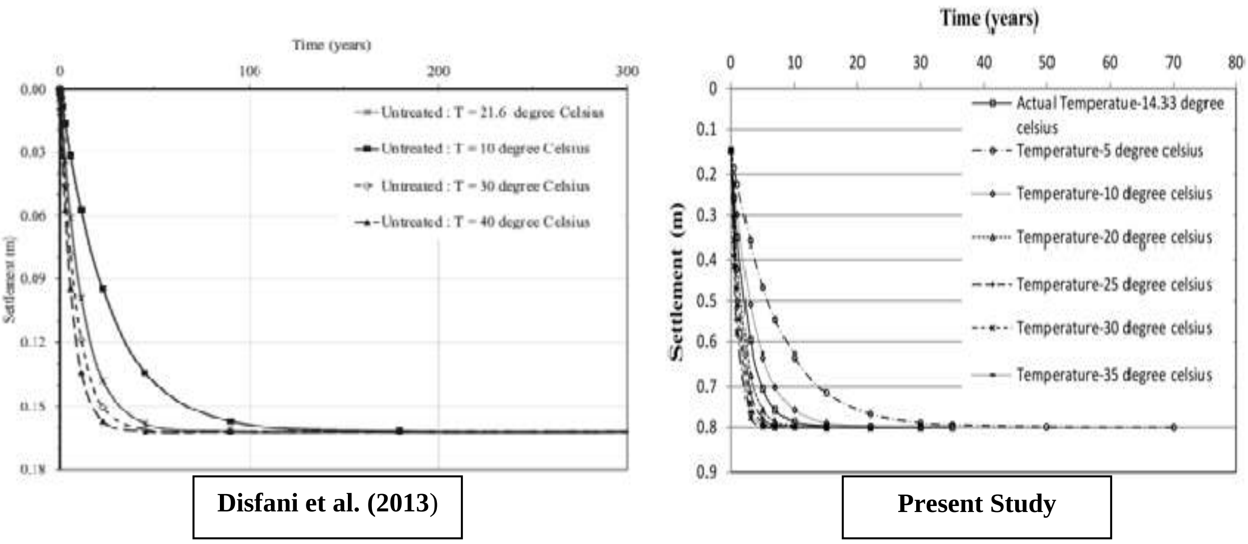


Fig. 4.23 Biodegradation settlement of embankment using untreated biosolids with changing Temperature (T)

Whereas the biodegradation settlement analyzed in present study indicates that after 30 years of construction there will be no effect of moisture content on amount of biodegradation settlement. The effect of changing temperature on biodegradation induced settlement as shown in Fig. 4.23 suggests that biosolid layer with higher value of temperature reach the maximum settlement at a faster rate and after 50 years of the construction the biodegradation settlement is the same for all possible scenarios.

CHAPTER 5

CONCLUSION

5.1 General

This section is a summary of the most important conclusions reached with this research. Biosolids samples obtained from Biosolids Stockpile Area, Kankhal Wastewater Treatment Plant were tested to investigate the geotechnical characteristics of biosolids and the suitability of biosolids as stabilized fill material. Based on the geotechnical laboratory test results and literature survey following conclusions can be made:

a) The detailed literature survey revealed that the biosolids produced as waste materials can be a good construction material for embankments as a fill material.

b) Biosolids utilization is increasing in civil engineering applications; however the need is to increase the percentage utilization and to use the other potential industrial by-products along with biosolids in order to assess their efficacy as potential stabilization agents.

c) Based on the geotechnical laboratory test results, the biosolid samples show high moisture content and low specific gravity which is substantially lower than natural inorganic soils.

d) The biosolids samples fall under (OH) classification i.e. (silt with high compressibility) as per Bureau of Indian Soil Classification System (ISC) The liquid limit, plastic limit and plasticity indices found to be high that are comparable to common organic soils, so biosolids it could be classified as organic soil in geotechnical terms from Atterberg limit test results.

e) The particle density of biosolids under standard compaction effort was found to be in the range between (0.73 to 0.76 gm/cc) which is lower than that of values specified in code for a fill material, whereas the optimum moisture content of the biosolids is high due to their high water absorption capacity.

e) Compaction test results indicates low maximum dry density (MDD) so biosolids need to be stabilized with an additive to enable its usage as a fill material.

5.2 Scope for Future Work

1) Using of waste materials such as fly ash, crushed bricks and lime for the amendment of biosolids and study the effect on geoenvironmental properties and leachate production.

APPENDIX

APPENDIX-A

Results of Geotechnical Parameters of Biosolids

A.1 Moisture Content Test Results

Temperature maintained in oven =60°C

Drying Period = 26 to 27 hours

BS[a] Sample No.	IS sieve Used	Weight of BS [a] taken	Weight of empty container (W_1) (g)	Weight of (container+BS) (W_2) (g)	Weight of (container +dry BS) (W_3) (g)	Water Content (%)
BS1-1	2mm	50 g	20.1	69	44	105
BS1-2	2mm	50 g	20.9	70.9	45.5	103
BS1-3	2mm	50 g	20.1	70.1	44.7	103
BS2-1	10mm	300g	467.1	767.1	614.6	103
BS2-2	10mm	300g	433.3	733.3	581.9	102
BS2-3	10mm	300g	452.8	752.8	601.9	101
BS3-1	20mm	500g	467.1	967.1	717.2	100
BS3-2	20mm	500g	433.3	933.3	680.4	102
BS3-3	20mm	500g	452.8	952.8	701.3	101

[a] Biosolids

Results

Sample No.	Moisture Content (%)
BS-1	103-105

BS-2	101-103
BS-3	100-102
Range	**100-105**

A.2 Specific Gravity Test Results

a) Density Bottle Method

Room Temperature = 26°C

IS sieve used = 2mm

Total mass of biosolid taken =10g

1) Determination of Specific gravity of kerosene at 27°C

Parameter	**50 ml DB[a]**	**25 ml DB[a]**
Weight of Density Bottle (W_1) (gm)	28.6	21.9
Weight of (DB +Water) (W_2) (gm	80	47.1
Weight of (DB+ Kerosene) (W_3) (gm)	68.6	41.5
Sp. Gravity of Kerosene (G_k) at room temperature	0.78	0.78
G_k^b at 27°C = $\frac{\text{Gw at (26°C)}}{\text{Gw at (27°C)}} \times G_k$ at (27°C)	0.78	0.78

[a] Density Bottle
[b] Specific Gravity of Kerosene

2) Determination of Specific gravity of Biosolids at 27°C

Parameter	**50 ml DB**	**25 ml DB**
Weight of Density Bottle (W_1) (gm)	28.6	30.4
Weight of (DB + Kerosene) (W_2) (gm)	68.6	68.8
Weight of (DB+ Kerosene+ BS[a]) (W_3) (gm)	74.3	74.4

Weight of BS (W_4) (gm)	10	10
Sp. Gravity of BS (G_{bs}^{b}) at 27°C = $\frac{W4}{W4+W2-W3} \times G_k$ at 27°C	1.81	1.77

[a] Biosolids
[b] Specific Gravity of Biosolids

Result- Specific Gravity of Biosolids = (1.77-1.81)

b) Pycnometer Method

Room Temperature = 26°C

IS sieve used = 2mm

Total mass of biosolid taken =200g

1) Determination of Specific gravity of kerosene at 27°C

Parameter	Sample 1	Sample 2
Weight of Pycnometer(W_1) (gm)	460.8	462.1
Weight of (P^{a} +Water) (W_2) (gm)	1181.7	1190.8
Weight of (P+ Kerosene) (W_3) (gm)	1026.2	1030.6
Sp. Gravity of Kerosene (G_k^{b}) at room temperature	0.78	0.78
G_k at 27°C = $\frac{Gw \text{ at } (26°C)}{Gw \text{ at } (27°C)} \times G_k$ at (27°C)	0.78	0.78

[a] Pycnometer
[b] Specific Gravity of Kerosene

2) Determination of Specific gravity of Biosolids at 27°C

Parameter	Sample 1	Sample 2
Weight of Pycnometer (W_1) (gm)	460.8	462.1
Weight of (P + BS) (W_2) (gm)	661.4	660.3
Weight of (P+ Kerosene+ BS) (W_3) (gm)	1109.3	1116.7
Weight of (P+ Kerosene) (W_4) (gm)	1026.2	1030.6

Sp. Gravity of BS (G_{bs}) at 27°C = $\frac{(W2-W1)}{(W2-W1)-(W3-W4)} \times G_k$ at 27°C	1.33	1.37

Result – Specific Gravity of Biosolid = (1.33-1.37)

A.3 Grain Size Analysis Results (Wet Sieve Analysis)

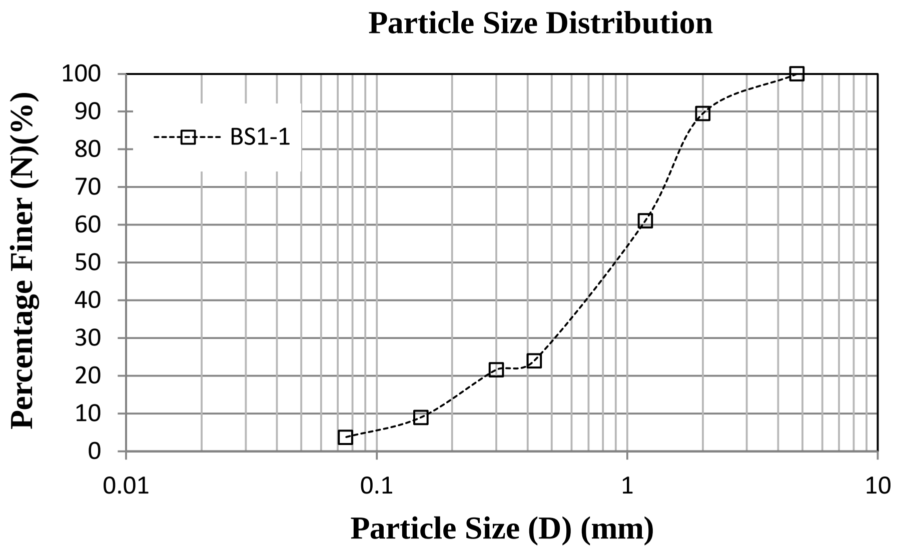
<u>Biosolids Sample– 1-1</u>

Total mass taken = 200 gm

Mass of soil retained on 0.075 mm IS Sieve =190 gm

Mass of soil passing from 0.075 mm IS Sieve=10 gm

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve + BS (g)	Weight Retained (g)	% Retained	Cumulative % Retained	% Finer (N)
4.75	392	392	0	0	0	100
2	405.5	425.5	20	10.53	10.53	89.47
1.18	361	415	54	28.42	38.95	61.05
0.425	343.5	414	70.5	37.11	76.05	23.95
0.3	344	348.5	4.5	2.37	78.42	21.58
0.15	352.5	376.5	24	12.63	91.05	8.95
0.075	328.5	338.5	10	5.26	96.32	3.68
Pan	257.5	264.5	7	3.68	100.00	0.00
Sum			190			



From Graph,

$\mathbf{D_{10} = 0.175}$

$\mathbf{D_{60}} = \mathbf{1.23}$

$\mathbf{D_{30} = 0.518}$

C_u and C_C is calculated using the following equations,

$\mathbf{C_u = [D_{60} / D_{10}]} = [1.23/0.175] = 7.03$

$\mathbf{C_c = [D_{30}^2 / D_{60} * D_{10}]} = [0.518^2/1.23*0.175] = 1.24$

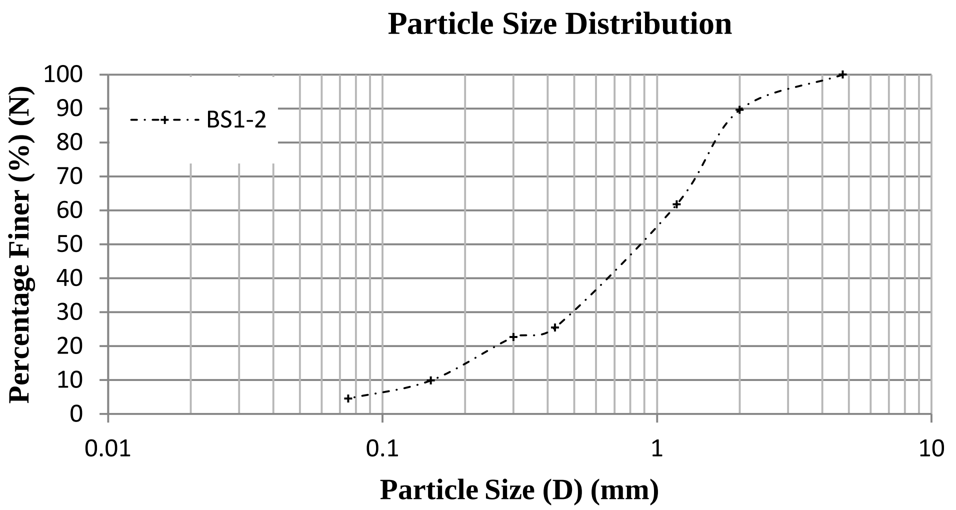
<u>Biosolids Sample – 1-2</u>

Total mass taken = 200 gm

Mass of soil retained on 0.075 mm IS Sieve = 197 gm

Mass of soil passing from 0.075 mm IS Sieve= 3 gm

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve + BS (g)	Weight Retained (g)	% Retained	Cumulative % Retained	% Finer (N)
4.75	392	392	0	0	0	100
2	405.5	426	20.5	10.41	10.41	89.59
1.18	361	415.8	54.8	27.82	38.22	61.78
0.425	343.5	415	71.5	36.29	74.52	25.48
0.3	344	349.5	5.5	2.79	77.31	22.69
0.15	352.5	377.7	25.2	12.79	90.10	9.90
0.075	328.5	339	10.5	5.33	95.43	4.57
Pan	257.5	266.5	9	4.57	100	0
Sum			197			



From Graph,

D_{10} = 0.161

D_{60} = 1.23

D_{30} = 0.46

C_u and C_C is calculated using the following equations,

C_u = [D_{60} / D_{10}] = [1.23/0.161] = 7.64

C_c = [D_{30}^2 /D_{60} *D_{10}] = [0.46^2/1.23*0.161] = 1.06

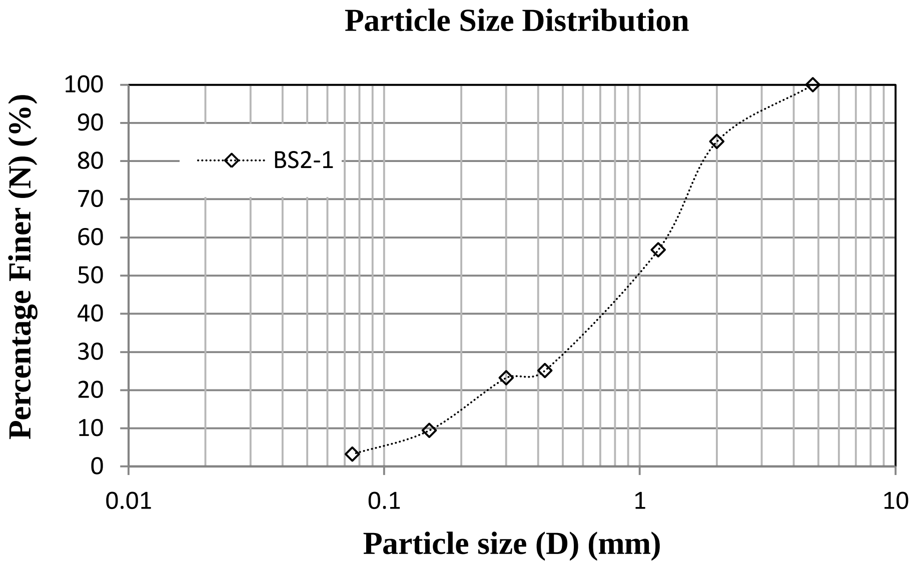
<u>Biosolids Sample – 2-1</u>

Total mass taken = 200 gm

Mass of soil retained on 0.075 mm IS Sieve = 185 gm

Mass of soil passing from 0.075 mm IS Sieve= 15gm

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve + BS (g)	Weight Retained (g)	% Retained	Cumulative % Retained	% Finer (N)
4.75	392	392	0	0	0	100
2	405.5	433	27.5	14.86	14.86	85.14
1.18	361	413.5	52.5	28.38	43.24	56.76
0.425	343.5	402	58.5	31.62	74.86	25.14
0.3	344	347.5	3.5	1.89	76.76	23.24
0.15	352.5	378	25.5	13.78	90.54	9.46
0.075	328.5	340	11.5	6.22	96.76	3.24
Pan	257.5	263.5	6	3.24	100.00	0.00
Sum			185			



From Graph,

D_{10} = 0.178

D_{60} = **1.4**

D_{30} = 0.52

C_u and C_C is calculated using the following equations,

C_u = [D_{60} / D_{10}] = [1.4/0.178] = 7.87

C_c = [D_{30}^2 /D_{60} *D_{10}] = [0.52^2/1.4*0.178] = 1.08

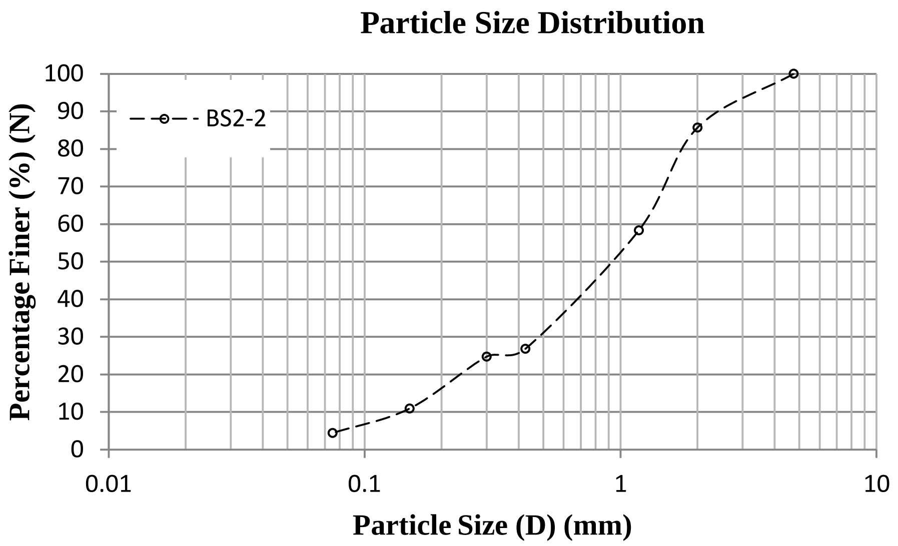
<u>Biosolids Sample -2-2</u>

Total mass taken = 200 gm

Mass of soil retained on 0.075 mm IS Sieve = 192 gm

Mass of soil passing from 0.075 mm IS Sieve= 8 gm

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve + BS (g)	Weight Retained (g)	% Retained	Cumulative % Retained	% Finer (N)
4.75	392	392	0	0	0	100
2	405.5	433	27.5	14.32	14.32	85.68
1.18	361	413.5	52.5	27.34	41.67	58.33
0.425	343.5	404	60.5	31.51	73.18	26.82
0.3	344	348	4	2.08	75.26	24.74
0.15	352.5	379	26.5	13.80	89.06	10.94
0.075	328.5	341	12.5	6.51	95.57	4.43
Pan	257.5	266	8.5	4.43	100.00	0.00
Sum			192			



From Graph,

D_{10} = 0.152

D_{60} = 1.4

D_{30} = 0.49

C_u and C_C is calculated using the following equations,

C_u = [D_{60} / D_{10}] = [1.4/0.152] = 9.21

C_c = [D_{30}^2 /D_{60} *D_{10}] = [0.49^2/1.4*0.152] = 1.12

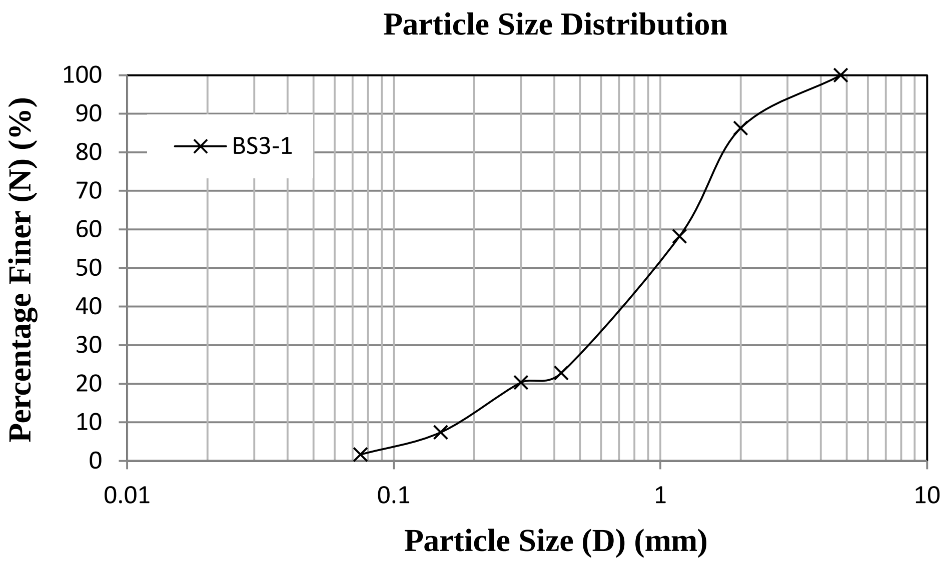
<u>Biosolids Sample – 3-1</u>

Total mass taken = 200 gm

Mass of soil retained on 0.075 mm IS Sieve = 182 gm

Mass of soil passing from 0.075 mm IS Sieve= 18 gm

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve + BS (g)	Weight Retained (g)	% Retained	Cumulative % Retained	% Finer (N)
4.75	392	392	0	0	0	100
2	405.5	430.5	25	13.74	13.74	86.26
1.18	361	412	51	28.02	41.76	58.24
0.425	343.5	408	64.5	35.44	77.20	22.80
0.3	344	348.5	4.5	2.47	79.67	20.33
0.15	352.5	376	23.5	12.91	92.58	7.42
0.075	328.5	339	10.5	5.77	98.35	1.65
Pan	257.5	260.5	3	1.65	100.00	0.00
Sum			182			



From Graph,

D_{10} = 0.19

D_{60} = 1.39

D_{30} = 0.58

C_u and C_C is calculated using the following equations,

C_u = [D_{60} / D_{10}] = [1.39/0.19] = 7.32

C_c = [D_{30}^2 /D_{60} *D_{10}] = [0.58^2/1.39*0.19] = 1.27

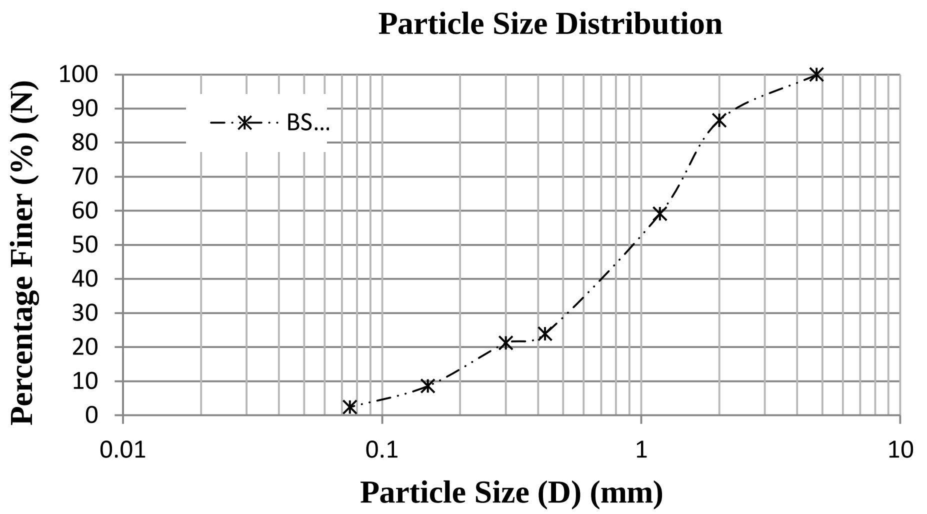
Biosolids Sample – 3-2

Total mass taken = 200 gm

Mass of soil retained on 0.075 mm IS Sieve = 186 gm

Mass of soil passing from 0.075 mm IS Sieve= 14 gm

Sieve Size (mm)	Weight of sieve (g)	Weight of sieve + BS (g)	Weight Retained (g)	% Retained	Cumulative % Retained	% Finer (N)
4.75	392	392	0	0	0	100
2	405.5	430.5	25	13.44	13.44	86.56
1.18	361	412	51	27.42	40.86	59.14
0.425	343.5	409	65.5	35.22	76.08	23.92
0.3	344	349	5	2.69	78.76	21.24
0.15	352.5	376	23.5	12.63	91.40	8.60
0.075	328.5	340	11.5	6.18	97.58	2.42
Pan	257.5	262	4.5	2.42	100.00	0.00
Sum			186			



From Graph,
D_{10} = 0.176
D_{60} = 1.39
D_{30} = 0.52
C_u and C_C is calculated using the following equations,
C_u = [D_{60} / D_{10}] = [1.39/0.176] = 7.90
C_c = [D_{30}^2 /D_{60} *D_{10}] = [0.52^2/1.39*0.176] = 1.11

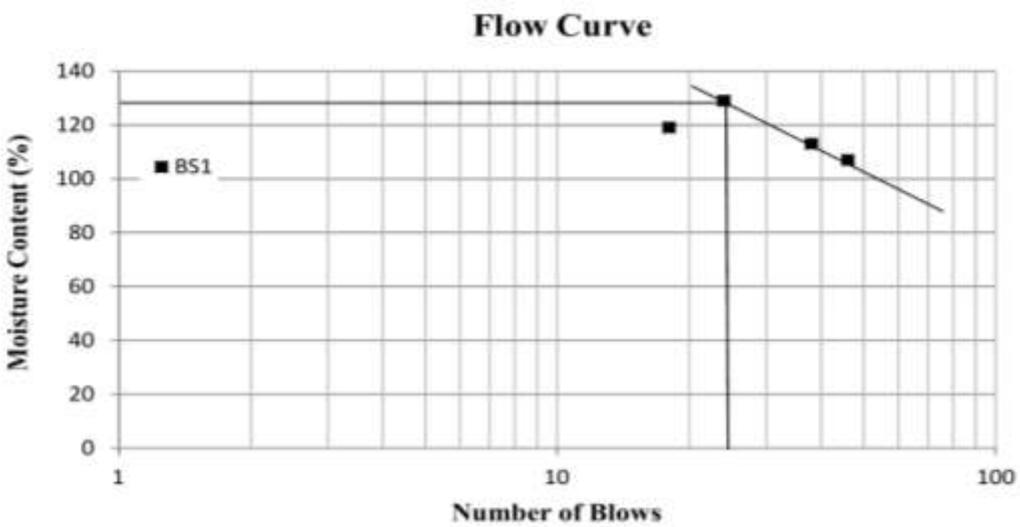
A.4 Liquid Limit Test Results

<u>Biosolid Sample No – 1</u>
Total mass of biosolid taken = 120 gm
IS sieve used = 425 micron
Temperature maintained in oven = 60^oC
Drying period = 26 hrs
Determination of Moisture content

Determination No.	**1**	**2**	**3**	**4**
1) No of Blows	18	24	38	46
2) Container No.	A1	A2	A3	A4
3) Mass of container (gm) (W_1)	19.5	20.7	19.1	20.4
4) Mass of container + wet soil (gm) (W_2)	26.3	24.2	24	23.5
5) Mass of container + dry soil (gm) (W_3)	22.6	22.23	21.4	21.9

6) Moisture content (%) = $\frac{(W2 - W3)}{(W3 - W1)} \times 100$	119	129	113	107

No of blows	Moisture content (%)
18	119
24	129
38	113
46	107



Result

Liquid Limit of Biosolids (LL) for sample (1) (%) =127

Biosolid Sample No – 2

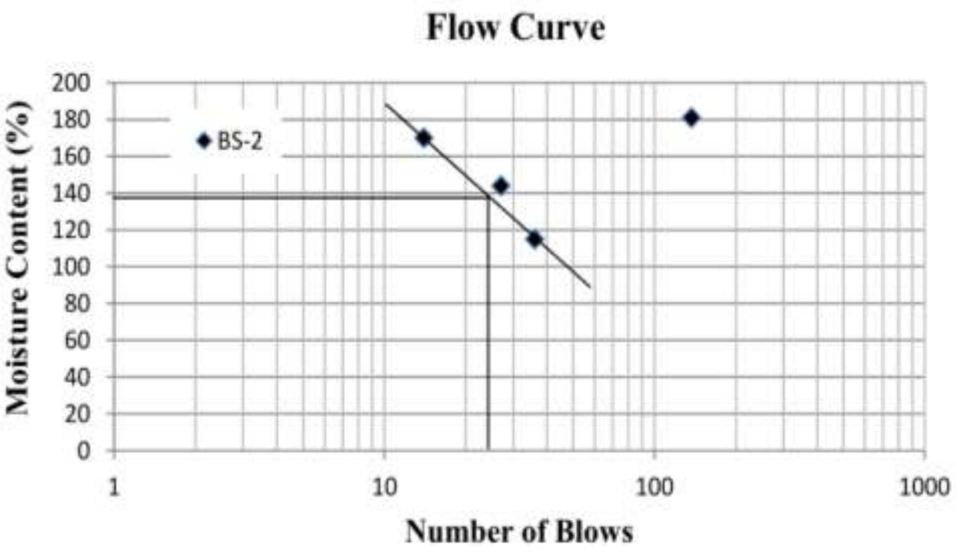
Total mass of biosolid taken = 120 gm
IS sieve used = 425 micron
Temperature maintained in oven = 60^{o}C
Drying period = 26 hrs

Determination of Moisture content

Determination No.	1	2	3	4
1) No of Blows	14	27	36	137
2) Container No.	A9	A10	A11	A12

3) Mass of container (gm) (W_1)	20.4	19.3	19.9	18.8
4) Mass of container + wet soil (gm) (W_2)	25.8	23.2	24.2	23.3
5) Mass of container + dry soil (gm) (W_3)	22.4	20.9	21.9	20.4
6) Moisture content (%) = $\frac{(W2 - W3)}{(W3 - W1)} \times 100$	170	144	115	181

No of blows	Moisture content (%)
14	170
27	144
36	115
137	181



Result

Liquid Limit of Biosolids (LL) for sample (2) (%) =138

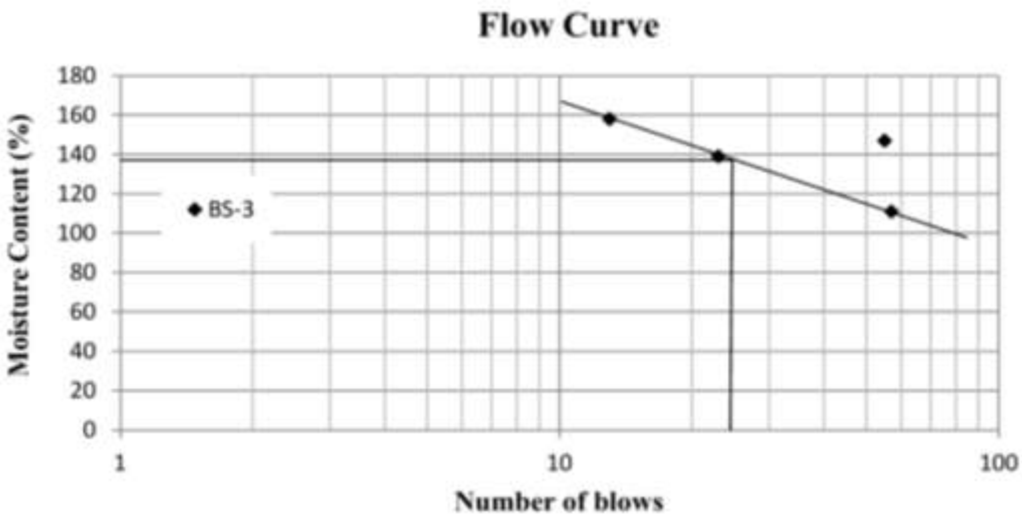
Biosolid Sample No – 3

Total mass of biosolid taken = 120 gm
IS sieve used = 425 micron
Temperature maintained in oven = 60^{o}C
Drying period = 26 hrs

Determination of Moisture content

Determination No.	1	2	3	4
No of Blows	13	23	55	57
Container No.	A9	A10	A11	A12
Mass of container (gm) (W_1)	19.3	19.6	19.1	19.3
Mass of container + wet soil (gm) (W_2)	24.2	25.34	22.8	23.3
Mass of container + dry soil (gm) (W_3)	21.2	22	20.6	21.2
Moisture content (%) = $\frac{(W2 - W3)}{(W3 - W1)} \times 100$	158	139	147	111

No of blows	Moisture content (%)
15	158
29	139
34	147
42	111



Result

Liquid Limit of Biosolids (LL) for sample (3) (%) =138

A.5 Plastic Limit Test Results

Total mass of biosolid taken = 30 gm
IS sieve used = 425 micron
Temperature maintained in oven = 60^{o}C
Drying period = 26 hrs

Biosolid Sample No.	**1**	**2**	**3**
Container No.	B1	B2	B3
Mass of container (gm) (W_1)	17.15	19.3	20.1
Mass of container + wet soil (gm) (W_2)	25.6	32.25	25.93
Mass of container + dry soil (gm) (W_3)	21.5	25.95	23
Moisture content (%) = $\frac{(W2 - W3)}{(W3 - W1)} \times 100$	94	95	101
Average Plastic Limit (%)	**96**		
Range	**(94 -101) %**		

A.6 Shrinkage Limit Test Results

Total mass of biosolid taken = 30 gm
IS sieve used = 425 micron
Temperature maintained in oven = $60^{o}C$
Drying period = 26 hrs

Soil Sample No.	1	2	3
Weight of Shrinkage Dish (g)	34.2	31.8	24.3
Weight of (SD^a +wet soil) (g)	61.1	56.6	52.9
Weight of wet soil (g) (W_1)	26.9	24.8	28.6
Weight of (SD+ dry soil) (g)	45.5	42	36.3
Weight of dry soil (g) (W_2)	11.3	10.2	12
Weight of empty Mercury dish (g)	308.8	308.8	308.8
Weight of (mercury dish+ mercury displaced)(g)	513.5	526.8	540
Weight of mercury displaced (g)	204.7	218	231.2
Volume of dry pat (V_2) (ml) (mass/density)	15	16	17
Volume of shrinkage dish (V_1) (ml)	25	24	24
Shrinkage Limit, (Ws) (%) = $\frac{[(W1-W2)-(V1-V2)*\text{density of water}]*100}{W2}$	50.8 ~ 51	65	80
Shrinkage Ratio, SR = (W_2/V_2*density of water)	0.75	0.64	0.71
Volumetric Shrinkage, VS = $(V_1-V_2)/V_2 *100$	65.54	49.72	41.18
a) Average Shrinkage Limit, Ws (%)	**65.26 ~ 65**	**-**	-
Range	**(51 to 80)**	**-**	-
b) Average Shrinkage Ratio, SR	**0.7**	**-**	-

Range	**(0.64 to0.75)**	**-**	-
c) Average Volumetric Shrinkage, VS	**52.14 ~ 52**	**-**	-
Range	**(41 to 65)**	**-**	-

[a] Shrinkage Dish

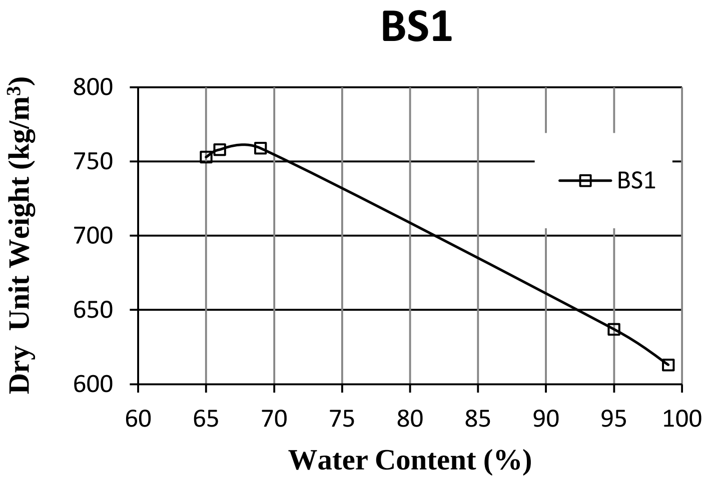
A.7 Compaction Test Results

Biosolid Sample No (1)

Type of Test = Standard Proctor Test (Light Compaction)
Diameter of Mould = 100 mm
Height of Mould = 127.3 mm
Volume of Mould = 1000 cc
Weight of Mould = 5.4863 kg
No. of Layers = 3
No. of Blows = 25

Mass of empty mould +base plate) (kg)	5.4863	5.4863	5.4863	5.4863	5.4863
Mass of (mould +base plate+ compacted soil) (kg)	6.7275	6.7474	6.768	6.726	6.7029
Mass of compacted soil (kg)	1.2412	1.2611	1.2817	1.2397	1.2166
Mass of compacted soil (g)	1241.2	1261.1	1281.7	1239.7	1216.6
Volume of mould (ml or cc)	1000	1000	1000	1000	1000
Bulk density (M/V) (g/ml)	1.2412	1.2611	1.2817	1.2397	1.2166
Water content (w)	0.648648649	0.663736264	0.689427	0.945205	0.985251
Dry Density (g/ml)	0.752859016	0.757992734	0.758659	0.637311	0.612819
Dry Density (kg/m^3)	753	758	759	637	613
Dry Density (kN/m^3)	7.4	7.4	7.4	6.2	6.0

Water Content Determination					
Mass of empty container (g) (W_1)	19.1	20.3	19.3	19.9	18.7
Mass of (Container + wet soil) (g)) (W_2)	80.1	96	96	76.7	86
Mass of (container +dry soil)(g)(W_3)	56.1	65.8	64.7	49.1	52.6
Water content (w)	0.648648649	0.663736264	0.689427	0.945205	0.985251
Water content (%)	65	66	69	95	99



Compaction Curve for Biosolid Sample No (1)

Water Content	Dry Density
65	753
66	758
69	759
95	637
99	613

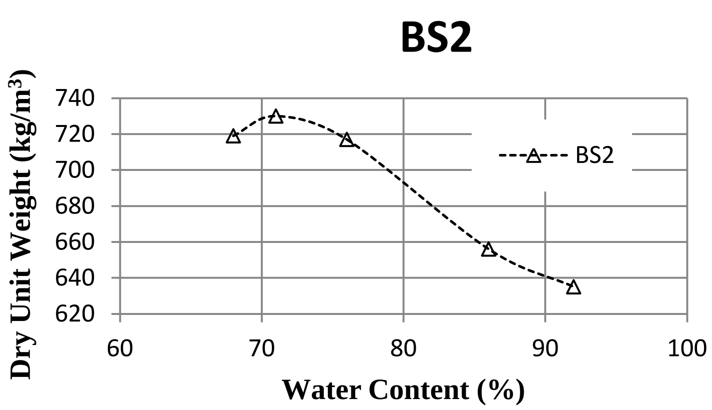
Results **1) OMC = 67.80%**
2) MDD = 760.2 kg/m^3 = 7.4 kN/m^3

Biosolid Sample No (2)

Type of Test = Standard Proctor Test (Light Compaction)
Diameter of Mould = 100 mm
Height of Mould = 127.3 mm
Volume of Mould = 1000 cc
Weight of Mould = 5.4863 kg
No. of Layers = 3
No. of Blows = 25

Mass of (empty mould +base plate) (kg)	5.4849	5.4849	5.4849	5.4849	5.4849
Mass of (mould+ base plate+	6.6923	6.7335	6.7459	6.7044	6.7031

compacted soil) (kg)					
Mass of compacted soil (kg)	1.2074	1.2486	1.261	1.2195	1.2182
Mass of compacted soil (g)	1207.4	1248.6	1261	1219.5	1218.2
Volume of mould (ml or cc)	1000	1000	1000	1000	1000
Bulk density (M/V) (g/ml)	1.2074	1.2486	1.261	1.2195	1.2182
Water content (%)	0.679525223	0.71043771	0.758333	0.859223	0.917476
Dry Density (g/ml)	0.71889364	0.729988583	0.717156	0.655919	0.635314
Dry Density (kg/m^3)	719	730	717	656	635
Dry Density (kN/m^3)	7.045	7.154	7.028	6.428	6.226
Water Content determination					
Mass of empty container (g) (W_1)	18.9	19.4	21.3	19.3	18.9
Mass of (Container +wet soil) (g)) (W_2)	75.5	70.2	84.6	95.9	97.9
Mass of (container +dry soil)(g)(W_3)	52.6	49.1	57.3	60.5	60.1
Water content (w)	0.679525223	0.71043771	0.758333	0.859223	0.917476
Water content (%)	68	71	76	86	92



<u>Compaction Curve for Biosolid Sample No (2)</u>

Water Content	Dry Density
68	719
71	730
76	717
86	656
92	635

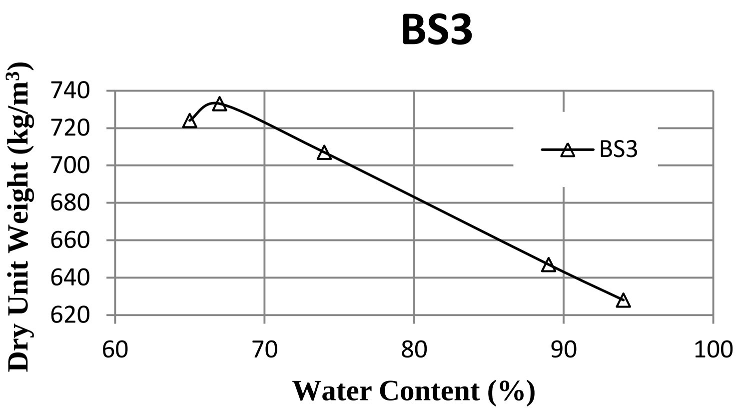
<u>Results</u> **1) OMC = 71%**

2) MDD = 731 kg/m^3 = 7.2 kN/m^3

Biosolid Sample No (3)
Type of Test = Standard Proctor Test (Light Compaction)
Diameter of Mould = 100 mm
Height of Mould = 127.3 mm
Volume of Mould = 1000 cc
Weight of Mould = 5.4863 kg
No. of Layers = 3

Mass of (empty mould +base plate) (kg)	5.4849	5.4849	5.4849	5.4849	5.4849
Mass of (mould +base plate +compacted soil) (kg)	6.681	6.7088	6.7187	6.7095	6.7031
Mass of compacted soil (kg)	1.1961	1.2239	1.2338	1.2246	1.2182
Mass of compacted soil (g)	1196.1	1223.9	1233.8	1224.6	1218.2
Volume of mould (ml or cc)	1000	1000	1000	1000	1000
Bulk density (M/V) (g/ml)	1.1961	1.2239	1.2338	1.2246	1.2182
Water content (%)	0.652733119	0.669312169	0.744076	0.891967	0.940887
Dry Density (g/ml)	0.723710311	0.733176228	0.707423	0.647263	0.627651
Dry Density (kg/m^3)	724	733	707	647	628
Dry Density (kN/m^3)	7.092	7.185	6.933	6.343	6.151
Water Content determination					
Mass of empty container (g) (W_1)	19.1	19.3	19.1	19.4	18.9
Mass of (Container +wet soil) (g)) (W_2)	70.5	82.4	92.7	87.7	97.7
Mass of (container +dry soil)(g)(W_3)	50.2	57.1	61.3	55.5	59.5
Water content (w)	0.652733119	0.669312169	0.744076	0.891967	0.940887
Water content (%)	65	67	74	89	94

Compaction Curve for Biosolid Sample No (2)



Water Content	Dry Density
65	724
67	733
74	707
89	647
94	628

Results **1) OMC = 66.20%**
2) MDD = 734 kg/m^3 = 7.2 kN/m^3

Standard compaction test results

Parameters \ Sample No.	Sample No (1)	Sample No (2)	Sample No (3)
MDD (kg/m^3)	760	731	734
OMC (%)	67.8	71	66.20
Average value of MDD (kg/m^3)	742	-	-
Average value of OMC (%)	68	-	-
Range (MDD) (kg/m^3)	(731 to 760)	-	-
Range (OMC) (%)	(66 to 71)	-	-

A.8 California Bearing Ratio Test Results (For Soaked Condition)

Biosolid Sample No-1

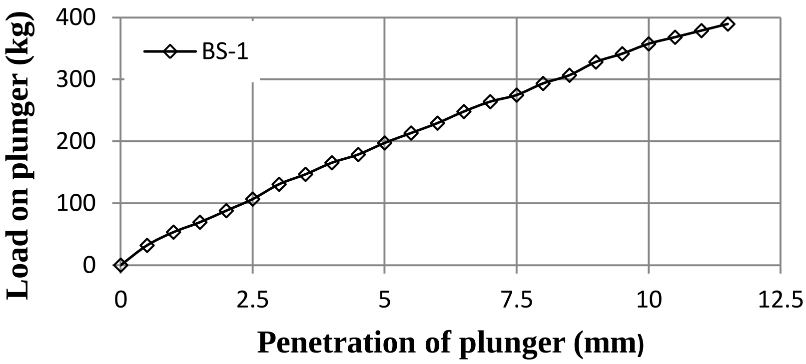
Type of Test – CBR (Using Standard Compaction Effort)

Dial Gauge Readings

Penetration (mm)	Load Dial gauge Reading	Load (kg)
0	0	0
0.5	1.2	31.992
1	2	53.32
1.5	2.6	69.316
2	3.3	87.978
2.5	4	106.64
3	4.9	130.634
3.5	5.5	146.63
4	6.2	165.292
4.5	6.7	178.622
5	7.4	197.284
5.5	8	213.28
6	8.6	229.276
6.5	9.3	247.938
7	9.9	263.934
7.5	10.3	274.598
8	11	293.26
8.5	11.5	306.59
9	12.3	327.918

9.5	12.8	341.248
10	13.4	357.244
10.5	13.8	367.908
11	14.2	378.572
11.5	14.6	389.236

Load Penetration curve for Biosolid (Sample No-1)



Results

CBR (2.5 mm) (%) = 8

CBR (5mm) (%) = 10

Biosolid Sample No-2

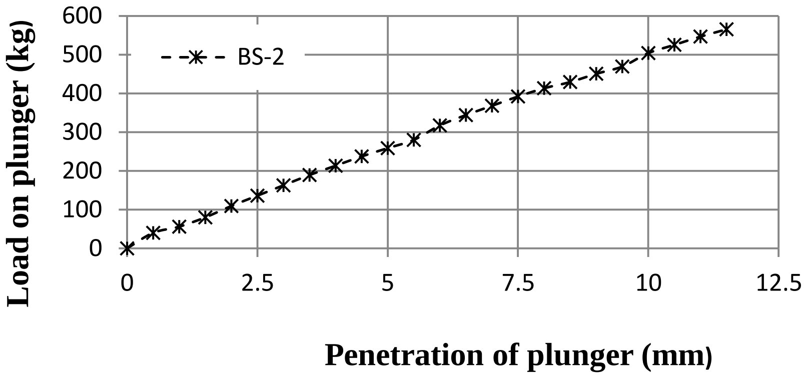
Type of Test – CBR (Using Standard Compaction Effort)

Dial Gauge Readings

Penetration (mm)	Load Dial gauge Reading	Load (kg)
0	0	0
0.5	1.5	39.99
1	2.1	55.986
1.5	3	79.98
2	4.1	109.306
2.5	5.1	135.966
3	6.1	162.626
3.5	7.1	189.286
4	8	213.28
4.5	8.9	237.274
5	9.7	258.602
5.5	10.5	279.93
6	11.9	317.254
6.5	12.9	343.914
7	13.8	367.908
7.5	14.7	391.902
8	15.5	413.23
8.5	16.1	429.226
9	16.9	450.554
9.5	17.6	469.216

10	18.9	503.874
10.5	19.7	525.202
11	20.5	546.53
11.5	21.2	565.192

Load Penetration curve for Biosolid (Sample No-2)



Results

CBR (2.5 mm) (%) = 10

CBR (5mm) (%) = 13

Biosolid Sample No-3

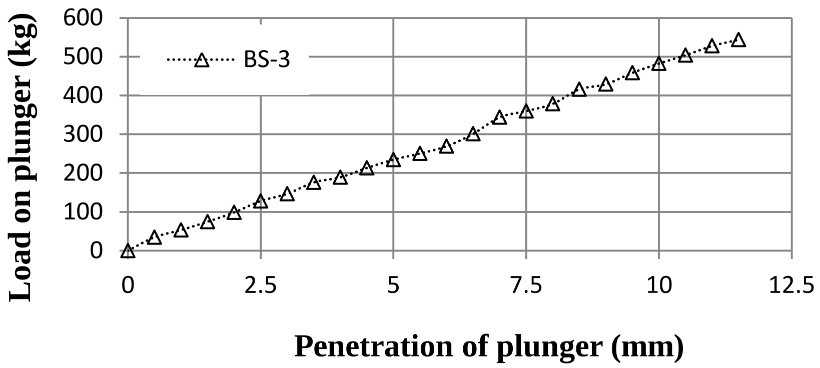
Type of Test – CBR (Using Standard Compaction Effort)

Dial Gauge Readings

Penetration (mm)	Load Dial gauge Reading	Load (kg)
0	0	0
0.5	1.3	34.658
1	2	53.32
1.5	2.8	74.648
2	3.7	98.642
2.5	4.8	127.968
3	5.5	146.63
3.5	6.6	175.956
4	7.1	189.286
4.5	8	213.28
5	8.8	234.608
5.5	9.4	250.604
6	10.1	269.266
6.5	11.3	301.258
7	12.9	343.914
7.5	13.5	359.91
8	14.2	378.572
8.5	15.6	415.896
9	16.1	429.226
9.5	17.2	458.552
10	18.1	482.546

10.5	18.9	503.874
11	19.8	527.868
11.5	20.4	543.864

Load Penetration curve for Biosolid (Sample No-3)



Results

CBR (2.5 mm) (%) = 9

CBR (5mm) (%) = 11

A.9 California Bearing Ratio Test Results (For Un-Soaked Condition)

Biosolid Sample No-1

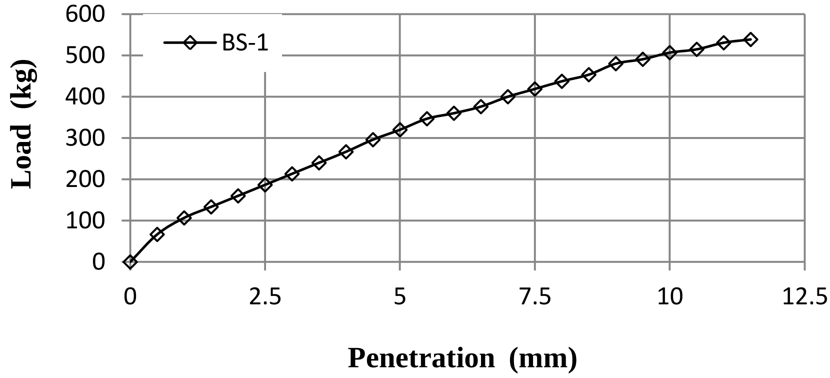
Type of Test – CBR (Using Standard Compaction Effort)

Dial Gauge Readings

Penetration (mm)	Load Dial gauge Reading	Load (kg)
0	0	0
0.5	2.5	66.65
1	4	106.64
1.5	5	133.3
2	6	159.96
2.5	7	186.62
3	8	213.28
3.5	9	239.94
4	10	266.6
4.5	11.1	295.926
5	12	319.92
5.5	13	346.58
6	13.5	359.91
6.5	14.1	375.906
7	15	399.9
7.5	15.7	418.562
8	16.4	437.224
8.5	17	453.22
9	18	479.88
9.5	18.4	490.544

10	19	506.54
10.5	19.3	514.538
11	19.9	530.534
11.5	20.2	538.532

Load Penetration curve for Biosolid (Sample No-1)



Results

CBR (2.5 mm) (%) = 14

CBR (5mm) (%) = 16

Biosolid Sample No-2

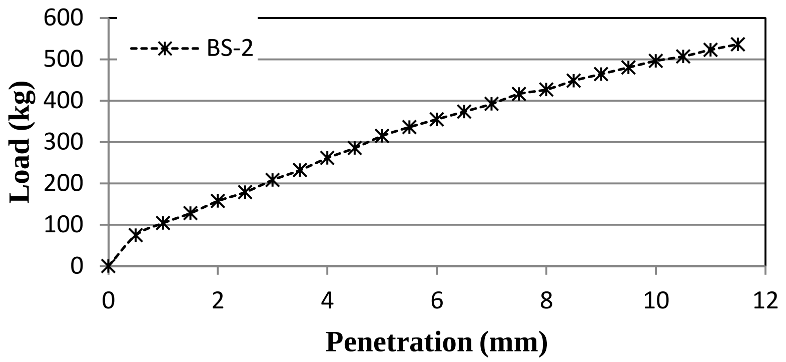
Type of Test – CBR (Using Standard Compaction Effort)

Dial Gauge Readings

Penetration (mm)	Load Dial gauge Reading	Load (kg)
0	0	0
0.5	2.8	74.648
1	3.9	103.974
1.5	4.8	127.968
2	5.9	157.294
2.5	6.7	178.622
3	7.8	207.948
3.5	8.7	231.942
4	9.8	261.268
4.5	10.7	285.262
5	11.8	314.588
5.5	12.6	335.916
6	13.3	354.578
6.5	14	373.24
7	14.7	391.902
7.5	15.6	415.896
8	16	426.56
8.5	16.8	447.888
9	17.4	463.884
9.5	18	479.88
10	18.6	495.876

10.5	19	506.54
11	19.6	522.536
11.5	20.1	535.866

Load Penetration curve for Biosolid (Sample No-2)



Results

CBR (2.5 mm) (%) = 13

CBR (5mm) (%) = 15

Biosolid Sample No-3

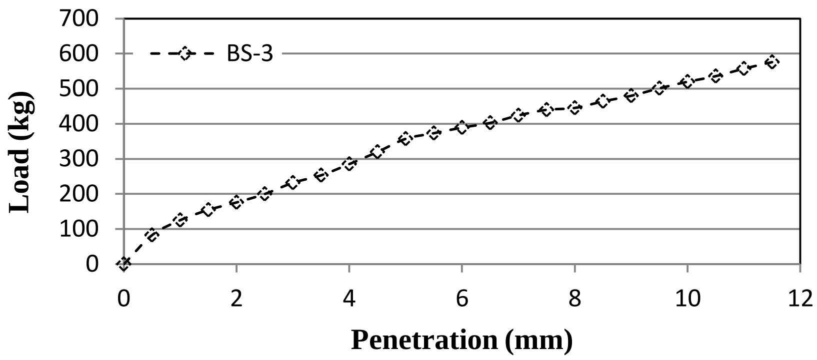
Type of Test – CBR (Using Standard Compaction Effort)

Dial Gauge Readings

Penetration (mm)	Load Dial gauge Reading	Load (kg)
0	0	0
0.5	3.1	82.646
1	4.7	125.302
1.5	5.8	154.628
2	6.6	175.956
2.5	7.5	199.95
3	8.7	231.942
3.5	9.5	253.27
4	10.7	285.262
4.5	12	319.92
5	13.4	357.244
5.5	14	373.24
6	14.6	389.236
6.5	15.1	402.566
7	15.9	423.894
7.5	16.5	439.89
8	16.7	445.222
8.5	17.4	463.884
9	18	479.88
9.5	18.8	501.208
10	19.5	519.87

10.5	20.1	535.866
11	20.9	557.194
11.5	21.6	575.856

Load Penetration curve for Biosolid (Sample No-3)



Results

CBR (2.5 mm) (%) = 15

CBR (5mm) (%) = 17

APPENDIX-B

Results of Theoretical Analysis of Biosolids

B.1 Theoretical Modeling

	pH=2	**pH=3**	**pH=4.23**	**pH=5**	**pH=6**	**pH=7**	**pH=8**	**pH=9**	**pH=10**	**pH=11**	**pH=12**
Time (year)	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$	$S_{b\ (m)}$
0	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142
0.5	0.142	0.153	0.257	0.422	0.779	0.231	0.623	0.422	0.223	0.153	0.142
1	0.143	0.165	0.354	0.586	0.754	0.781	0.754	0.586	0.296	0.165	0.143
3	0.147	0.208	0.596	0.777	0.8	0.8	0.8	0.777	0.504	0.208	0.147
5	0.15	0.249	0.706	0.798	0.8	0.8	0.8	0.798	0.626	0.249	0.15
7	0.154	0.286	0.757	0.8	0.8	0.8	0.8	0.8	0.698	0.286	0.154
10	0.159	0.388	0.787	0.8	0.8	0.8	0.8	0.8	0.754	0.388	0.159
15	0.167	0.413	0.798	0.8	0.8	0.8	0.8	0.8	0.788	0.413	0.167
22	0.179	0.498	0.8	0.8	0.8	0.8	0.8	0.8	0.798	0.498	0.179
30	0.192	0.573	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.573	0.192
35	0.2	0.61	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.61	0.2
50	0.233	0.688	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.688	0.233
70	0.253	0.745	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.745	0.253
90	0.282	0.773	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.773	0.282
100	0.295	0.781	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.781	0.295
150	0.358	0.797	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.797	0.358
200	0.413	0.799	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.799	0.413
250	0.461	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.461
300	0.503	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.503
500	0.625	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.625
700	0.697	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.697
1000	0.754	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.754

1100	0.765	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.765
1500	0.788	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.788
2100	0.798	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.798
2500	0.799	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.799

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