Performance of Recycled Glass-Biosolids Blends under Repeated Loading

M. M. Disfani[1], H. Haghighi[2], M. M. Y. Ali[2] and A. Arulrajah[3]

[1] Lecturer; [2] PhD Candidates; [3] Associate Professor
Centre for Sustainable Infrastructure, Faculty of Engineering and Industrial Science, Swinburne University of Technology, P.O. Box 218 (H38), Hawthorn, VIC 3122, Australia; PH (613) 9214-4943 FAX (613) 9214-8264; email: mmiridisfani@swin.edu.au

ABSTRACT

In an attempt to enhance the engineering properties of wastewater biosolids; geotechnical characteristics of its blends with recycled crushed glass (another waste material) were investigated. Blends of 60%, 70%, 80% and 90% of recycled glass mixed with biosolids were examined through an extensive geotechnical laboratory program. Results of the experimental study were compared with the engineering requirements of structural fill material used in road embankment fills and suggested that certain blends of recycled glass-biosolids have the potential to substitute natural material in such applications. The resilient modulus is the engineering property that models the behaviour of material under repetitive loading similar to what happens in roads under traffic loading. The behaviour of recycled glass-biosolids blends with different moisture content was studied under repeated loading. The results were analysed to examine the effect of recycled glass ratio and also water content on permanent deformation and resilient modulus of the blends.

Keywords: Recycled glass, biosolids, repeated load triaxial test

1 INTRODUCTION

Waste materials have been defined as any type of material by-product of human and industrial activity that has no lasting value (Tam and Tam 2006). The amount of waste generated by industrial and municipal sectors is increasing with an escalating speed and this trend magnifies the current problem of solid waste disposal in landfills. Recycling and subsequent reuse of waste materials can redirect the waste materials from landfills back into consumption loop and at the same time reduce the demand for natural resources (Disfani et al. 2011a). While sustainable usage of waste materials in geotechnical engineering applications has shown considerable social and economic benefits, lack of technical knowledge and concerns over possible environmental risks are still great barriers against maximising the substitution of recycled material instead of virgin resources (Disfani et al. 2011a; 2012; Wartman et al. 2004). Several types of waste materials; recycled crushed glass and biosolids among them are increasingly and commonly used in geotechnical engineering applications.

Sludge is the mixture of solids–water pumped out of wastewater treatment lagoons which shows the characteristics of a liquid or slurry typically containing 2–15% of oven dried solids (Arulrajah et al. 2011). Biosolids is the product of further treatment of sludge and shows the characteristics of an oven dried solid typically containing 50–70% by weight of bulk solids (Arulrajah et al. 2011). The increasing quantity of wastewater biosolids produced annually and escalating demand for virgin material around the globe has brought more attention to the recycling and reuse of biosolids in a move toward a more sustainable society. In the state of Victoria, Australia, more than 2 million tons of biosolids are currently stored in lagoons or stockpiles with a further annual production of 66,700 tons per annum (DNRE 2002).

Recycled glass is the mixture of glass particles in different colours which often comprises a range of debris such as paper, food remains, and plastic caps. Recycled glass particles in general have an angular shape and usually contain a certain level of flat and elongated particles. The percentage of flat and elongated particles in the mixture and the degree of angularity of particles mainly depend on the crushing process (FHWA 1998). The waste stream (municipal or industrial) from which the glass bottles or glass pieces have been obtained along with the crushing procedure implemented in the recycling site play the most important roles on the debris content, gradation curve and flakiness index of recycled glass (Landris 2007). These parameters subsequently affect other geotechnical characteristics of recycled glass, properties of which vary from one supplier to another (Disfani et al. 2011a; Wartman et al. 2004; Landris 2007).

The idea of blending recycled glass and biosolids was examined in order to overcome the deficiencies of each of these two recycled material when used on their own and to enhance their strength properties. It was expected that the blends will combine the high friction properties of recycled glass with the cohesion characteristic of biosolids in order to achieve an optimum shear strength level. The Fine Recycled Glass and Biosolids (FRG/Bio) blends were prepared in a range of proportions. Geotechnical tests including particle size distribution (sieve and hydrometry analysis), Atterberg limits, standard compaction, hydraulic conductivity, CBR and direct shear tests were undertaken on the blends. The laboratory test results were compared with road authorities' requirements for embankment fill material. In the next step the behaviour of the blends under repeated loading (similar to what happens under road pavements) was studied using a Repeated Load Triaxial (RLT) testing system.

2 ENGINEERING CHARACTERSITICS OF BIOSOLIDS

The characteristics of the biosolids vary from one treatment plant to another since the properties of biosolids depend on factors such as the composition of the wastewater, method of treatment process (US EPA 2005) and age of the biosolids (Arulrajah et al. 2011). Even within a specific treatment plant, the characteristics of the biosolids can change from time to time due to varying composition of incoming wastewater (US EPA 2005).

The biosolids samples for this research were obtained from the top of three existing stockpiles in the biosolids stockpile area, Western Treatment Plant (WTP), located approximately 50 km to the west of Melbourne, Australia (Arulrajah et al. 2011). The normal process at the WTP is to pump sewage sludge from treatment lagoons into sludge drying pans. After a 6–9 months drying period in the sludge drying pans the biosolids are then harvested and stored in biosolids stockpile area for a minimum of 3 years (DNRE 2002). Geotechnical laboratory investigation was performed on three different samples of the biosolids and the average values of selected tests are reported in Table 1.

Table 1: Select engineering characteristics of biosolids and FRG

Test – Parameter		Bio	FRG
Maximum particle size (mm)		9.5	4.75
Fine particle content – < 0.075 mm (%)		40–56	5.4
Sand size particle content – 0.075–2.36 mm (%)		40–44	94.6
Gravel size particle content -> 2.36 mm (%)		4–16	9.2
Coefficient of uniformity (C_u)		100–360	7.6
Coefficient of curvature (C_c)		0.3–0.4	1.3
Atterberg limits: LL, PL and PI (%)		100, 69, 31	NA [a]
Classification according to Australian system (Standards Australia 1993)		OH	SW–SM
Specific gravity (G_s)		1.86–1.88	2.48
Loss on ignition (%)		35.4–38.5	1.3
Standard compaction	$\gamma_{d\ max}$ (kN/m^3)	7.9–8.0	16.7
	w_{opt} (%)	51–53	12.5
Hydraulic conductivity (10^{-7} m/sec)		1.24–1.60	1.7
1–D consolidation test (oedometer and creep)	Coefficient of consolidation (m^2/year)	0.04–0.97	NA
	Compression index	0.38–0.45	NA
	Recompression index	0.048–0.055	NA
	Coefficient of secondary consolidation	0.003–0.02	NA
California Bearing Ratio (CBR)		1.0	18–21
Direct shear test - σ_n : 60–240 kPa	φ' (°)	35	42–43
	c' (kPa)	46	0
Triaxial shear tests[b] –σ_c : 60–240 kPa	φ' (°)	37.2	38
	c' (kPa)	6.9	1.0

[a] Not Applicable
[b] CU and CD testing methods were used for Bio and FRG specimens respectively.

As shown in Table 1; Biosolids samples are classified as organic material with high plasticity according to Australian Soil Classification System (Standards Australia 1993). The specific gravity of

1.87 obtained for biosolids is considerably lower than that of natural inorganic soils. The dry unit weight of the compacted biosolids obtained through standard Proctor compaction tests is low compared to inorganic soils but is in line with the low particle density of biosolids (Arulrajah et al. 2011). The hydraulic conductivity of biosolids determined using falling head method suggests that biosolids will be classified as very low according to hydraulic conductivity classifications proposed by Terzaghi et al. (1996). Results of oedometer consolidation and creep tests are summarised in Table 1 with testing details described in Arulrajah et al. (2011). Values of coefficient of consolidation suggest that biosolids possess medium to high consolidation potential while the values of coefficient of secondary consolidation suggest that biosolids show behaviour similar to normally consolidated clays (Arulrajah et al. 2011; Head 1994). The CBR values reported in Table 1 clearly insinuate that untreated biosolids should be stabilized before application as an engineered fill (Arulrajah et al. 2011). Results of strain controlled drained direct shear tests performed on densely compacted biosolids samples showed that the cohesion property of the biosolids is relatively high while the friction property is moderate (Arulrajah et al. 2011). It is believed that the relatively high values of friction angle obtained for compacted biosolids are the result of high content of coarse sand size particles (about 50%) of aged biosolids. Results of CU triaxial shear tests performed on compacted biosolids samples indicate relatively high internal friction angles which are comparable to those of typical silty sand mixtures. This is again believed to be due to high percentage of coarse size particles (around 50%) in the biosolids studied in this research (Arulrajah et al. 2011). Figure 1 presents the gradation curve of the pure biosolids sample.

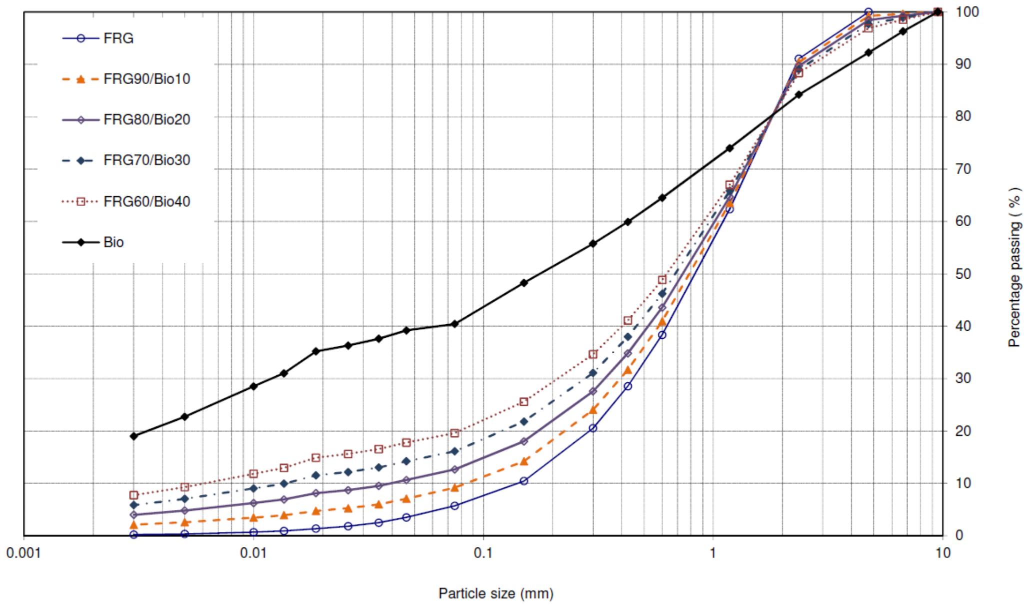

Figure 1. Gradation curves of Bio, FRG and their blends

3 ENGINEERING CHARACTERSITICS OF RECYCLED CRUSHED GLASS

To provide a better insight into geotechnical and environmental engineering characteristics of recycled crushed glass, an extensive laboratory study was carried out on three different sources of recycled glass produced in Victoria, Australia (Disfani et al. 2011a). Suitability of using these recycled glass sources in a range of geotechnical engineering applications along with possible environmental risks associated with their use in road work applications are discussed in Disfani et al. (2011a; 2012).

Fine Recycled Glass (FRG) is the main by-product of the glass recycling industry in Victoria. Results of select geotechnical laboratory tests including particle size distribution (sieve and hydrometry analysis), particle density, loss on ignition, standard compaction tests, hydraulic conductivity, CBR, direct shear and triaxial shear tests are presented in Table 1. While the specific gravity of FRG is approximately 10% lower than natural occurring sand and gravel mixtures (Disfani et al. 2011a) compaction tests results indicate the high workability of FRG over a wide range of water content. Hydraulic conductivity tests confirm excellent drainage characteristics of FRG compared to natural aggregates with the same soil classification. Results of drained direct shear test indicate that the shear strength parameters of FRG are close to those of natural sand mixtures with angular particles. CD triaxial shear test results confirmed direct shear test results, though the values of internal friction angle obtained through triaxial shear tests are generally lower than those found through direct shear (Disfani et al. 2011a). FRG was found to exhibit geotechnical engineering behaviour similar to a well graded sand mixture with lack of cohesion as a concern in some applications of FRG. Figure 1 depicts the gradation curve of pure FRG sample.

4 FRG/BIO BLENDS

In order to improve the strength and compression (settlement) characteristics of biosolids and at the same time add some cohesive properties to FRG samples, the two waste materials were blended to various proportions. Geotechnical characteristics of blends of FRG and Bio: FRG90/Bio10, FRG80/Bio20, FRG70/Bio30 and FRG60/Bio40 (the suffix after FRG represents the percentage of Fine Recycled Glass and the suffix after Bio represents the percentage of biosolids in the mixtures) were investigated. Figure 1 presents gradation curves of aforementioned blends. Figure 1 implies that the particle size distribution of the FRG source becomes constantly finer with the addition of biosolids. Table 2 presents the classification and index properties of the FRG/Bio blends. Table 2 shows that the soil classification of the samples changes from SW–SM for higher FRG contents to SP–SM for blends with FRG contents of 70 and 60%. Values of LL and PL presented in Table 2 imply that FRG source strongly influences the Atterberg limits of the biosolids through blending with a linear relationship (Disfani et al. 2011b).

Table 2: Index properties of FRG/Bio blends

Blend	Fine content (< 0.075 mm) (%)	Sand content (0.075–2.36 mm) (%)	Gravel content (> 2.36 mm) (%)	C_U	C_c	LL	PL	PI	Classification (Standards Australia 1993)
FRG90/Bio10	9.2	81.2	9.6	10.0	1.4	39.5	22.5	17	SW–SM
FRG80/Bio20	12.7	77	10.3	25.8	2.8	52.1	28.7	23.4	SW–SM
FRG70/Bio30	16.1	72.9	11	68.0	5.6	61.5	35.6	25.9	SP–SM
FRG60/Bio40	19.6	68.7	11.7	149.2	8.0	70.7	39.8	30.9	SP–SM

Table 3 presents selected geotechnical characteristics of FRG/Bio blends. Results of standard compaction tests suggest that 10% increase in the biosolids content of the blends results in an approximate linear decline of 8.5% in the maximum dry unit weight of the samples. For the optimum water content an increase of 3–4% was observed versus a 10% increase in the biosolids content of the blends (Disfani et al. 2011b). Table 3 also presents the results of CBR and drained direct shear tests performed on FRG/Bio blends. Details of testing procedure and test graphs are presented in details in Disfani et al. (2011a; b) and Arulrajah et al. (2011). Considering the gradation curves, compaction test results and CBR values of FRG/Bio blends it can be concluded that Blends of FRG/Bio presented in Table 3 have the potential to be used as structural fill material in road embankments (EPA Victoria 2004). Special technical and environmental management considerations including limiting the thickness of FRG/Bio layer to the maximum of 0.5 m and confining the FRG/Bio layer in an impermeable clay layer or geomembrane should be implemented in such applications (Suthagaran 2010). EPA Victoria (2004), Disfani et al. (2011b) and Suthagaran (2010) have provided more details on this application of biosolids and FRG/Bio blends.

Table 3: Select geotechnical properties of FRG/Bio blends

Blend	Standard compaction		K (10^{-7} m/sec)	CBR test		Direct shear test	
	w_{opt} (%)	$\gamma_{d,max}$ (kN/m^3)		CBR value	Swell (%)	φ' (°)	c' (kPa)
FRG90/Bio10	14.7	15.6	2.47	11	0.34	43.8	9.7
FRG80/Bio20	19.0	14.3	2.24	5	0.68	45.6	9.8
FRG70/Bio30	23.0	13.0	1.33	5	0.94	38.4	19.6
FRG60/Bio40	27.0	12.1	0.48	4	1.50	44.0	19.9

5 RLT TEST ON FRG/BIO BLENDS

A thorough assessment of using recycled material in applications which will face cyclic loading during their life time (e.g. road work applications such as road pavement and embankment fills) should study the behaviour of the material under repeated loads. The RLT test provides permanent deformation and resilient modulus parameters that uniquely describe the material response to traffic loading under prevailing physical conditions. AustRoads testing methodology (AG: PT/T053) was chosen to perform the RLT tests on FRG/Bio blends in this research. Results of RLT tests including permanent deformation and resilient modulus are extremely dependent on the compaction method used for sample preparation (AustRoads 2000) and as such all FRG/Bio samples were prepared using dynamic compaction method (with the application of standard Proctor compaction energy). 100 × 200 mm (diameter × height) test specimens were compacted in 5 layers at optimum moisture content to reach at least 98% of maximum dry unit weight presented in Table 3. Specimens were subsequently left to dry back to 90% and 70% of their optimum moisture content. AustRoads (2000) guide suggests a static confining pressure of 50 kPa and a repeated deviator stress of 150, 250 and 350 kPa with 10,000 repetitions for each stage for lower subbase material. It is generally accepted that if the RLT test aims to characterise the permanent deformation and resilient modulus of a specified pavement layer for the purpose of pavement design, the aforementioned repeated cyclic stress and static confining stress can be changed (AustRoads 2000). In AustRoads (2000) testing methodology for base, upper subbase and lower subbase material the suggested repeated deviator stress decreases by the amount of 100 kPa for each stage. Considering these two facts along with the fact that FRG/Bio blends are intended to be used at the bottom of road embankment fills a static confining stress level of 50 kPa and repeated deviator stress levels of 50, 150 and 250 kPa with 10,000 repetitions for each stage were selected for FRG/Bio specimens studied in this research.

Table 4 presents RLT test results on FRG/Bio blends. All blends failed before reaching the stage 2 (σ_c : 50 & $\Delta\sigma_d$: 150 kPa) or at the first cycled of beginning of this stage. As such only results of first loading stage are shown in Table 4. All FRG/Bio blends tested with the moisture content of 90% failed before the end of first stage, while the number of cycles that the specimens lasted increased with the rise in Bio content of the blends (the number of cycled that the specimens failed are mentioned in the footnotes of Table 4). On the other hand all FRG/Bio blends with the moisture content of 70% made it all the way through 10,000 loading cycles of the first stress stage. This clearly shows the effect of moisture content on the ability of FRG/Bio blends to stand cyclic loading.

Table 4: RLT test results for FRG/Bio blends

Blend	Permanent strain testing	Sample moisture content (% of the w_{opt})	Stage 1 (σ_c : 50 & $\Delta\sigma_d$: 50 kPa)
FRG90/Bio10	Permanent strain (micro-strain)	90	15302 [a]
		70	10908
	Resilient modulus (MPa)	90	460 [a]
		70	88
FRG80/Bio20	Permanent strain (micro-strain)	90	13202 [b]
		68	7613
	Resilient modulus (MPa)	90	195.6 [b]
		68	73
FRG70/Bio30	Permanent strain (micro-strain)	90	11921 [c]
		70	8576
	Resilient modulus (MPa)	90	124.7 [c]
		70	66.5
FRG60/Bio40	Permanent strain (micro-strain)	90	13156 [d]
		70	8023
	Resilient modulus (MPa)	90	55 [d]
		70	43

[a] Failed after 50 cycles.
[b] Failed after 2500 cycles.
[c] Failed between 5000 and 7500 cycles.
[d] Failed after 7500 cycles.

Figure 2 shows the trend of change for permanent deformation and resilient modulus for both moisture contents that the tests were performed at. As both figures clearly show with the addition of more FRG to FRG/Bio blends the permanent deformation and the resilient modulus (the resilient modulus values are measured for the last loading cycle) of the material both increase. Similarity in the trend of change for both graphs and also similarity in shape of trendlines suggest consistency between test results. For both moisture contents the minimum permanent deformation happens for samples with 70% FRG. Increasing FRG beyond this level increases the permanent deformation of the samples.

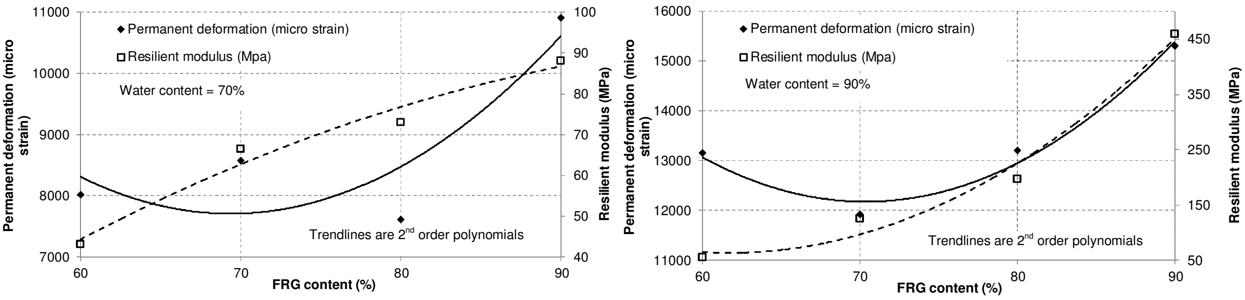

Figure 2. Change of permanent deformation and resilient modulus for FRG/Bio blends

6 CONCLUSION

The idea of blending two different recycled materials in an attempt to improve their shear strength and deformation characteristics were examined for the very first time. Fine Recycled Glass (FRG) and Biosolids (Bio) in various ratios were mixed and geotechnical laboratory experimentation was carried out on them. Test results suggest that blends with FRG content of 60% and higher show a good potential to substitute natural material in road embankment fills with the implementation of technical and environmental considerations. A preliminary RLT test program showed that blends with FRG content of 70% show the lowest permanent deformation while samples with higher moisture content possess higher level of deformation. Further experiments are under way on other blends.

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