Shear strength behaviour of recycled glass-biosolids mixtures

Mahdi Miri Disfani, PhD candidate
Arul Arulrajah, Senior lecturer
Visvalingam Suthagaran, PhD candidate
Faculty of Engineering and Industrial Sciences - Swinburne University of Technology, Melbourne, Australia
Myint Win Bo
Principal/Director, DST Consultants, Ontario, Canada

ABSTRACT
To enhance the shear strength properties of pure Fine Recycled Glass (FRG) and pure Biosolids (Bio), the innovative idea of blending these two materials was studied. The blended FRG-Bio material has the advantage of combining the high friction characteristics of recycled glass with the cohesive characteristics of biosolids. The Direct Shear Test results, California Bearing Ratio results along with other geotechnical test results indicated that 50FRG/50Bio, 60FRG/40Bio and 70FRG/30Bio blends provide a sufficiently high shear strength and friction angle for their usage as an embankment fill material. The findings showed the potential of blended recycled glass-biosolids to be used as a viable alternative to natural materials in road embankment applications.

RÉSUMÉ
Pour mettre en valeur les propriétés de résistance au cisaillement du Verre Recyclé Fin (VRF) pur et des Biosolides purs (Bio), l'idée novatrice de mélanger ces deux matériaux a été étudiée. Le mélange VRF-Bio a l'avantage de combiner les caractéristiques de haut frottement du verre recyclé et les propriétés de cohésion des biosolides. Les résultats de l'essai de cisaillement, les résultats de l'indice californien C.B.R et les résultats d'autres essais géotechniques indiquent que des mélanges 50VRF/50Bio, 60VRF/40Bio et 70VRF/30Bio fournissent une résistance au cisaillement et un angle de frottement suffisamment élevés pour être utilisés comme matériaux de remblayage pour les remblais. Les découvertes indiquent le potentiel d'utilisation des mélanges verre recyclé-biosolides comme alternative aux matériaux naturels dans les applications pour les remblais routiers.

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 growing quantities and types of waste materials, shortage of landfill spaces, and lack of natural earth materials highlight the urgency of finding innovative ways of recycling and reusing waste materials. Additionally, recycling and subsequent reuse of waste materials has the capacity to reduce the demand for natural resources, thus leading to lower energy usage and gas emissions. Ultimately, this can lead to a more sustainable environment.

Recycled Glass is a mixture of different colored glass particles and is often comprised of a wide range of debris (mainly paper, plastic, gravel, metals, and food waste). The presence of different colored glass and diverse types of debris are the primary obstacle in reusing recycled glass in bottle production industries. Recycled glass passing through a 9.5 mm sieve does not carry its original shape and to some extent resembles natural and quarried aggregates (Wartman et al. 2004). Recycled glass particles are generally angular shaped and contain some flat and elongated particles. The degree of angularity and the quantity of flat and elongated particles mainly depend on the crushing process (FHWA 1998).

In recent years, extensive research has been carried out on the feasibility of using recycled glass in a number of civil and geotechnical engineering applications. The geotechnical applications of recycled glass include its use as asphalt aggregate, backfill material in embankments, drainage material, filter media, and road pavement material. Depending on the nature of the geotechnical application of recycled glass, specific geotechnical parameters are of paramount importance. At the same time, certain factors affect the geotechnical characteristics of recycled glass.

It is believed that the waste stream from which the glass bottles or glass particles have been produced controls the quality of the material, especially the amount of debris in the mixture (Landris 2007). The particle size distribution and debris level of the product is partly determined by the machinery and procedures in crushing and sieving waste glass used by the glass supplier. Consequently, the geotechnical characteristics of recycled glass vary from one supplier to another (Landris 2007). This has led to varying results for tests on the geotechnical characteristics of recycled glass. However, even with these variations, such tests are invaluable in in assessing the behaviour of recycled glass in comparison with natural sand and gravel aggregate or other recycled materials.

Three different sources of recycled glass with maximum particle size of 19 mm, 9.5 mm, and 4.75 mm were laboratory tested in this study. The main difference among these three sources is the maximum particle size and consequently their particle size distribution. Particle size distribution influences other geotechnical properties such as hydraulic conductivity, compaction characteristics and shear strength parameters. Current experimental works undertaken at Swinburne University of Technology (SUT), Australia on crushed recycled glass sources passing the 9.5 mm and 4.75 mm sieves show satisfactory geotechnical characteristics regarding usage in road embankment applications. The results confirm the lack of cohesion among particles as a principle consideration in the shear strength of recycled glass. This is likely due to smooth surfaces of crushed glass particles and lack of fine clay size particles in the mixture.

Biosolids (Bio) is treated sewage sludge suitable for beneficial use in accordance with the relevant regulations. The quantity of municipal biosolids produced annually in the world has increased dramatically over the decades. Annually, 66,700 dry tonnes of biosolids are produced from wastewater treatment plants in Victoria. This includes 39,700 dry tonnes per annum of biosolids from the Eastern and Western Treatment Plants in Melbourne, Australia which are managed by Melbourne Water Corporation (NRE 2002).

The characteristics of the biosolids depend on various factors such as the type of waste, type of treatment process and age of the biosolids. Depending on the nature of the construction project, the engineering characteristics of biosolids must be investigated to determine the viability of biosolids as a construction material. California Bearing Ratio (CBR), bearing capacity and the shear strength of biosolids are essential parameters to be investigated when biosolids are intended to be used as an embankment fill material or other appropriate road applications. Current research undertaken at SUT has investigated the geotechnical engineering properties of untreated biosolids. The experimental results indicate that untreated biosolids particles lack sufficient shear strength and friction.

To overcome the deficiencies of recycled glass and biosolids when used on their own and to enhance their strength properties, the innovative idea of blending these two materials was studied. The blended mixture combines the high friction properties of recycled glass with the cohesion characteristic of biosolids to achieve a reasonable shear strength level. The Fine Recycled Glass and Biosolids (FRG-Bio) mixtures were prepared in a range of proportions. Geotechnical tests including particle size distribution, standard and modified compaction tests, Direct Shear Tests (DST) and California Bearing Ratio (CBR) tests were undertaken on all mixtures.

2 RECYCLED GLASS SOURCES

Three different sources of recycled glass with different maximum particle sizes were obtained from Alex Fraser Group and Visy Recycling in Melbourne, Australia. The three recycled glass sources were termed Fine Recycled Glass (FRG), Medium Recycled Glass (MRG) and Coarse Recycled Glass (CRG) based on their maximum particle size which was 4.75 mm, 9.5 mm and 19 mm respectively. The main difference between these three sources of recycled glass was the maximum particle size which influences the particle size distribution of the mixture and other geotechnical engineering characteristics.

Table 1 presents the physical properties of as-received recycled glass samples based on their particle size distribution test results. FRG is classified as well graded sand mixture with little amount of silt size particles according to the Australian soil classification system (AS 1993). MRG is classified as well graded gravel mixture due to dominant gravel content with some silt size particles. CRG is classified as poorly graded gravel.

Table 1. Basic properties of as-received samples based on AS 1726-1993 Standard

Resource	Classification	Coefficient of uniformity (C_u)	Coefficient of curvature (C_c)	Fine Content (< 0.075 mm) (%)	Gravel Content (2.36 mm >) (%)	Sand Content (0.075-2.36 mm) (%)
FRG	SW-SM	7.6	1.3	5.4	9.2	85.4
MRG	GW- GM	16.3	2.2	5.2	53	41.8
CRG	GP	2.6	1.2	0.9	96.4	2.7

The particle size distribution results obtained after conducting standard and modified compaction tests on all three sources showed noticeable before and after differences in the gradation curve of the CRG sample. The content of sand size particles in the CRG sample increased significantly after the compaction tests. The sand content of the as-received sample increased from 2.7% to 9.1% after standard compaction and to 24.8% after modified compaction. The content of gravel size particles decreased considerably from 96.4% for the as-received sample to 88.8% after standard compaction and to 71.9% after modified compaction. This change is explained by the gravel size glass particles crushing and decreasing in size to sand particles under compaction. Such a perceptible change can be attributed to the high amount of gravel size glass particles in the CRG source which makes the mixture susceptible to crushing during compaction. On the other hand, for the MRG source, with 53% gravel content, the effect is much lower. For the FRG source, with 9.2% gravel content, there is no crushing under the standard compaction energy and a negligible change under the modified compaction energy. This behaviour points out that FRG and MRG sources are stable mixtures during the engineering operations including handling, spreading and especially compaction while CRG is not.

Segregation is defined as particle size separation process that results when a nominally homogeneous mixture of soil particles is spread using mechanical action (Sutherland and Grabinsky 2003). Segregation can cause a homogeneous mixture to be divided into two different parts with completely different geotechnical characteristics from the primary homogeneous mixture. The CRG source was found to be vulnerable to segregation. This is likely due to poor particle size distribution, low friction resistance due to smooth surface of glass particles, and also poor ability to absorb and hold moisture. The CRG source consisted of a sizeable amount of elongated and flat shaped particles and high debris content. It was also found that the CRG source possesses little ability to absorb and hold moisture which impacts on its compaction behaviour. These characteristics along with perceptible change in particle size distribution curves of the CRG samples before and after compaction led the authors to conclude that CRG source may not be an ideal material for geotechnical engineering applications.

Consequently, only the results of experimental work undertaken by the authors on FRG and MRG sources will be presented in this paper.

3 GEOTECHNICAL CHARACTERISTICS OF FRG AND MRG SOURCES

Figure 1 presents compaction curves for the FRG and MRG sources which were found to possess similar characteristic convex shapes to natural aggregates (Wartman et al. 2004). The compaction curves of FRG and MRG were also found to be similar to the compaction curves of poorly graded sand. The increase in water content results in a decrease in the dry unit weight and a subsequent increase up to the optimum water content. Capillary tension in the pore water is the main reason for the decrease of dry unit weight at lower water contents (Das 1983). The main reason that both FRG and MRG sources showed the behaviour of poorly graded sand in the compaction tests (even though they have been classified as well graded mixtures), would be the poor ability of the glass particles in holding and absorbing water. Zero air void curves for the FRG (G_s=2.48) and MRG (G_s=2.5) sources are also drawn in Figure 1.

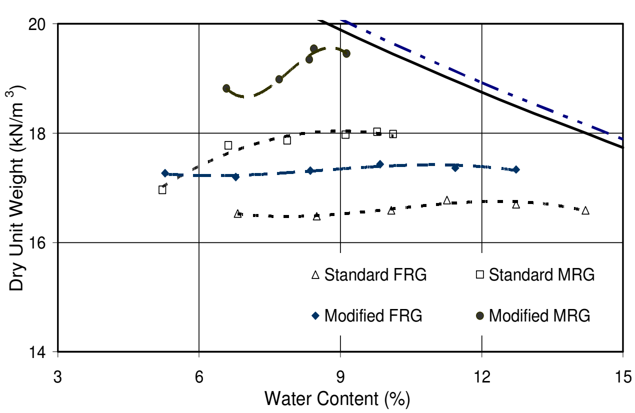

Figure 1. Compaction test results on FRG and MRG

The low sensitivity of FRG to moisture content changes in comparison to natural aggregate is evident from the flatter compaction curves. It gives the FRG source stable compaction and good workability over a wide range of water contents in geotechnical engineering applications (Wartman et al. 2004).

Table 2 presents the results of both standard and modified compaction tests with some other basic test results on the as-received FRG and MRG samples. The values of maximum dry densities obtained for FRG and MRG are 10% to 15% lower than the values found for the natural aggregate with the same soil classification (Craig 1992). This is likely due to lower specific gravity values of the recycled glass sources compared to natural aggregates.

Table 2. Geotechnical properties of FRG and MRG

Test	Standard	FRG	MRG
Specific gravity (G_s)	AS 1141.5 and AS 1141.6.1	2.48	2.5
Organic content (%)	ASTM D 2947-00	1.3	0.5
Debris level (visual method) (%)	AGI[1]23.1 & 23.2	7	5
Debris level (weight method) (%)	CWC[2] chart	1.23	2.01
pH value	AS 1289.4.3.1	9.87	10.14
LA abrasion value (%)	ASTM C 131-06	24.8	25.4
Standard proctor	AS 1289.5.1.1		
γ_d (kN/m^3)		16.7	18
w_{opt} (%)		12.5	9
Modified proctor	AS 1289.5.2.1		
γ_d (kN/m^3)		17.5	19.5
w_{opt} (%)		10	8.8
Hydraulic conductivity (m/s)	BS 1377-5	1.7 E -5	2.85 E -5
California Bearing Ratio (CBR)	AS 1289.6.1.1		
Using standard compaction effort		18-21	31-32
Using modified compaction effort		42-46	73-76
Direct Shear Test (DST)	BS 1377-7		
Internal friction angle (degree)			
σ_n (30-120 kPa)		45-47º	----
σ_n (60-240 kPa)		42-43º	----
σ_n (120-480 kPa)		40-41º	----

[1] American Geological Institute
[2] (Clean Washington Center 1998)

The test results suggest that both of the recycled glass sources possess specific gravity values at approximately 15% less than the natural aggregate, though there is little difference between specific gravity values of the FRG and MRG sources.

The results of the organic content test proved that although the 1.3% organic content value obtained for the FRG source is considered low, it is higher than the MRG source organic content. The higher organic content value of the FRG source is likely due to a higher percentage of paper material in this source.

The FRG source has a lower value for debris level by weight as compared to the MRG source. This trend was noted to be the opposite for the debris level obtained by visual method. Table 2 also indicates that the debris level obtained by the weighing method is less than one fifth and less than half of the value obtained by the visual method for the FRG and MRG sources. The primary reason for this is that a high percentage of debris in the FRG source is comprised of low density material, especially paper. For the MRG source, the debris mainly consists of low density material such as wood, plastic and a lower amount of paper.

Various tests were undertaken to assess the durability and resistance of aggregate materials. One of which is the Los Angeles abrasion test (LA), commonly used in highway and materials engineering to assess the abrasion resistance of aggregate materials (Wartman et al. 2004). The results of the LA abrasion tests show that the FRG and MRG sources have similar LA abrasion values and these values are similar to the LA abrasion value of crushed rock samples tested previously at SUT. The LA abrasion value of MRG is slightly higher than FRG and this might be the result of the higher debris level of the MRG source.

The hydraulic conductivities of both the FRG and MRG sources are classified as medium according to permeability classifications (Terzaghi et al. 1996). Considering obtained hydraulic conductivity values, both FRG and MRG possess good drainage characteristics similar to the hydraulic conductivity of natural aggregates having the same soil classification and degree of compaction. In engineering applications, the hydraulic conductivity of a fill material often plays an important role in material selection. High hydraulic conductivity is usually more beneficial than low hydraulic conductivity for granular fill material (Clean Washington Center 1998).

Two series of specimens were prepared for the California Bearing Ratio (CBR) tests conducted; one by applying standard compaction effort and the other by using modified compaction effort. The CBR values of the FRG source for both standard and modified compaction efforts were lower than those of the MRG source. This trend seems to be related to higher values of maximum dry density obtained for the MRG source in both the standard and modified compaction tests. The higher maximum dry density for MRG (considering that its specific gravity is approximately equal to FRG) is an indication of better compaction which results into better particles contact and eventually better shear performance of the MRG source.

Direct shear tests were undertaken on the FRG source in accordance with the BS 1377-7 method. The maximum particle size of the test specimen should not exceed 1/5 of the specimen height. As such, with the 10×10 cm shear box having the effective depth of 4 cm, only the FRG samples with the maximum particle size of 4.75 mm were tested. Five different normal stress levels were applied to the test samples. The internal friction angle of FRG was found to decrease from 47º to 40º with normal stress increasing from 30 kPa to 480 kPa. The internal friction angle of FRG is similar to that of dense sand with angular grains (Das 1983) which suggests that the FRG source exhibits the satisfactory friction characteristics for usage in some geotechnical engineering applications.

The results from laboratory tests imply that the FRG and MRG sources show comparatively acceptable engineering characteristics to be used as alternatives for natural aggregate in appropriate geotechnical engineering applications. Even though the FRG source has lower debris level (weight method), lower LA abrasion value and flatter compaction curve giving this source good workability over a wide range of moisture contents, however, the MRG source has the benefit of higher maximum dry density and higher CBR value which would result in better shear performance.

The results of direct shear tests showed that the FRG source suffers from lack of cohesion resistance between particles. This was likely the result of smooth surface of the glass particles and little amount of fine particles (which are mainly silt size particles according to hydrometer test results) in the mixture.

4 LABORATORY STUDY ON BIOSOLIDS

Biosolid sampling for this research was carried out from the top of three existing stockpiles in the biosolids stockpile area, Western Treatment Plant, located approximately 50 km to the west of Melbourne, Australia. Bulk samples were collected in large bags which were sealed to retain the natural moisture content. Geotechnical laboratory investigation was performed on three different samples and the average values have been reported. Table 2 presents a summary of test results of untreated biosolid samples.

Biosolid samples were classified as organic material with high plasticity according to Australian Soil Classification system (AS 1993). The hydraulic conductivity of biosolid samples was determined using falling head method and was classified as very low according to hydraulic conductivity classifications (Terzaghi et al. 1996).

The higher value of specific gravity found for biosolid samples in this research in comparison to other research works is probably due to higher percentage of sand and silt size particles in the biosolid material. Anyhow it is still in the range of specific gravity values found for biosolids in other research works (O'Kelly 2006). As a result the maximum dry density of the biosolid material in this research was found to be higher than the values found by O'Kelly (2006).

Results from direct shear tests showed that the cohesion property of the biosolid material is relatively high while the friction property is low. The high percentage of fine particles in the mixture and the nature of the biosolids are believed to be the main reasons for low friction angle of the biosolids. The low CBR value proves the significant compressive behaviour of the material.

Table 3. Geotechnical properties of pure biosolids

Test	Standard	Results
Soil classification	AS 1726-1993	OH
Coefficient of uniformity (C_u)		26
Coefficient of curvature (C_c)		0.3
Gravel content		4
(2.36 mm >) (%)		
Sand content		54.6
(0.075 – 2.36 mm) (%)		
Fine content		41.4
(< 0.075 mm) (%)		
Liquid limit (%)	AS 1289.3.1.1	104
Plastic limit (%)	AS 1289.3.2.1	80
Plasticity index	AS 1289.3.3.1	24
Specific gravity (G_s)	AS 1289.3.5.1	1.8
Organic content (%)	ASTM D 2947-00	25.9
pH value	AS 1289.4.3.1	4.8
Standard proctor	AS 1289.5.1.1	
γ_d (kN/m^3)		8.1
w_{opt} (%)		53
Modified proctor	AS 1289.5.2.1	
γ_d (kN/m^3)		8.9
w_{opt} (%)		40
Hydraulic conductivity (m/s)	AS 1289.6.7.2	1.24 E -7
California Bearing Ratio (CBR)	AS 1289.6.1.1	
Using standard compaction effort		1
Using modified compaction effort		4
Direct Shear Test (DST)	BS 1377-7	
Internal friction angle (degree) - (σ_n: 30-120 kPa)		9-10º
Cohesion coefficient (kPa) - (σ_n: 30-120 kPa)		25

5 FRG AND BIOSOLIDS MIXTURES

To enhance the strength characteristics of recycled glass and biosolids, the two materials were blended to various proportions and the shear strength behaviour of the mixtures was investigated. Although both FRG and MRG sources, presented appropriate geotechnical engineering characteristics, the research focused on the mixtures of FRG and Biosolids. This was mainly because FRG was the key production of both Alex Fraser Group and Visy Recycling. Furthermore, MRG was produced for only a short period of time and was not available subsequently to continue the research.

FRG-Bio blends with percentages composed of FRG90/Bio10, FRG80/Bio20, FRG70/Bio30, FRG60/Bio40, FRG50/Bio50, FRG40/Bio60, FRG30/Bio70, FRG20/Bio80 and FRG10/Bio90 were tested to obtain the basic geotechnical characteristics. The number after FRG represents the percentage of Fine Recycled Glass and the number after Bio represents the percentage of Biosolids in the mixtures.

Figure 2 presents particle size distribution curves of pure FRG and Biosolid (Bio) samples and also the blends. It is apparent that the particle size distribution of the FRG source becomes constantly finer with the addition of biosolids. The fine content of the mixtures increased from 5.4% for pure FRG to 41.4% for pure biosolids (Bio) and consequently the soil classification of the samples changed from SW-SM for pure Fine Recycled Glass (FRG) to OH for pure Biosolids (Bio).

Figures 3 and 4 respectively present the standard and modified compaction curves of pure FRG and Biosolids as well as those of blended mixtures. Zero air void lines for G_s=2.48 (pure FRG) and G_s=1.8 (pure Biosolids) have been drawn. However the value of G_s will be varying with ratio of mixture between FRG and Bio. The addition of more Biosolids to pure FRG samples will result in decreasing the specific gravity of the mixture from 2.48 to 1.8 gradually. Figures 3 and 4 show that with the addition of more biosolids to the mixture the compaction curves move from just under the FRG zero air void line (G_s = 2.48) toward just under the Bio zero air void line (G_s = 1.8).

The compaction curves of pure biosolids were found to be similar to material categorized as OH and it is convex shaped as expected (Grubb et al. 2006). For the pure biosolid samples the maximum dry density values in both standard and modified compaction tests were higher than what has been found in research done by O'Kelly (2006). On the other hand the optimum water content value was lower than what has been obtained for biosolids by O'Kelly (2006). This trend is likely due to higher specific gravity and higher amount of sand and silt size particles of biosolid samples in the current research as compared to what has been done by O'Kelly (2006).

Figure 5 illustrates the variation of maximum dry unit weight versus the FRG percentage in the blended samples. 10% increase in the FRG amount of the mixture results in an approximate linear increase of 8.5% in the maximum dry unit weight of the samples for both compaction efforts. The decrease in the maximum dry density of the mixtures with the addition of more biosolids to FRG is considered a disadvantage in road embankment applications. The trend lines drawn using the data in Figure 5 are the second order polynomials.

Figure 6 presents the optimum water content values against FRG percentage in the mixtures. For the optimum water content a decrease of 3-4% was observed versus a 10% increase in the FRG percentage of the mixture. The trend lines drawn based on the optimum water content values in Figure 6 are second order polynomials and the related R squared values show a minor discrepancy between the results.

Biosolids are considered as biodegradable solid wastes. In the case of their application as fill material, their potential for decomposition over a long period of time results in additional settlement which contributes to the total settlement. Biodegradation settlement for biosolids can be calculated by the methods proposed by Park et al. (2007). Biosolids used in this research has been stored for approximately 20 years in the stockpiles and some of the biodegradation has already happened.

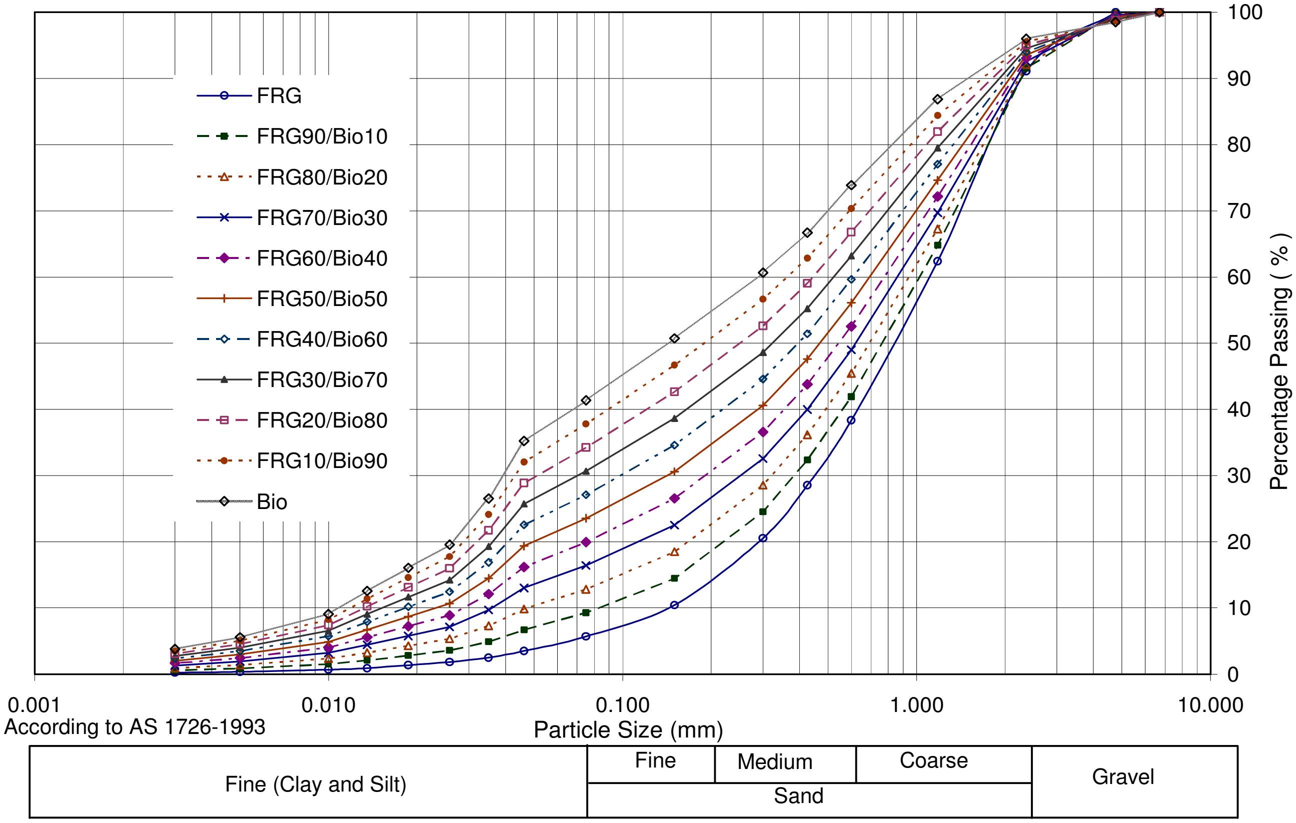

Figure 2. Particle size distribution curves of pure and blended samples

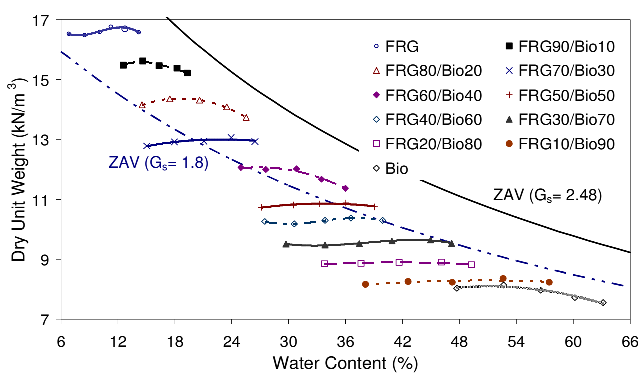

Figure 3. Standard compaction curves of the mixtures

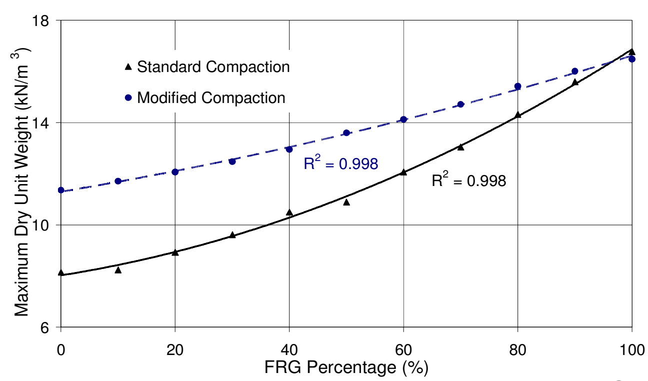

Figure 5. Maximum dry unit weight versus FRG percentage

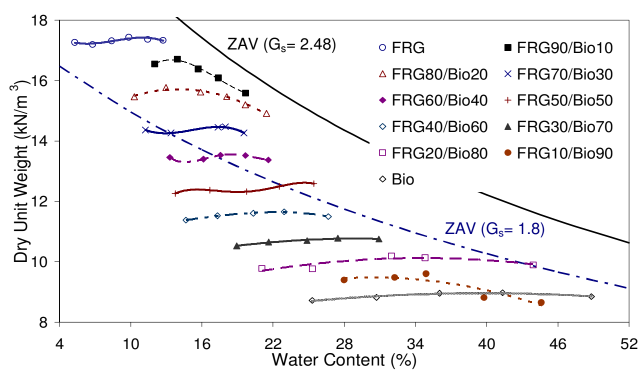

Figure 4. Modified compaction curves of the mixtures

6 CBR VALUES OF FRG/BIO MIXTURES

To assess the suitability of the blended material for road embankment applications, California Bearing Ratio (CBR) tests were conducted on the mixtures. The blended specimens for CBR tests were prepared using both standard and modified compaction efforts. Figure 7 shows the variation of CBR values of the mixtures with the change in the FRG percentage. CBR values of the blended material increased slightly with the increase of FRG percentage from 0 to 40% in the mixture. By adding more FRG to the mixtures and subsequent increase of FRG percentage from 40% to 100%, the CBR values raised significantly. This trend seems to be the same for the samples prepared by using standard and modified compaction efforts.

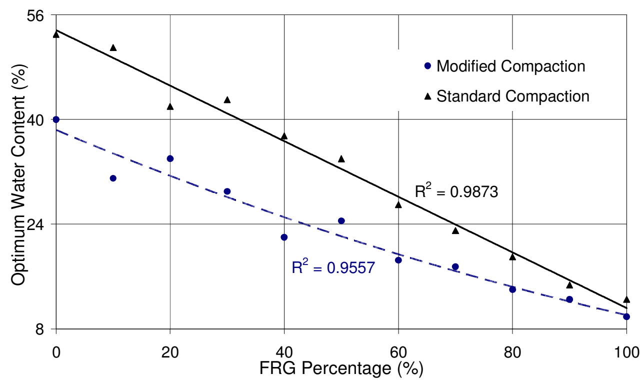

Figure 6. Optimum water content versus FRG percentage

The trend lines drawn using the CBR values in Figure 7 are the second order polynomials. The reported CBR values are the average value for two series of tests conducted on the blended material and in the event of a noticeable difference between the results, the test was repeated. As such, the relatively low R-squared values (although the R-Squared value obtained for samples prepared using modified compaction effort is slightly higher) should be the outcome of some uncontrolled factors affecting the CBR tests. Figure 7 suggests that adding FRG to biosolid material can enhance its resistance against compressive forces and consequently its performance in road work applications will improve.

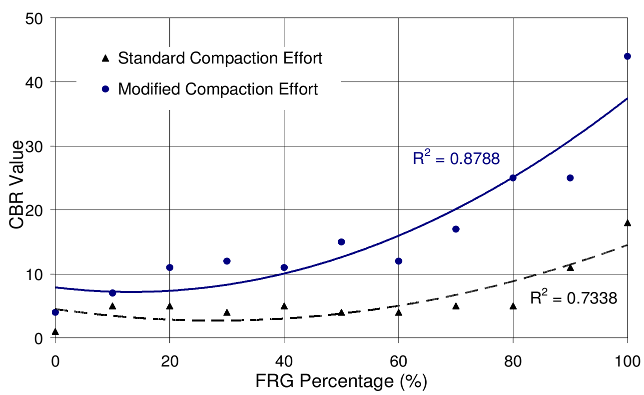

Figure 7. CBR values versus FRG percentage

7 SHEAR STRENGTH OF FRG/BIO MIXTURES

To assess the shear strength of the blended material, direct shear tests were conducted on 10 by 10 cm size square samples. Essential controls have been carried out to ensure that the dry unit weight and the moisture content of the samples were within the accepted boundaries. Five different normal stress levels (30 kPa, 60 kPa, 120 kPa, 240 kPa, and 480 kPa) were applied on the blended material. Figure 8 illustrates the shear stress-shear strain relationship of the FRG50/Bio50 sample.

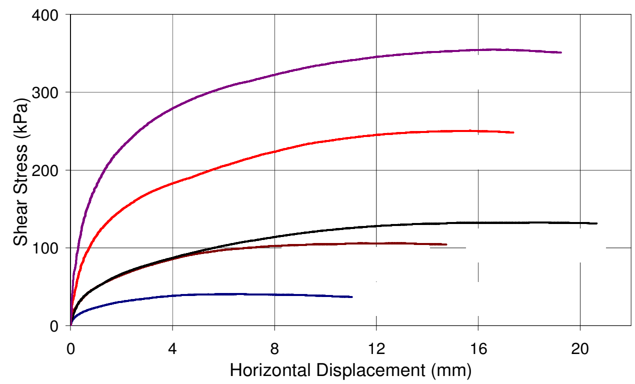

Figure 8. Shear stress-shear strain relationship for FRG50/Bio50 sample

Figure 9 shows the variation of cohesion coefficient (kPa) and internal friction angle (degree) of samples versus the change in FRG percentage for the stress level of 30 - 120 kPa. Trendlines drawn using second order polynomials on Figure 9 present the order of change of the shear strength parameters. The trendline drawn for the internal friction angle values suggests that with the increase of FRG percentage from 0 to 50% the internal friction angle of the blended material will increase gradually from 10º to 43º. Further increase of the FRG percentage up to 80% result no noticeable change. With FRG percentage increasing from 80% to 100% (pure FRG sample) a general decrease in the internal friction angle was observed based on the trendline profile. The internal friction angle represents the shear resistance of soil which has been produced by the frictional force developed between soil particles. Better interlocking between particles of a specific material will create a higher friction angle. Higher values of the internal friction angle for samples containing 60% to 70% FRG is the sign of increased interlocking between the particles.

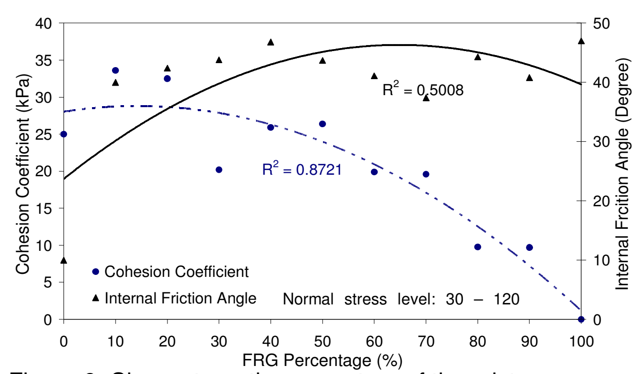

Figure 9. Shear strength parameters of the mixtures

Figure 9 shows that with the addition of FRG to biosolid samples (from 0% FRG to 30% FRG) the cohesion coefficient value remained approximately constant. This trend was followed by a continuous decrease of the cohesion coefficient (for samples containing 30% to 100% FRG). The rate of decrease is lower for FRG values up to 60% as shown by the trendline developed in Figure 9. Taking into account the low percentage of fine particles in the FRG and the higher percentage of clay size particles in biosolids, the trend of change in the cohesion coefficient seems reasonable.

Considering the specific deficiencies of direct shear test, the lower R-squared values and the discrepancy between the results in Figure 9 appears to be acceptable. An extended triaxial testing program on the blended material is currently in progress to verify the trend of change in shear strength parameters.

To determine the optimum mixtures possessing the maximum shear strength, curves representing shear strength envelopes for various normal stress levels have been developed as shown in Figure 10.

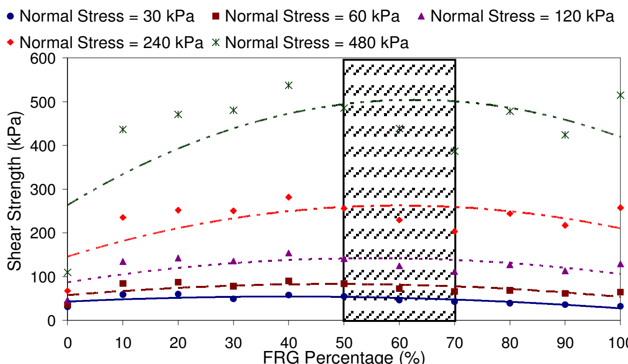

Figure 10. Shear strength envelopes versus FRG percentage

The shaded area in Figure 10 shows the maximum shear strength which can be obtained for different normal stress levels. Figure 10 illustrates that the maximum shear strength has been achieved for FRG percentage varying from 50% to 70% and the highest shear strength value belongs to FRG60/Bio40 mixture for all normal stress levels. The differences between the shear strength values for low normal stress levels is small, however this difference becomes noticeable when the normal stress level is increasing from 30 kPa to 480 kPa.

8 CONCLUSION

An innovative idea of blending recycled glass and biosolids in various ratios was investigated to assess the application of the blended material in road embankment applications. Geotechnical laboratory tests were undertaken on the pure and blended materials. Results of direct shear tests suggested that mixtures containing 50% to 70% FRG specially FRG60/Bio40 mixture produce the highest shear strength level. CBR values and particle size distribution of these mixtures indicated their potential to be used as a stabilised fill in road embankment applications. Triaxial shear tests and hydraulic conductivity tests on the blended material are in progress.

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