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Physical properties and compaction characteristics of ETP and WTP biosolids

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ABSTRACT

In Australia, over 300,000 dry tonnes of biosolids are produced and millions of dollars expended for their management annually. Biosolids are the end product and the main solid component collected from the wastewater treatment process. In this study, some of the geotechnical properties of two biosolids samples from the Eastern Wastewater Treatment Plant (ETP) and Western Wastewater Treatment Plant (WTP) in Melbourne were investigated. Laboratory tests, including liquid limit, plastic limit, particle density, particle size distribution, organic content, linear shrinkage, and chemical analysis were undertaken to evaluate the properties of each biosolids sample. The compaction characteristics of the ETP biosolids combined with different percentages of clayey sand were investigated, to gauge the suitability for use as possible construction and road materials. This paper presents some of the results of this ongoing investigation.

Keywords: Compaction, Biosolids, Organic soil, Recycling, Waste management

1 INTRODUCTION

Biosolids are normally referred to as the major by-product of the wastewater sludge treatment process. Sludge is a sticky liquid, which, generally, contains up to 8% of dry solids and is collected from the wastewater treatment process, but, which has not undergone further treatment (AWA, 2012). In contrast, Melbourne Water biosolids contain between 50% and up to 96% of solids, and, have undergone further treatment to significantly reduce volatile organic matter, thereby producing a stabilised product suitable for beneficial uses (ANZBP, 2012).

Over the decades, the growth of implementing new treatment plants, continuous upgrading of treatment processes, and stringent controls concerning the quality of wastewater discharges have given rise to increasing the annual production of biosolids (Rulkens, 2007, Arulrajah et al., 2011, O'Kelly, 2004). Australia currently produces approximately 300,000 dry tonnes of biosolids annually, from which over half (55%) is applied to agricultural land for beneficial use. In addition, just under a third (30%) is disposed of in land fill or stockpiled and the balance (15%) is used in composting, forestry, land rehabilitation or incinerated (AWA, 2012). Furthermore, in 2013, Melbourne Water produced around 78,650m³ of biosolids, and it is important to point out that 3,000,000m³ of biosolids are presently stock-piled at the Eastern Treatment Plant (ETP) and Western Treatment Plant (WTP) in Melbourne, which are suitable for forestry, farming, producing energy and structural fill (Melb. Water, 2014). It is notable that, in Australia, the average cost for biosolids management is in the order of A\$300 per dry tonne, which equates to about A\$90 million per year. As a similar trend has been observed in recent years in several developed and developing countries, it is of great interest and widely accepted throughout the world that there is an urgent need for reusing biosolids in a sustainable way.

Although attempts have been made to understand the engineering properties of biosolids, they are limited, and need further investigation. The characteristics of sludge and biosolids have been studied in various countries including Australia, Hong Kong, the United States, Turkey, Singapore, and England (Puppala et al., 2007, Hundal et al., 2005, O'Kelly, 2004, Arulrajah et al., 2011)

Puppala et al. (2007) evaluated the physical and engineering properties of a control cohesive soil amended with two types of material, biosolids and dairy manure. This study concluded that the biosolids and the dairy manure compost can provide engineering benefits to control soil when used in

moderate proportions, because the physical and engineering properties are directly related to the amount of organic matter present in the biosolids and dairy manure.

O'Kelly (2004) presented the geotechnical characteristics of the sludge from the Tullamore municipal wastewater treatment plant in the United Kingdom. The properties including compaction, shear strength, and consolidation were determined to assess its suitability as a landfill (sludge-to-landfill) material. In this study, sludge was dewatered to the optimum moisture content (OMC) for compaction, placed in a landfill in layers and compacted to the maximum dry density (MDD), thereby maximising the operational life of the landfill site. The geometry of the landfill is of the utmost importance in terms of its stability, and, therefore, effective-stress strength properties were used to determine the factor of safety against the slope stability of the landfill.

Arulrajah et al. (2011) reviewed the research of Hundal et al. (2005) who studied the geotechnical characteristics of untreated biosolids including the compressibility, consolidation, and shear strength parameters. The biosolids samples were obtained from a municipal wastewater treatment plant in Chicago, USA. Based on the experimental results, Hundal et al. (2005) concluded that the biosolids can be regarded as a potential alternative for embankment construction, and, moreover, the bearing capacity of biosolids can be enhanced by blending biosolids with topsoil or other residuals.

Disfani et al. (2009a) and Disfani et al. (2009b) assessed the geotechnical properties of biosolids, which were obtained from the existing biosolids stockpiles, WTP in Melbourne, Australia. Preliminary tests were conducted on samples made purely from recycled glass, and, also blended biosolids and recycled glass mixtures. The geotechnical properties including particle size distribution, compaction test, and direct shear test were performed for both, pure and blended mixtures. Disfani et al. (2009a), and Disfani et al. (2009b) 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.

Suthagaran et al. (2007), Suthagaran et al. (2008a), and Suthagaran et al. (2008b) investigated the geotechnical properties of biosolids stabilised with cement and lime, and found that the stabilised biosolids can be used as an engineering fill. In addition, this study presented the geotechnical properties of untreated biosolids. Moreover, Suthagaran et al. (2010) conducted another study to assess the geotechnical characteristics of biosolids, which were produced at WTP in Melbourne, Australia. The tests included consolidation, triaxial shear strength, hydraulic conductivity, compaction, California bearing ratio, Atterberg limits, particle density, and particle size distribution. According to the results, the biosolids samples were found to be classified as organic fine-grained soils of medium to high plasticity. The particle density of biosolids ranged between 1.75 Mg/m^3 and 1.79 Mg/m^3 , which is considerably lower compared to natural organic soil. The consolidation behaviour of biosolids indicated that biosolids have similar behaviour to organic soils.

The end-use of biosolids depends heavily on the characteristics of the biosolids, which could vary around the world as the properties of biosolids depend markedly on factors, such as the quality and composition of the wastewater, method and extent of treatment process (primary, secondary, or tertiary treatment), methods used for the stabilisation of biosolids, and age of the biosolids. It is noteworthy that the properties of the biosolids can vary from time to time, even within the same treatment plant due to the variations in the incoming wastewater composition (NSW DPI, 2009, Suthagaran et al., 2010, Silveira et al., 2003, O'Kelly, 2004).

Compaction is the densification of soil by the removal of air, which is achieved by applying mechanical energy, and is a feasible alternative to many soil stabilization techniques from an economic or engineering point of view (Yesim and Sridharan, 2004). Generally, compaction improves the engineering properties of the soil by increasing the soil strength, bearing capacity, slope stability, and by reducing the hydraulic conductivity and undesirable settlement and volume changes (Holtz et al., 1981, Das, 2008).

One of the earliest studies on the compaction behaviour of soil was done by Proctor (1933), who developed the principles of compaction. Proctor explained the compaction curve in terms of the capillary and lubrication theory. Thereafter, many researchers investigated the mechanism of the densification stages and developed theories including the viscous water theory (Hogentogler, 1936), pore pressure theory in unsaturated soils (Hilf, 1956), physiochemical theory (Lambe, 1959), and effective stress theory (Olson, 1963). In addition, Lee and Suedkamp (1972) used 35 different soil samples and conducted more than 700 compaction tests to establish four types of compaction curve, namely, bell shaped, one and one-half peaks, double peak, and odd shaped with no distinct MDD or OMC.

In recent years, the use of biosolids in civil engineering applications has been of great interest and has become an innovative approach to the management of biosolids. Therefore, knowledge concerning the compaction behaviour and geotechnical properties of biosolids assumes great importance from the viewpoint of sustainable development. In this study, the compaction characteristics of an ETP biosolids sample incorporating different proportions of clayey sand were investigated. In addition, the physical and chemical properties of the ETP biosolids sample, as well as of a biosolids sample from WTP, were investigated. The objective was to evaluate the suitability of these biosolids as construction or road materials.

2 MATERIALS AND METHODS

The biosolids samples used in this study were collected from existing stockpiles at the ETP and WTP in Melbourne (Figure 1). The biosolids sample, from ETP was more than 12 years old, while the WTP biosolids were almost 4 years old. Since this paper presents some of the results of an ongoing study on the use of biosolids in fired-clay bricks, an experimental soil, which is used by Boral Bricks Pty Ltd, was used as a blending material during the evaluation of the compaction characteristics of the ETP biosolids.



ETP Biosolids



WTP Biosolids

Figure 1. Biosolids samples used in the study

Geotechnical laboratory tests liquid limit, plastic limit, particle size distribution, linear shrinkage, and compaction – were conducted according to the Australian Standards (AS 1289.0, 2000), while the organic content test was conducted as per the British Standards (BS 1377-3, 1990). The chemical composition of the experimental soil and biosolids samples were quantified by X-ray fluorescence (XRF). All the geotechnical properties were tested in triplicate and the average values of the results are reported.

3 RESULTS AND DISCUSSION

3.1 Physical properties of the biosolids and the experimental soil

The geotechnical properties were determined for the ETP and WTP biosolids in Melbourne, Australia, and the experimental soil provided by Boral Bricks Pty Ltd. Table 2 shows the summary of the test results of the biosolids samples and soil, used in the study.

The chemical compositions of the experimental soil and two biosolids samples, which were determined by XRF, are shown in Table 1. The experimental soil presents a typical composition and mainly consists of Silica (SiO_2), Alumina (Al_2O_3), and Ferric Oxide (Fe_2O_3), with minor contents of MgO , P_2O_5 , and TiO_2 . Both the ETP and WTP biosolids samples are basically formed by silica, alumina, and ferric oxide, which are the major oxide components, with small amounts of MgO , K_2O , and TiO_2 . It is important to note that the WTP biosolids contain a relatively higher percentage of CaO and P_2O_5 compared to the ETP biosolids and the experimental soil.

The specific gravity of the biosolids samples and the soil was determined by using a density bottle for the fine fraction of the particles, and by weighing in water for particles retained on a 2.36 mm sieve, according to the Australian Standards (AS 1289.3.5.1, 2006). Kerosene was used as a density liquid instead of deionized or distilled water, to avoid the dissolving of the water-soluble salts, that could be present in the biosolids. However, distilled water was used as a density liquid in measuring the specific gravity of the experimental soil. The specific gravity of the ETP and WTP biosolids samples were found to be 2.51 and 2.14 respectively, while the soil had the highest specific gravity of 2.69.

Both biosolids samples showed a relatively lower specific gravity compared to the soil, as expected, revealing that the biosolids samples contained a higher amount of organic matter than the experimental soil (Tay et al., 2001).

Table 1: Chemical composition of the biosolids samples and the experimental soil

Oxide Content (%)	ETP Biosolids	WTP Biosolids	Soil
SiO₂	58.41	46.91	63.73
Al₂O₃	17.50	15.90	19.50
Fe₂O₃	10.55	8.60	7.40
K₂O	0.98	2.82	5.33
MgO	1.10	1.35	1.17
TiO₂	2.37	2.15	1.26
P₂O₅	3.63	4.75	1.04
CaO	2.74	7.70	0.29

Table 2: Geotechnical properties of the biosolids samples and soil

Test/ Property	Standard	ETP Biosolids	WTP Biosolids	Soil
Specific Gravity (G_s)	AS 1289.3.5.1	2.51	2.14	2.69
Liquid limit (%)	AS 1289.3.1.1	46	53	32
Plastic limit (%)	AS 1289.3.2.1	27	41	19
Plasticity index (%)	AS 1289.3.1.1	19	12	13
Gravel content (2.36 mm >) (%)	AS 1726-1993	0.4	13.4	1.2
Sand content (0.075 - 2.36 mm) (%)	AS 1726-1993	87.5	76.0	74.6
Silt Content (0.002- 0.075 mm) (%)	AS 1726-1993	11.1	9.6	22.2
Clay Content (< 0.002 mm) (%)	AS 1726-1993	1.0	1.0	2.0
Coefficient of uniformity (C_u)	AS 1726-1993	8.0	18.6	50.0
Coefficient of curvature (C_c)	AS 1726-1993	2.0	1.8	4.2
Australian soil classification	AS 1726-1993	SM	SW-SM	SC
Linear shrinkage (%)	AS 1289.3.4.1	9.0	9.5	6.5
Organic Content (%)	BS 1377-3	7	NA	1.2

The Atterberg limit test was performed on the biosolids and soil samples to determine their plasticity characteristics. The liquid limit (LL) of the ETP and WTP biosolids ranged between 46% and 53% while the plastic limit (PL) of the ETP and WTP biosolids samples ranged between 27% and 41%. The plasticity index (PI) was found to be in the range of 19% and 12%. In addition, the LL, PL, and PI of the experimental soil was 32%, 29%, and 13%, respectively (Table 2).

The particle size distribution of all samples was achieved by means of sieve analysis. The test results of the particle size distribution are summarised in Table 2. According to the particle size distribution test results, the ETP and WTP biosolids contain 0.4% and 13.4% of gravel size particles, while the soil sample contains 1.2%. The ETP biosolids have the highest percentage of sand particles. In contrast, the soil and the WTP biosolids contain 74.6% and 76% of sand particles, respectively. The percentage of fine particles (<0.075 mm) of the ETP and WTP biosolids slightly varied from 12.1% to 10.6%, while the soil had the highest percentage (24.2%) of fine particles (Figure 2). Based on the results of the particle size distribution and the Atterberg Limits, the ETP biosolids and WTP biosolids can be

classified as silty sand (SM) and well graded silty sand (SW-SM), respectively. Moreover, the experimental soil can be classified as clayey sand (SC) according to the Australian Standards (AS 1726, 1993).

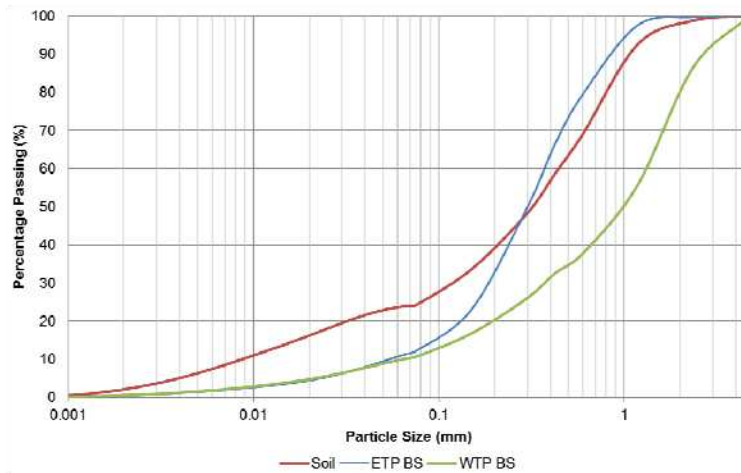


Figure 2. Particle size distribution for the biosolids samples and soil

The linear shrinkage, which is an indirect method of estimating the plasticity of soils (Sivakugan et al., 2011) can be calculated as the percentage reduction in the length of the bars of the soil samples prepared at the liquid limit condition, after they have been air dried for 24 h followed by oven drying at 105°C until no further length reduction is observed. The linear shrinkage of the ETP and WTP biosolids samples, as shown in Table 2, varied from 9.0% to 9.5% whilst the soil had a linear shrinkage of 6.5%.

The ETP biosolids have a significantly higher organic content of 7% compared to 1.23% for the soil (Table 2). It is important to point out that the organic content of the samples has a considerable influence on the plasticity index, strength, and compressibility characteristics (Puppala et al., 2007).

3.2 Compaction characteristics of the biosolids

Figure 3 shows the results of the standard proctor compaction test on the ETP biosolids. It can be seen that the MDD and OMC for the ETP biosolids were 1.53 Mg/m³ and 23%, respectively.

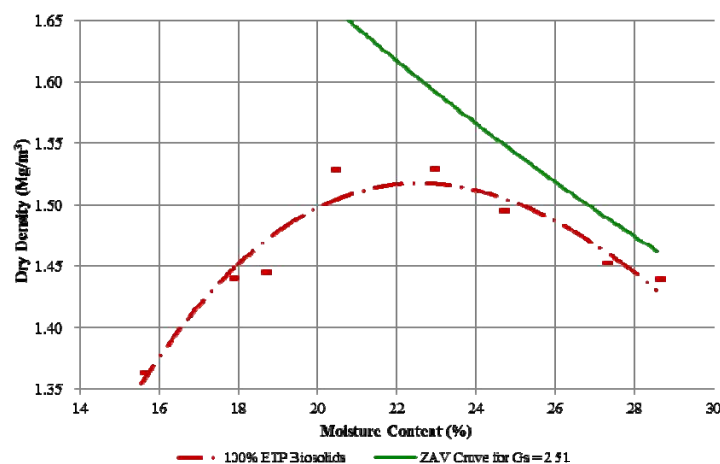


Figure 3. Compaction curve for the ETP biosolids

A series of compaction tests were conducted on different percentages (0% to 100%) of the ETP biosolids samples incorporating the soil. Figure 4 and Table 3 show the density-water content data for the different percentages of the ETP biosolids incorporating the soil. The MDD and OMC of different ETP biosolids mixtures were found to be functions of the percentage of the biosolids in the mixture. The MDD decreased and OMC increased as the percentage of the ETP biosolids increased. Moreover, the MDD of 100% ETP biosolids (1.53 Mg/m³) was significantly lower than that of pure soil

with 0% of ETP biosolids (1.78 Mg/m^3), which is believed to be the result of the higher organic content in the ETP biosolids, which, in turn, reduced the particle density.

The MDD and OMC vary linearly with the percentage of ETP biosolids, as given in Equations 1 and 2. The trend lines of this linear variation are also shown in Figure 5. The R square values in Equations 1 and 2, indicate that there are strong correlations ($R^2 = 0.95$ and 0.97) between the MDD and OMC with the percentage of the ETP biosolids in the sample. The compaction behaviour of WTP biosolids is still under investigation and will be presented in a future publication.

Table 3: Compaction test results for the ETP biosolids

Percentage of ETP biosolids (%)	MDD (Mg/m^3)	OMC (%)
0	1.780	16
5	1.775	16
15	1.765	17
25	1.760	17
35	1.700	19
50	1.630	20
75	1.550	21
100	1.530	23

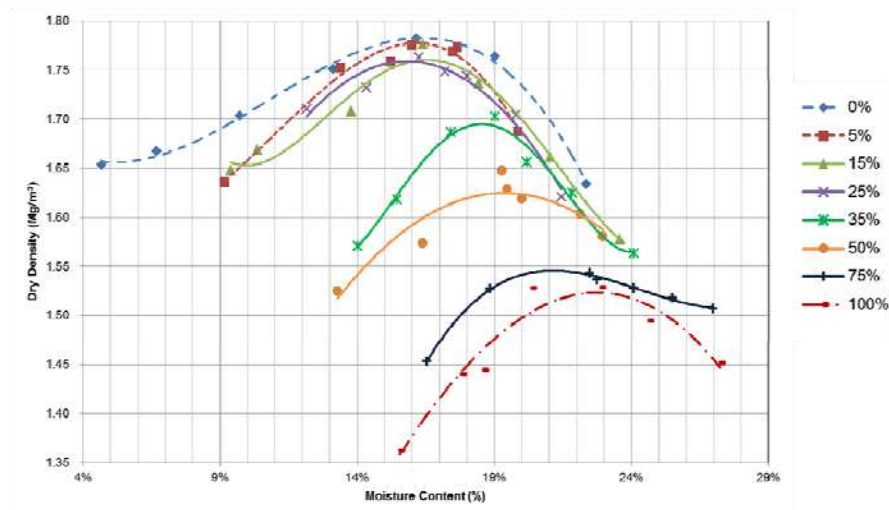


Figure 4. Standard compaction curves for different percentages (0% to 100%) of ETP Biosolids

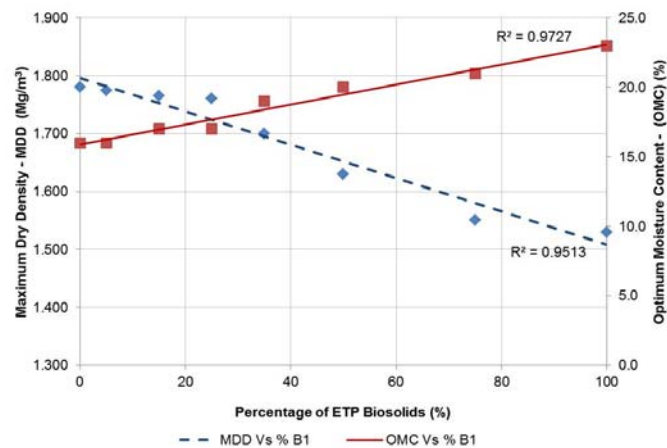


Figure 5. Variation of the MDD and OMC with the different percentages of ETP biosolids

$$\text{MDD} = 1.7958 - 0.0029 (\text{B1}) \quad (\text{R}^2 = 0.9513) \quad (1)$$

$$\text{OMC} = 15.8782 + 0.0720 (\text{B1}) \quad (\text{R}^2 = 0.9727) \quad (2)$$

Where, MDD is the maximum dry density in Mg/m^3 , OMC is the optimum moisture content as a percentage, and B1 is the percentage of ETP biosolids.

The particle size distribution, shape of the soil grains, and the amount and type of clay minerals present in the sample have a considerable influence on its compaction behaviour. According to Figure 4, all the compaction curves are Bell shaped with a single-peak point; this type of curve is generally found in soils that have approximate liquid limit boundaries of 30 and 70 (Das, 2008, Lee and Suedkamp, 1972). It is noteworthy that the ETP biosolids resulted in an increase in OMC and a decrease in MDD from the experimental soil. The variations are primarily attributed to both the percentage of the organic matter and the fine particles present in the respective biosolids-soil mixtures.

4 CONCLUSION

Wastewater biosolids samples produced at ETP and WTP in Melbourne, Australia, were tested to investigate their physical properties and compaction characteristics. It was found that the ETP and WTP biosolids can, respectively, be classified as silty sand (SM) and well-graded silty sand (SW-SM), according to the Australian Standard. The linear shrinkage of the biosolids samples ranged between 9.0% and 9.5%. Moreover, the organic content of the ETP biosolids and experimental soil was 7% and 1.2%, respectively.

The compaction behaviour of biosolids is important, when applying biosolids as a construction material. The results indicated that the OMC and MDD of the ETP biosolids were linearly proportional to the percentage of the incorporated biosolids in the experimental soil. The OMC increased and the MDD decreased, as the percentage of the ETP biosolids incorporated in the experimental soil increased. The organic content and particle size distribution of the tested biosolids-soil mixtures had a considerable influence on their compaction characteristics.

The geotechnical properties of the experimental biosolids indicated that they have similar characteristics as clayey silty sands, which can be incorporated with an appropriate soil for the use as a construction material such as in manufacturing of fired clay bricks (Ukwatta et al. 2014).

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