Geotechnical properties of biosolids stabilised with lime and cement

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ABSTRACT

Biosolids are a mixture of water and organic material, which are a by-product from domestic and industrial sewage treatment processes. Biosolids for this research were obtained from a wastewater treatment plant located in west of Melbourne, Australia. As part of this research, an extensive suite of geotechnical tests were undertaken on wastewater biosolids stabilised with the optimum percentage of lime and cement, to evaluate their properties and potential use as an embankment structural fill material. Engineering tests undertaken include moisture content, specific gravity, Atterberg limits, particle size analysis, organic content, standard compaction, California Bearing Ratio, hydraulic conductivity, pH, consolidation and unconfined compression strength. This paper describes the procedures followed to determine the optimum dosage of lime and cement as stabilisers for biosolids samples. Test results on pure biosolids indicate high initial moisture content, Low pH value and average organic content compare to other organic soils. The standard compaction results indicate that the stabilisation of biosolids with both additives increase the maximum dry density and decrease the optimum water content. Reduction in liquid limit and plasticity index was noticed when additives were added to biosolids. Results indicate that the hydraulic conductivity values of biosolids decrease with optimum percentage of additives, which is an indication of decreasing void ratio of material. The compressibility of biosolids was improved by additives specially lime treated samples. Both stabilisers significantly raise the CBR value and unconfined compressive strength of pure biosolids. Possible applications of the stabilised mixture in road embankments are also discussed.

Keywords: biosolids, wastewater, stabilisation, additives

1 INTRODUCTION

Geotechnical aspects of waste and recycled materials have been studied in the past two decades in many countries. One of the main challenges of these studies is finding an innovative way to reuse these solid wastes in a variety of engineering applications as substitutes for virgin materials in construction industry. In theory, reusing the recycled materials seems to be a simple solution while in reality there are several difficulties to assure that end users, such as road authorities, will accept and reuse these waste materials as a substitute for naturally occurring materials. Consequently, technical feasibly assessments such as extensive laboratory testing, numerical modelling and in some cases field trial testing are required to meet the road authorities, consultants and contractors requirements.

Biosolids are solid waste by-product from sewage treatment process, comprising mainly a mix of organic and inorganic compounds including household and industrial wastes. ANZBP (2013) reported the production of solid biosolids is approximately 330,000 tonnes per year in Australia. The average solids content of biosolids is around 30% and this equates to approximately 1.3 million tonnes of biosolids in dewatered form, which is also called wet. Furthermore, almost 30% of biosolids (96,000 tonnes dry basis) is generated in the state of Victoria where most biosolids are produced in Western and Eastern wastewater treatment plants (ANZBP, 2013).

Biosolids samples for this research were collected from biosolids stockpiles at a wastewater treatment plant, which is located approximately 30 km west of Melbourne. The treatment plant currently serves over 20,000 properties in Melbourne western suburbs and treats a flow of nearly 13 million litres of sewage a day (CWW, 2014). The treatment process starts from the time that the raw sewage enters the plants. Initially, cotton buds, bits of plastic and debris are removed from the sewage. Next, biosolids are separated from the treated sewage and cleaned for the second time (CWW, 2014). Then, the left over water is removed from the biosolids, loaded into holding bins and taken to a recycling facility. The biosolids sampled for this research were air-dried for almost eight years and collected from an old lagoon.

The geotechnical characteristics of pure biosolids are similar to commonly found organic soils in nature (Disfani, 2011). Organic soils naturally have low shear strength and high compressibility, which can be problematic in construction of roadways (Hampton and Edil, 1998). The key design parameters in roadwork and highway embankments are mainly obtained from the results of compaction, consolidation and strength tests (Arulrajah et al., 2011). Maghoolpilehrood et al. (2013) reported that untreated biosolids have a soaked CBR of about 1.0%, indicating poor load bearing characteristics, which requires treatment with appropriate additives in order to be used as a substitution for embankment fill material. Lim et al. (2002) reported a CBR value of 2.74% for compacted sewage sludge and higher values for treated biosolids with lime and fly ash.

Ciancio et al. (2014) studied the interaction between lime and soil. Their study indicates that lime stabilisation improves the strength, stiffness, plasticity/workability and water absorption of the raw soil. According to this study the lime-soil reaction can be described as cation exchange, pozzolanic reaction or carbonation. Cation exchange normally occurs in presence of water while pozzolanic reaction is temperature related, and carbonation happens when lime reacts with carbon dioxide present in the air (Ciancio et al., 2014).

Chemical stabilisation increases soil strength and stiffness through chemical reactions (Tastan et al., 2011). Lim et al. (2006) claimed that by adding cement to organic soils such as biosolids the compressibility and stiffness of materials improved to support light structures in some applications as a fill material. The short-term effect of chemical stabilisation results in improved workability and provides an immediate reduction in settlement, plasticity indices, swell and shrinkage potential. In the long-term, chemical reactions are accomplished over a period of time depending on the rate of chemical breakdown and hydration of the silicates and aluminates which can result in further amelioration and binds soil grains together by the formation of cementitious materials (Lim et al., 2002). For cementation to occur and enhance over this long-term period, sufficient sources of pozzolans, either from the soil itself or from the chemical additive, is required (Lim et al., 2002; Tastan et al., 2011). Results of the existing research studies indicate that treated biosolids have higher strength properties, improved permeability and lower secondary consolidation values (Maghoolpilehrood et al., 2013). The current research was conducted to determine the geotechnical properties of biosolids when mixed with different percentages of cement and lime.

Geotechnical laboratory tests in accordance with relevant Australian or ASTM testing methods were undertaken on samples of biosolids and their mixtures with cement and lime to determine their geotechnical characteristics. The suite of laboratory tests undertaken included moisture content, specific gravity, Atterberg limits, particle size analysis, organic content, standard compaction, California Bearing Ratio, hydraulic conductivity, pH, consolidation and unconfined compression strength. Establishing the potential use of biosolids as a construction material in embankments is the main objective of this research.

2 MATERIALS AND METHODS

A series of laboratory tests were performed on specimens collected from biosolids stockpiles at waste water treatment plant in Melbourne. Laboratory experiments were conducted on untreated biosolids along with biosolids stabilised with 5% lime and 5% cement. The optimum dosages of lime and cement were selected based on a series of laboratory tests. All test specimens were cured for a period of 24 hours, at room temperature of 20-25 °C and relative humidity of 95% to 99%, prior to the laboratory testing.

The biosolids samples were taken from several spots at a depth of 0.2 to 1 m from old lagoon in the treatment plant. Then, the samples were mixed properly to obtain representative biosolids samples. Hydrated lime and ordinary General Purpose (GP) Portland cement were adopted to modify the biosolids in this study. Lime is chemically transforms unstable soils into a structurally sound construction foundation (Austroads, 1998). Lime is particularly important in road construction for modifying and improving the engineering properties of subgrade soils, subbase and base materials and also can be used to improve engineering characteristics of biosolids (Austroads, 1998). Portland cement can be used either to improve and modify the quality of soil or to transform the soil into a cemented mass, which significantly increases its strength and durability (Austroads, 1998).

The natural moisture content of biosolids was determined by drying the material at oven temperature of 50°C, as higher temperatures would cause loss of the organic content. The sieve analysis test was conducted according to the Australian standards (AS, 1996) to determine the grain size distribution curve of biosolids. For the fine-grained particles, hydrometer analysis was determined by following ASTM practice (ASTM, 2007a). Organic content test were conducted by the loss of ignition method ASTM practice (ASTM, 2007b). Particle density was undertaken according to Australian Standards (AS, 2000). Atterberg limits test was undertaken to determine the plastic and liquid limit of treated and untreated biosolids according to the Australian standard (AS, 2009). The pH values of biosolids and the mixtures were determined according to the Australian standards (AS, 1997). Standard proctor compaction effort was undertaken to determine the optimum moisture content (OMC) and maximum dry density (MDD) of treated and untreated biosolids samples following the Australian standard (AS, 2003). The samples were compacted in three layers, each layer by 25 blows with a 2.7 kg rammer falling freely from 300 mm in height.

California Bearing Ratio (CBR) tests were performed on specimens compacted at optimum water content using standard proctor compaction effort and soaked for four days with a 4.5 kg surcharge (AS, 1998). Unconfined Compressive Strength (UCS) tests were also conducted according to ASTM practice (ASTM, 2006). UCS specimens were compacted in three layers of predetermined mass using a standard proctor compaction machine and were cured for 1, 7 and 28 days. The compressibility characteristics of biosolids samples were determined using 63.5 mm diameter oedometer consolidation cells. The selected vertical stress levels for the oedometer tests were 30 kPa, 60 kPa, 120 kPa, 240 kPa, 480 kPa and loading duration of 1 day for each stage of consolidation, which was followed by an unloading sequence.

The optimum dosages of lime and cement were selected based on a series of laboratory tests. UCS test was used to determine the optimum dosage of cement for biosolids mixture following the TxDOT test procedure: Tex-120-E (TxDOT, 1999). To determine the optimum dosage of lime, pH concentration test results were analysed.

3 STABILISATION STUDIES

This section describes the procedures followed to determine the optimum dosages of lime and cement as stabilisers for biosolids samples.

3.1 Determination of optimum lime dosage

In this study, pH tests were undertaken to determine the optimum dosage of lime for biosolids samples. High pH has been widely used as an indicator of biochemical stabilisation because a pH above 11 leads to the immobilization of heavy metals as well as the destruction of pathogens and lowering of microbial activity (Kayser et al., 2011). A decrease in pH can lead to a surge in biodegradation of organic matter, and a subsequent decrease in strength. Because the organic content of biosolids is very high, limiting biodegradation is important and therefore, maintaining a pH above 11 is necessary (Kayser et al., 2011). On the other hand, Ciancio et al. (2013) suggested the optimum lime content is the minimum lime content required to produce a soil water pH of 12.4, which is also called lime-saturated solution.

Biosolids samples were dried at 50°C oven and sieved through 2.36 mm sieve. Different percentages of lime 3, 5, 7 and 9% were added to 30 g of biosolids samples by dry mass. Each biosolids and lime mixture was then mixed with 75 ml of distilled water in a 100 ml capacity beaker. After stirring the mixture properly, the pH of the mixture was measured at 0, 30, 60, 120, 180 and 240 mins intervals. *Figure 1* (a) shows pH values of mixtures versus the lime dosage in percentage for biosolids samples. The pH value of biosolids was significantly increased from 7.4 for pure biosolids to 12.1 when blended with 3% lime. Then, the growth of pH value trend of biosolids mixture plateaued when more than 5% lime was added. Therefore the 5% lime was selected as the optimum dosage representing the lowest amount of lime and nearly highest pH value.

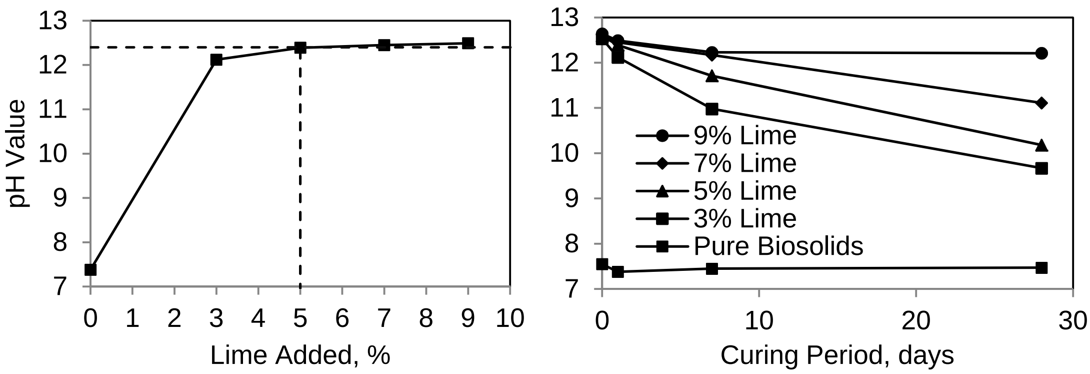

Figure 1(a). pH versus percent lime added (b). Variation of lime treated biosolids at different curing periods

The pH value of mixtures was also measured after 1,7 and 28 days intervals. The variations of pH values of lime treated and pure biosolids with curing period (days) are presented in *Figure 1* (b). The results illustrates that the pH values of lime treated mixtures has declined with curing time. This decline can be due to release of humic acid by organic substances in the Biosolids (Tastan et al., 2011). After 28 days of curing, the pH values of 5% lime treated biosolids were reduced by 19%. However, the pH value of untreated biosolids was initially decreased before starting to slightly increase after the first day.

3.2 Determination of optimum cement dosage

Optimum cement content of biosolids was determined using the TxDOT test procedure: Tex-120-E (TxDOT, 1999). Dosages of 0, 4, 8 and 10% cement content were used to prepare the specimens for UCS testing. The samples were compacted in 4 layers, each layer by 35 blows with a 2.7 kg hammer falling freely from 300mm in height. After the compaction and prior to shear test, the compacted samples were cured for 7 days inside the damp room. *Figure 2* illustrates the variation of cement dosage and the UCS values. *Figure 2* shows UCS values of cement treated specimen rose with the increase in amount of cement. The optimum cement content is defined as a percent of cement in a soil specimen that yields an UCS value of 1035 kPa (150 psi) for a treated subgrade soil at a 7-day curing period (TxDOT, 1999). Higher strengths (more than 1035 kPa) are not recommended because they can lead to cracking. The optimum cement dosage from this study for biosolids samples was 9%. However, the optimum cement percentage chosen for this research was 5%. This dosage was selected based on the CBR value of the mixture to use as embankment fill material.

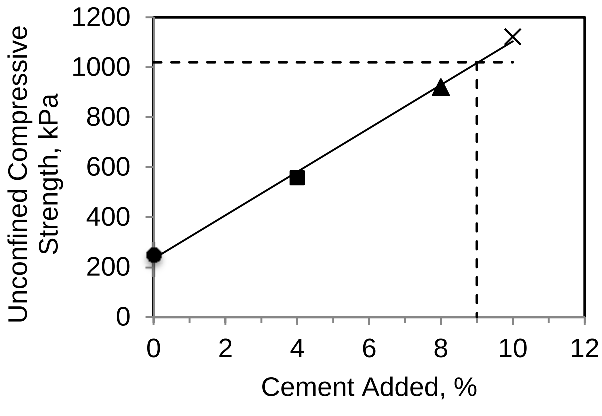

Figure 2. Determination of optimum cement dosage

4 RESULTS AND DISSCUSSIONS

The geotechnical properties of the stabilised biosolids are presented and compared with the values of the untreated biosolids in *Table 1*. The particle size distribution curve of biosolids sample is presented in *Figure 3*. This curve shows that biosolids contain around 50% of sand sized particles and more than 20% clay sized particles. The percentages of fine, sand and coarse frictions of biosolids are also presented in this figure.

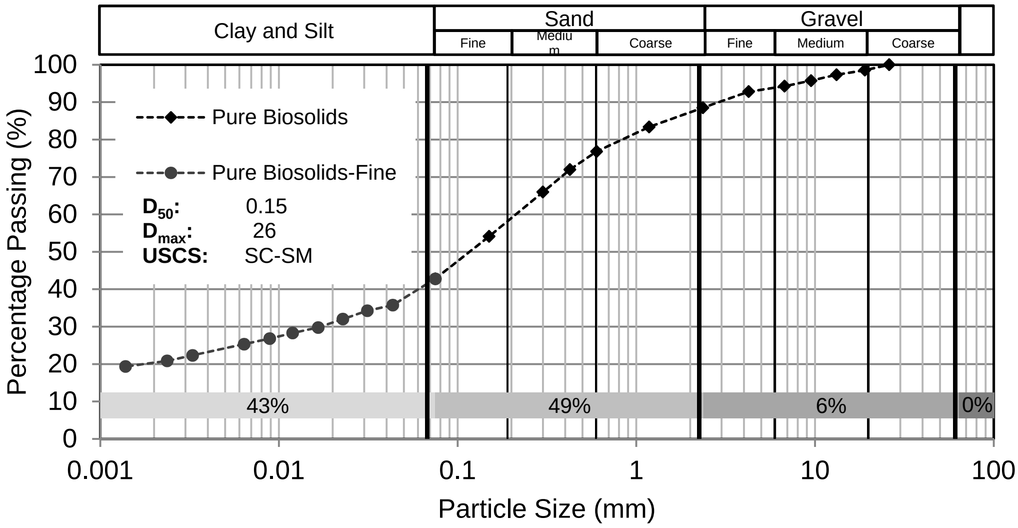

Figure 3. Gradation curves for biosolids

Organic content of biosolids was determined by the loss on ignition method. Karlsson and Hansbo (1989) stated soils having organic content in the range of 6% to 20% are characterized as medium organic soils. The average organic content of the biosolids was approximately 10% that can be classified as medium organic soil. The reason behind this low organic content compare to Western Treatment Plant (WPT) is a combination of clay from liner mixed with the Biosolids and the age of biosolids (Maghoolpilehrood et al., 2013).

Previous studies show that the specific gravity of the western treatment plant biosolids was 1.86-1.88, which is significantly lower than that of the inorganic soil and aggregates (Arulrajah et al., 2013). The specific gravity of the biosolids studied in this research was found to be 2.58, which is higher than the WPT biosolids. The high specific gravity of the biosolids is expected due to the high clay content in this material and a moderate organic content. The natural moisture content of the biosolids samples was found to be high around 40%, which is higher than its optimum moisture content.

Table 1: Engineering properties of stabilised biosolids

Engineering Parameters of stabilised biosolids	Pure Bio	Lime 5%	Cement 5%
Organic Content (%)	10.4	---	---
Specific Gravity, G_s	2.58	---	---
Natural Moisture Content in 50°C Oven (%)	33.6	---	---
Natural Moisture Content in 100°C Oven (%)	40	---	---
Optimum Moisture Content (%)	28	25.8	25.6
Maximum Dry Density (kN/m^3)	1.36	1.38	1.41
Liquid Limit (%)	61.5	51.7	60
Plastic Limit (%)	25.1	45	35
Plastic Index	36.4	6.6	25
Linear Shrinkage (%)	16.1	5.7	13
pH	7.38	12.39	---
California Bearing Ratio, CBR (%)	6	27	42
Unconfined Compressive Strength, UCS (kPa) 1 Day 7 Days 28 Days	 84 87 92	 96 148 159	 205 231 245
Coefficient of Consolidation, C_v (m^2/yr)	1	2.1	1.7
Coefficient of Volume Change, m_v (m^2/kN)	6.65×10^{-5}	1.91×10^{-5}	2.17×10^{-5}
Hydraulic Conductivity, k (m/s)	2.15×10^{-9}	1.24×10^{-9}	1.15×10^{-9}

Atterberg limits test were conducted to measure the plastic limits and liquid limits and corresponding plasticity index of the untreated and treated biosolids. The results of Atterberg limits of untreated and treated biosolids are shown in *Table 1*. The results show that the liquid limits would decrease and plastic limits would increase by adding both cement and lime. In cement blend, the liquid limit decreased slightly but plastic limit increased by 40%. Liquid limit of lime treated mixture declined by 16% and plastic limit raised by 80%. Both cement and lime admixtures have positive influence on reducing the plasticity index respectively by 30% and 80%. Higher reduction in plasticity index of biosolids was noticed in lime treated mixture.

Linear shrinkage tests were undertaken to determine the amount of shrinkage that the untreated and treated biosolids samples undergoes from their liquid limit to their shrinkage limit. The results of shrinkage limit of treated and untreated biosolids are expressed as a percentage in *Table 1*. The biosolids mixtures with lime and cement had lower linear shrinkage than pure biosolids. But again the decrease was significant in lime treated material, which was 5.7%, almost 65% lower than pure biosolids.

The compaction characteristics including OMC and MDD of treated and untreated biosolids that were obtained through standard compaction tests are summarised in *Table 1*. *Figure 4* shows that the dry density of biosolids would increase by the additives while the optimum moisture content would decrease. The addition of 5% cement increased the maximum dry density of biosolids by 3%.

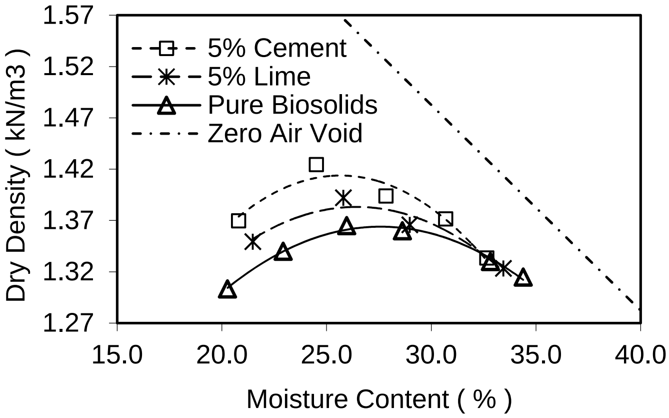

Figure 4. Compaction curves for pure and stabilised biosolids

The compressibility characteristics of biosolids samples were determined using 63.5 mm diameter oedometer consolidation cells. The specimens were compacted in one layer inside the standard compaction mould and then extruded by consolidation ring with the dimension of 20mm by 63.5 mm. The consolidation cells were filled by water immediately after starting the test to let specimen freely drainage from top and bottom. The loading sequence of 30-60-120-240-489 kPa and unloading sequence of 240-120-60-30 kPa were applied for duration of 1 day.

Figure 5 (a) shows the results of coefficient of consolidation calculated from consolidation test results. The variations of void ratio of each sample with the applied vertical pressure and coefficient of consolidation from consolidation test results are summarized in *Figure 5* (b). The results shows adding lime and cement significantly reduce the potential of blend for deformation and settlement. The lime stabilisation seems to be more effective in improving the compressibility and swelling behaviour of biosolids.

The hydraulic conductivity properties of the untreated and stabilised biosolids with lime and cement were computed from the maximum stresses of oedometer results for the coefficient of consolidation and indicate the biosolids to have a low permeability. The results of permeability tests are shown in *Table 1*. This results on stabilised biosolids indicate the coefficient of permeability range of 1.01 × 10-7 to 1.49 × 10-7 which is considered very low according to permeability classification.

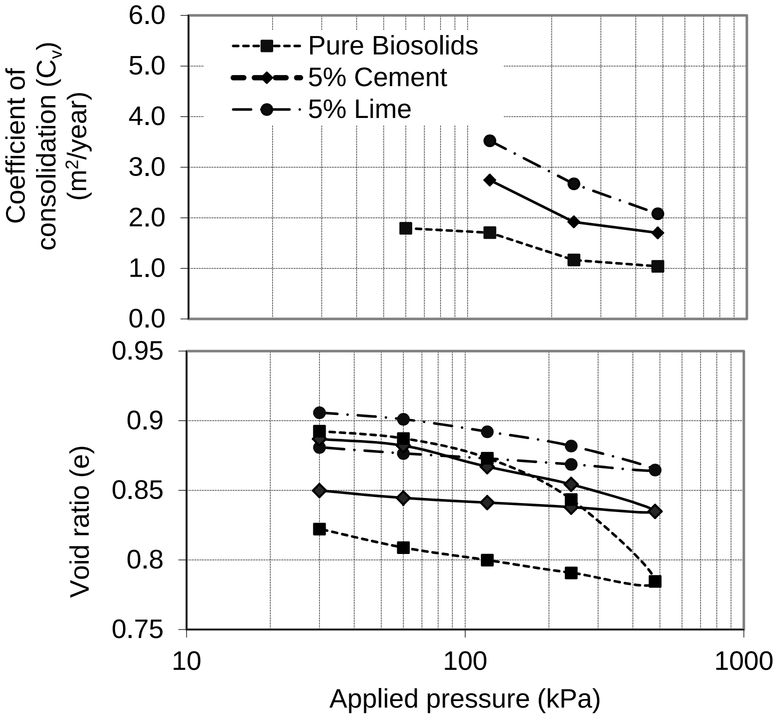

Figure 5 (a). Coefficient of consolidation versus applied pressure (b) void ratio versus applied pressure

CBR tests were performed in accordance with Australian Standard "Soil strength and consolidation tests – Determination of the California Bearing Ratio of a soil – Standard laboratory method for a remoulded specimen" (AS, 1998). The samples were compacted at their OMC and MDD content using standard compactive effort and tested upon completion of four days soaking condition. *Table 1* shows the CBR value of pure biosolids significantly increased by additives. The CBR value of cement treated biosolids was found to be higher than alternative lime treated samples. UCS tests were performed in accordance with ASTM practice (ASTM, 2006). UCS samples were compacted in three layers using standard compactive effort and were cured for 1, 7 and 28 days. *Figure 6* shows UCS values of pure and stabilised biosolids. Curing period was found to lead to an increase in the mean UCS value for all samples. The results show adding cement and lime will significantly increase the strength of biosolids.

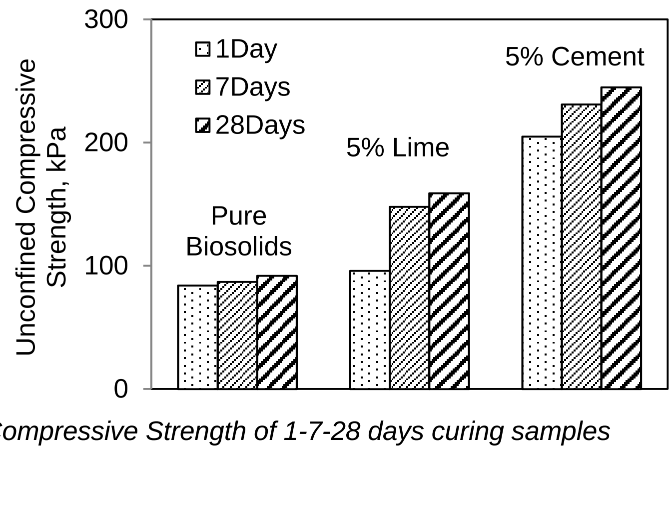

Figure 6. Unconfined Compressive Strength of 1-7-28 days curing samples

5 CONCLUSIONS

Biosolids samples were collected from the wastewater treatment plant in Melbourne, Australia and tested to investigate their geotechnical characteristics in both untreated and stabilised conditions. After stabilisation studies, 5% cement and 5% lime were chosen as optimum percentage of additive. Reduction in liquid limit and plasticity index was noticed while additives were added to biosolids. The shrinkage value of untreated biosolids was decreased significantly down to 65% by adding lime.

The influence of 7 and 28 days curing shows the decline in pH value of lime treated mixtures. The experimental laboratory results indicate that the maximum dry density of biosolids increases with both stabilisers while the optimum moisture content decreases. Cement and lime stabilised biosolids has been found to be a viable fill material for embankments. The stabilised biosolids meet the requirements of a Type B embankment fill material. The CBR values of the stabilised biosolids meet the minimum value of 2 specified by the local state road authorities for a Type B fill material.

Consolidation test results of stabilised biosolids provided coefficient of consolidation results that are useful for predicting settlements of stabilised biosolids embankments. The addition of lime seems to be more effective in improving the compressibility and also swelling behaviour of biosolids while increasing the strength to some extent. The addition of cement is more effective in increasing the strength of biosolids mixture. Further research is recommended on the impact of cement-lime blends on stabilising biosolids.

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