Technical Feasibility of Using Glass Cullet as an Engineering Fill in Reclamation and Earthworks

GEO Report No. 324

S.T.C. So, T.H.H. Hui & R.M.K. Lee

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

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Preface

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H.N. Wong
Head, Geotechnical Engineering Office
November 2016

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Foreword

This Technical Note presents the results of a study on the technical feasibility of using crushed waste glass (i.e. glass cullet) as an engineering fill in reclamation and earthworks. The study comprised a series of laboratory tests on glass cullet samples and a review of overseas experience on the applications of glass cullet. Recommendations on grading, sampling, testing requirements as well as design considerations on the use of glass cullet in reclamation and earthworks are provided.

The study was carried out by Dr Sunny T.C. So, Mr Thomas H.H. Hui and Mr Robert M.K. Lee under my supervision. Mr Tony M.F. Lau provided useful advice on the testing of glass cullet. Laboratory tests on glass cullet samples were carried out by Messrs H.L. Li, W.M. Chan and P.S. Chan. All contributions are gratefully acknowledged.

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Abstract

To save landfill space and promote the effective use of waste glass, CEDD has been commissioned by DEVB to undertake a study to examine the feasibility of using glass cullet as an engineering fill in reclamation and earthworks. This study comprised carrying out a review of overseas experience of using glass cullet as fill materials, conducting laboratory tests to determine the physical and engineering properties of glass cullet produced by local suppliers, and undertaking a review of the grading and testing requirements of glass cullet as a fill material in Hong Kong. Based on the results of the study, glass cullet would have quantifiable engineering properties similar to those of granular soils. With proper engineering control, the use of glass cullet as a fill material in both reclamation and earthworks should be acceptable. Recommendations on grading, sampling and testing requirements on the use of glass cullet for reclamation and earthworks are given.

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1 Introduction

Glass generally consists of 70% or more silica (SiO_2) and a small percentage of soda ash (Na_2CO_3), potash (K_2CO_3) and lime (CaO). It is chemically inert and will not release any toxic substance into the environment (EPD, 2014).

In Hong Kong, about 90,000 tonnes of glass containers are used every year (EPD, 2014), which are mainly for holding drinks and beverages. At present, the majority of glass containers are used once and they ultimately end up in landfills. Only a small portion of them is recovered for use as an engineering material to replace natural river sand for production of concrete paving blocks.

Waste glass takes up space when buried at landfills. To save landfill space and promote the effective use of waste glass, GEO of CEDD has been commissioned by DEVB to undertake a study to examine the feasibility of using crushed waste glass (i.e. glass cullet) as an engineering fill material in reclamation and earthworks.

The scope of this study report includes the following:

(a) review overseas experience of using glass cullet as fill materials, including the grading and testing requirements for various types of applications;

(b) conduct laboratory tests to investigate the physical and engineering properties of glass cullet produced in Hong Kong;

(c) examine the technical feasibility of using glass cullet as an engineering fill material in reclamation and earthworks; and

(d) recommend grading and testing requirements for glass cullet to be used in reclamation and earthworks.

This study only deals with the application of 100% glass cullet. Use of mixtures of glass cullet and other materials (such as soils) is not covered. Providing guidance on the allowable levels of various chemical substances in glass cullet is also outside the scope of this study. This report presents the findings of the study together with the recommended technical requirements for glass cullet to be used in reclamation and earthworks.

2 Overseas Experience of Using Glass Cullet as Fill Materials

2.1 General

Glass cullet is a mixture of different coloured glass fragments resulting from crushing of waste glass (predominately food and liquor containers) collected from different sources, which could be widely scattered. Studies on the physical and engineering properties of glass cullet have been conducted in many countries, including United States of America (USA), Australia, United Kingdom, etc. (Blewett & Woodward, 2000; CWC, 1993, 1996 & 1998; Ooi et al, 2008; Wartman et al, 2001; Wartman et al, 2004; Disfani, 2011). Glass cullet has

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been widely used in many construction applications in the USA (see Table 2.1), including general fill, base and sub-base for road works, utility bedding, drainage filter, landfill cover, etc. (CWC, 1998). The most common gradings of glass cullet in the applications are ¾ inch minus (i.e. maximum size of about 19 mm) and ¼ inch minus (i.e. maximum size of about 6.4 mm). CWC (1993) recommended the use of ¾ inch minus glass cullet as fill material in drainage and earthworks.

Glass cullet and soil-glass cullet mixtures have also been used in earthworks for supporting facilities with different loading conditions. Glass cullet has also been used in some roadway construction projects in various cities in the USA (e.g. Ocean City, Maryland; Orange County, New York; Warner, New Hampshire, Pierce County, Wisconsin, etc.), which account for about 10% of the road base materials (NSRA, 1997).

2.2 Physical and Engineering Properties of Glass Cullet as Determined by Clean Washington Centre (CWC)

Clean Washington Centre carried out a series of laboratory tests to determine the physical and engineering properties of glass cullet (CWC, 1993 & 1998). The results are shown in Tables 2.2 and 2.3 below.

The studies by CWC (1993 & 1998) indicated that ¾ inch minus glass cullet would have physical properties similar to those of natural granular materials, and concluded that glass cullet could be used as an alternative to the conventional granular materials. Compaction of glass cullet would be similar to that of granular materials. Pertinent observations on properties of glass cullet are summarised as follows:

(a) specific gravity of glass cullet is generally about 2.5 which is lower than that of natural aggregates with typical value of about 2.65;

(b) shear strength of glass cullet is about the same as natural aggregates, with friction angle ranging from 40^o to 50^o. Also, mixing glass cullet with aggregates apparently would not affect the shear strengths of the mixtures;

(c) under normal compaction and loading conditions (e.g. Standard Proctor test), there is little grading change on glass cullet. However, grading change was observed when glass cullet was subjected to heavy impact load (e.g. Modified Proctor test);

(d) compaction of glass cullet is relatively insensitive to moisture content if the fines content is less than 10%;

(e) good engineering performance would be expected for glass cullet with less than 5% debris (based on visual classification method, see section 2.4). No long-term settlement of the compacted glass cullet is expected if the debris content is limited to 5% to 10%;

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Table 2.1 Examples of Applications and Requirements of Glass Cullet in USA

State	Authority	Application	Size and Grading	Mix	Debris Content	Heavy Metal Content	Remarks
Washington	Washington State Department of Transportation	General fill and drainage	< ¾ inch, < 5% fines content	Max. 100% (by weight)	< 10% (by visual classification)	Total lead content < 80 ppm	-
		Road works	< 10% retained on 1/4 inch sieve	Max. 15% (by weight)	-	-	-
Nebraska	Nebraska State Recycling Association	General fill and drainage	< ¾ inch, < 5% fines content	Max. 100% (by weight)	< 10% (by visual classification)	Total lead content < 80 ppm	-
		Road works	< 10% retained on 1/4 inch sieve	Max. 15% (by weight)	-	-	-
Oregon	Oregon Department of Transportation	Drainage	< ½ inch, < 5% fines content	Max. 100% (by weight)	< 10% (by visual classification)	-	-
California	California Department of Transportation (CalTrans)	Road works	Follow the size criteria specified for aggregate applications by CalTrans	100% or mixed with asphalt concrete, cement concrete, lean concrete base, cement treated base	Free of organic material and other deleterious substances	-	Surfacing material required
Connecticut	-	Road works	< 1 inch	Max. 25% (by weight)	-	-	Cannot be placed within five feet from face of any slope
New York	New York State of Transportation (NYSDOT)	Road works	< 3/8 inch	Max. 30% (by volume) for embankment Max. 30% (by weight) for road works	< 5% (by volume) of ceramic and non-glass materials	-	Waste glass cannot be placed in contact with any synthetic liners, geogrids or geotexitle material
New Hampshire	New Hampshire Department of Transportation (NGDOT)	Road works	< 1/2 inch, < 1.5% between 4.75 mm and 75 μm	Max. 5% (by weight)	Small amount of ceramic and plate glass are permitted	Hazardous or toxic materials not allowed	NGDOT require all base course be tested from compliance

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Table 2.2 Physical Properties of Glass Cullet (CWC, 1993 & 1998)

Property	¾ inch Minus (CWC, 1993 & 1998)
Specific Gravity	1.96 - 2.52
Particle shape	Angular
Coefficient of Uniformity	3.3 - 16
Fines Content	0.2% - 1.4%
Debris Content	< 15% by visual classification
Maximum Dry Density (Standard Proctor)	1.59 - 1.72 Mg/m^3
Maximum Dry Density (Modified Proctor)	1.78 - 1.89 Mg/m^3
Crushability	Obvious change in grading was observed after Modified Proctor tests, but the fines content was only increased slightly. Samples with higher debris content would have relatively more significant changes in grading.

Table 2.3 Engineering Properties of Glass Cullet (CWC, 1993 & 1998)

Tests	Glass Cullet Content			
	0%	15%	50%	100%
Permeability	-	-	-	6.5×10^{-4} - 2.6×10^{-3} m/sec
Friction Angle from Direct Shear(1)	51^o	49^o - 51^o	52^o - 53^o	51^o
Friction Angle from Triaxial Shear(2)	44^o	44^o - 46^o	42^o - 43^o	-
California Bearing Ratio(2)	40 - 80(3)	90 - 115	42 - 95	-

Notes:
(1) Gravely sand was used to mix with glass cullet.
(2) Crushed rock was used to mix with glass cullet.
(3) Typical value range for crushed rock.

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(f) permeability of glass cullet is similar to that of medium sand and gravel which are commonly used as filter materials;

(g) glass cullet may have less resistance against abrasion when compared with crushed rock. Mixing glass cullet with aggregates would enhance its resistance against abrasion; and

(h) glass cullet is durable and mechanically sound. Mixing glass cullet with aggregates would further improve its bearing capacity and resilient modulus.

2.3 Grading Requirements of Glass Cullet Recommended by CWC

The grading requirement of glass cullet recommended by CWC (1993) for use as structural fill is given in Figure 2.1. The grading zone generally covers sand and gravel, with less than 5% of fines content. If the glass cullet is used in drainage applications, a relatively less stringent grading requirement, as shown in Figure 2.2, is recommended by CWC (op cit). In addition, the glass cullet-soil mix ratios and the maximum debris contents for different loading scenarios are given in Table 2.4.

Sieve Size	¾ inch (19 mm)	1/4 inch (6.35 mm)	No. 10 (2 mm)	No. 40 (425 µm)	No. 200 (75 µm)
Percent Passing	100	10 - 100	0 - 50	0 - 25	0 - 5

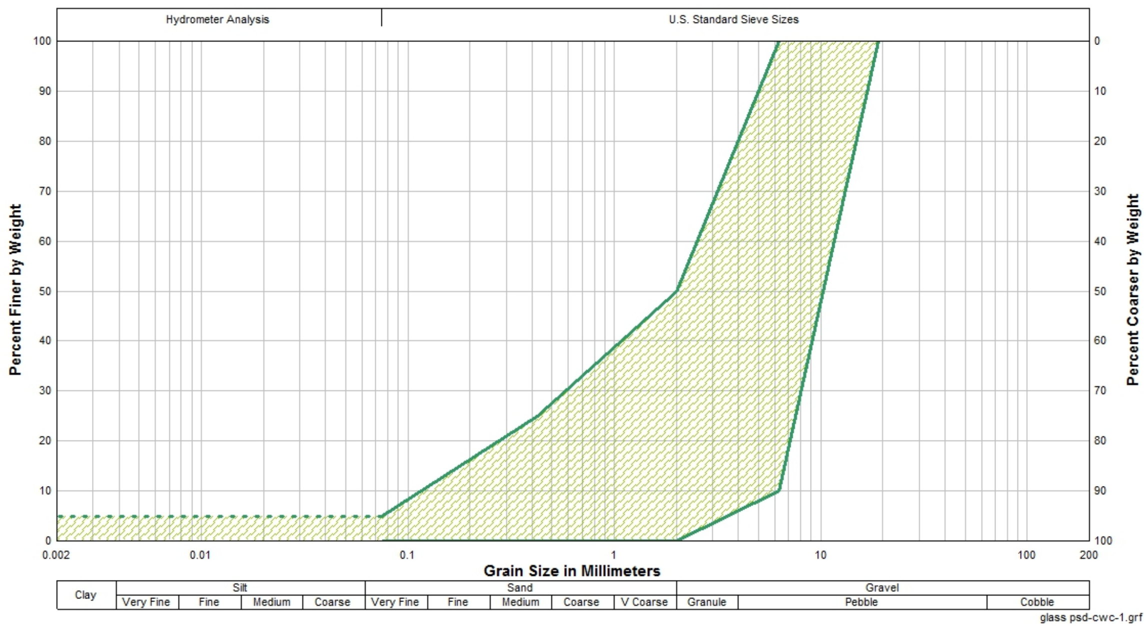

Figure 2.1 Grading of Glass Cullet Recommended by Clean Washington Centre for Use as Structural Fill (CWC, 1993)

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Sieve Size	¾ inch (19 mm)	1/4 inch (6.35 mm)	No. 10 (2 mm)	No. 40 (425 µm)	No. 200 (75 µm)
Percent Passing	100	10 - 100	0 - 100	0 - 50	0 - 5

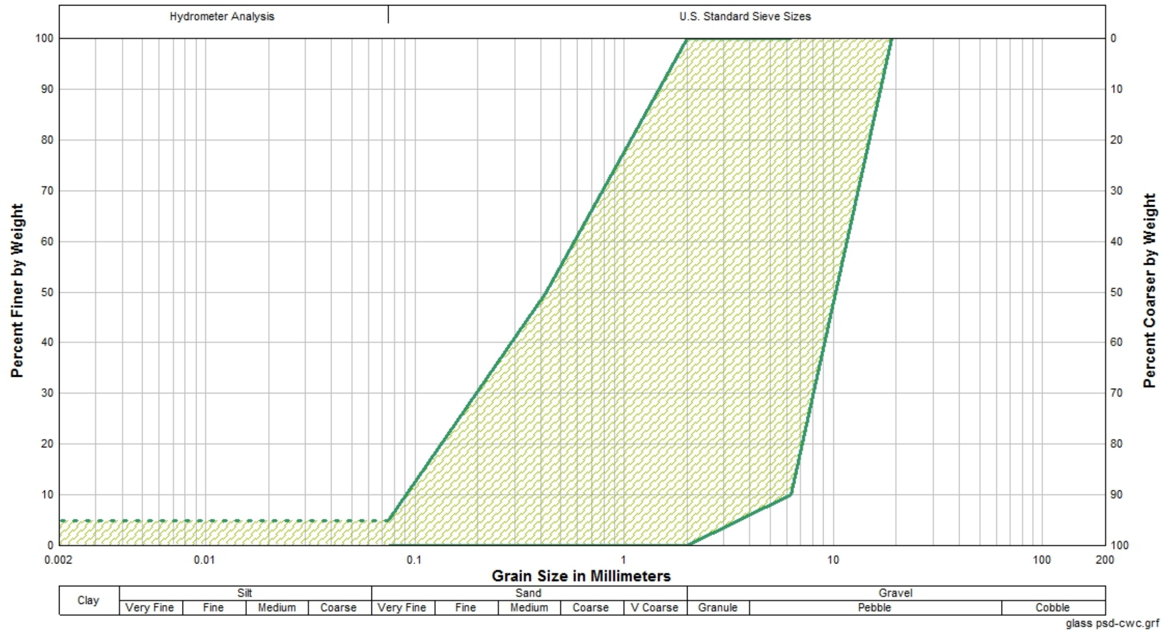

Figure 2.2 Grading of Glass Cullet Recommended by Clean Washington Centre for Drainage Applications (CWC, 1993)

2.4 Method of Determination of Debris Content Recommended by CWC

Debris contents as recommended by CWC (1993 & 1998) are to be determined by visual classification method. The method involves the placement of about 200 g of glass cullet in flat plate and the approximate % of debris content should be estimated with reference to the Percent Composition Charts (Figure 2.3) developed by American Geological Institute (AGI Data Sheets 15.1 and 15.2). Calibration exercises conducted by CWC (op cit) indicated that percentage of debris content estimated using visual classification method was about 2.5 to 5 times greater than that measured by weight.

CWC (1998) stated that the percentage determined by the visual classification method was neither mass nor volume percentages, but an indicator of the relative level of contamination in a glass cullet sample.

2.5 Requirements on Compaction in Different Loading Scenarios Recommended by CWC

Glass cullet is typically used in lightly loaded applications (e.g. pedestrian sideways) in which it should be compacted to 95% of the maximum dry density as determined using the Standard Proctor test method. In resisting heavy loads (e.g. footings and slabs) or

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fluctuating loads (e.g. compressors or vibrational machinery), mixing glass cullet with soil would be required in order to enhance the bearing resistance. Also, the maximum dry density should be determined using the Modified Proctor test method.

According to CWC (1996), for small load areas such as footings or piers, typical bearing capacities of 1,000 to 1,500 pounds per square foot (48 to 72 kPa) can be achieved by 100% glass cullet. For large load areas such as mat or rigid pavement, a subgrade reaction modulus in the range of 100 to 200 pounds per cubic inch (27.7 MPa/m to 55.4 MPa/m) could be considered.

Table 2.4 General Specifications on Glass Cullet Recommended by Clean Washington Centre

Loading Conditions	Maximum Cullet Content (% by weight)	Maximum Debris Content (%) – by Visual Classification	Minimum Compaction Level (%)
Load-support Applications			
Heavy, Stationary Loads	30	5	95
Fluctuating Loads	15	5	95
Non-loading	100	10	85
Light, Stationary loads	100	10	95
Lateral Loads	100	10	95
Roadway Applications			
Base Course	15	5	95
Subbase	30	5	95
Embankments	30	5	90
Utility Applications			
Water & Sewer Pipes	100	5	90
Electrical Conduit	100	5	90
Fiber Optic Lines	100	5	90
Drainage Applications			
Retaining wall	100	5	95
Foundation Drain	100	5	95
Drainage Blanket	100	5	90
French Drain	100	5	90
Leachate Collection	100	5	90
Miscellaneous Applications			
Landfill Cover	100	10	90
UST Backfill	100	5	90

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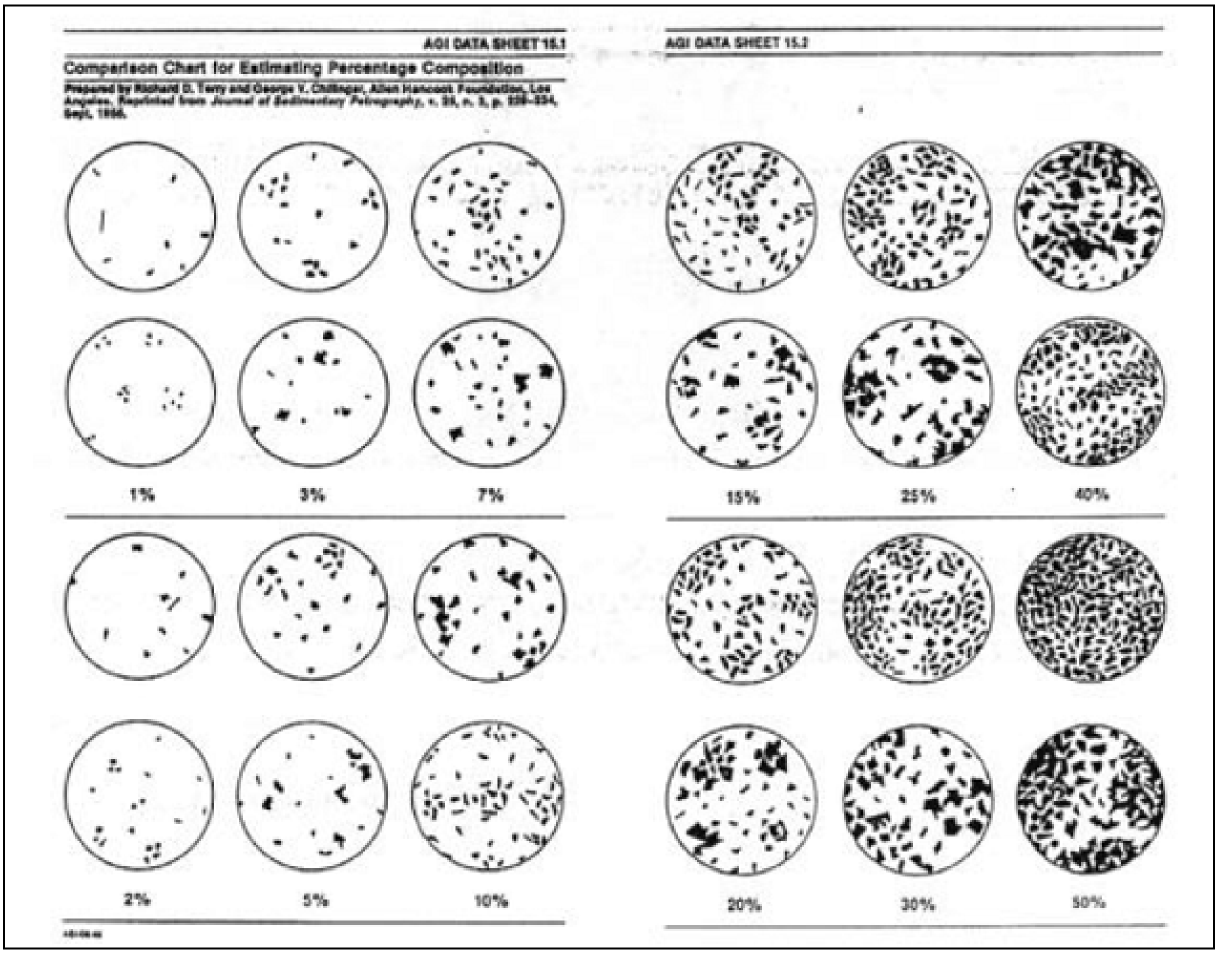

Figure 2.3 Percent Composition Charts (AGI Data Sheets 15.1 and 15.2) for Estimation of Debris Content in a Glass Cullet Sample (CWC, 1993 & 1998)

2.6 Other Recommendations on Handling of Glass Cullet

Other recommendations related to the handling of glass cullet (NSRA, 1997; CWC 1993 & 1998) are summarised below.

(a) total lead content in glass cullet should be less than 80 ppm;

(b) each lift in compaction of glass cullet should not exceed 8 inches (i.e. 200 mm) in loose thickness;

(c) frequency of in-situ density testing for earthworks is typically one per 1,000 square feet (i.e. about 100 m^2) of fill but not less than one per lift of fill. Either sand replacement test or nuclear densometer can be used for determination of the in-situ density of glass cullet;

(d) glass cullet should not be placed within five feet (i.e. about 1.6 m) from the face of any slope;

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(e) glass cullet can be used for backfill up to the last two feet (i.e. about 0.6 m) below the final grade supporting utilities;

(f) glass cullet should not be placed in direct contact with unprotected synthetic liners and geogrids;

(g) adequate safety measures should be provided in handling and testing of glass cullet, which should be similar to those for working with natural aggregates. Glass cullet dust is not considered hazardous by federal standards of USA and can be easily controlled by wet suppression; and

(h) avoid exposing glass cullet to the general public and appropriate permanent protective layers should be provided.

3 Grading and Testing Requirements of Fill Materials in Hong Kong

3.1 Fill Materials for Use in Earthworks

As specified in Section 6 of General Specification for Civil Engineering Works (GS) (HKSAR, 2006), fill materials for earthworks shall consist of naturally occurring or processed materials, or inert construction and demolition materials. The grading requirements for different types of fill materials are summarized in Table 3.1 below.

Table 3.1 Grading Requirements of Fill Materials for Earthworks (HKSAR, 2006)

Type of Fill Material	Percentage by Mass Passing					
	Size		BS Test Sieve			
	400 mm	200 mm	75 mm	20 mm	600 µm	63 µm
Fine Fill Material	-	-	100	-	-	-
General Fill Material	-	100	75 - 100	-	-	-
Special Fill Material	-	-	100	-	-	0 - 45
Granular Fill Material	-	-	100	-	0 - 5	-
Rock Fill Material/ Recycled Rock Fill Material (Grade 200)	-	100	20 - 75	0 - 59	-	-
Rock Fill Material (Grade 400)	100	20 - 75	10 - 30	0 - 25	-	-

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As shown in Table 3.1, fill materials for earthworks can have a wide range of grading. Typical tests on fill materials for complying with the above grading requirements comprises particle size distribution (PSD), liquid limit, plasticity index and coefficient of uniformity (C_u).

It is also stipulated in GS that fill materials shall not contain any of the following :

(a) material susceptible to volume change, including marine mud, soil with a liquid limit exceeding 65% or a plastic index exceeding 35%, swelling clays and collapsible soils;

(b) peat, vegetation, timber, organic, soluble or perishable material;

(c) dangerous or toxic material or material susceptible to combustion; and

(d) metal, rubber, plastic or synthetic material.

In addition, GS has specified the maximum sulphate content of fill materials to be placed in close proximity to concrete, cement or metalwork facilities.

Fill materials should be compacted in layers to a specified relative compaction after deposition. Typical tests to determine the relative compaction are sand replacement test and Proctor test, which are classified as compliance tests in GS.

3.2 Fill Materials for Use in Reclamation

The grading requirements for different types of fill materials for reclamation as specified in Section 21 of GS are summarized in Table 3.2 below. Type 1 underwater fill materials shall consist of natural materials extracted from the seabed or a riverbed, whereas Type 2 shall consist of material that has a C_u exceeding 5 and a plasticity index not exceeding 12.

For hydraulically placed fill, it is specified in Port Works Design Manual (PWDM) (CEO, 2002) that the fines content should be limited to about 10%. Where vibrocompaction is proposed for treatment (i.e. densification) of reclamation fill, there would be a more stringent requirement on the grading of fill materials. As shown in Figure 3.1, materials in "Zone B" and "Zone A" are considered to be "ideally suited for vibrocompaction" and "very well compactable" respectively.

Cone penetration test (CPT) and standard penetration test (SPT) are common methods for checking the degree of improvement or performance of fill densification after treatment. Details can be found in Section 2.8.5 of PWDM (CEO, 2002).

PWDM (CEO, 2002) also provides general guidance on the principles to estimate the rate and magnitude of different types of settlement (viz. primary consolidation settlement, secondary consolidation settlement and creep settlement) in marine fill.

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Table 3.2 Grading Requirements of Fill Materials for Reclamation

Type of Fill Material	Percentage by Mass Passing				
	Size		BS Test Sieve		
	700 mm	200 mm	75 mm	20 mm	63 µm
Underwater Fill Material (Type 1)	-	-	100	-	0 - 30
Underwater Fill Material (Type 2)	-	-	100	-	0 - 25
Rock Fill Material (Grade 75)	-	-	100	0 - 5	-
Rock Fill Material (Grade 100)	100	0 - 10	0 - 5	-	-
Recycled rock Fill Material (Grade 700)	100	0 - 10	0 - 5	-	-

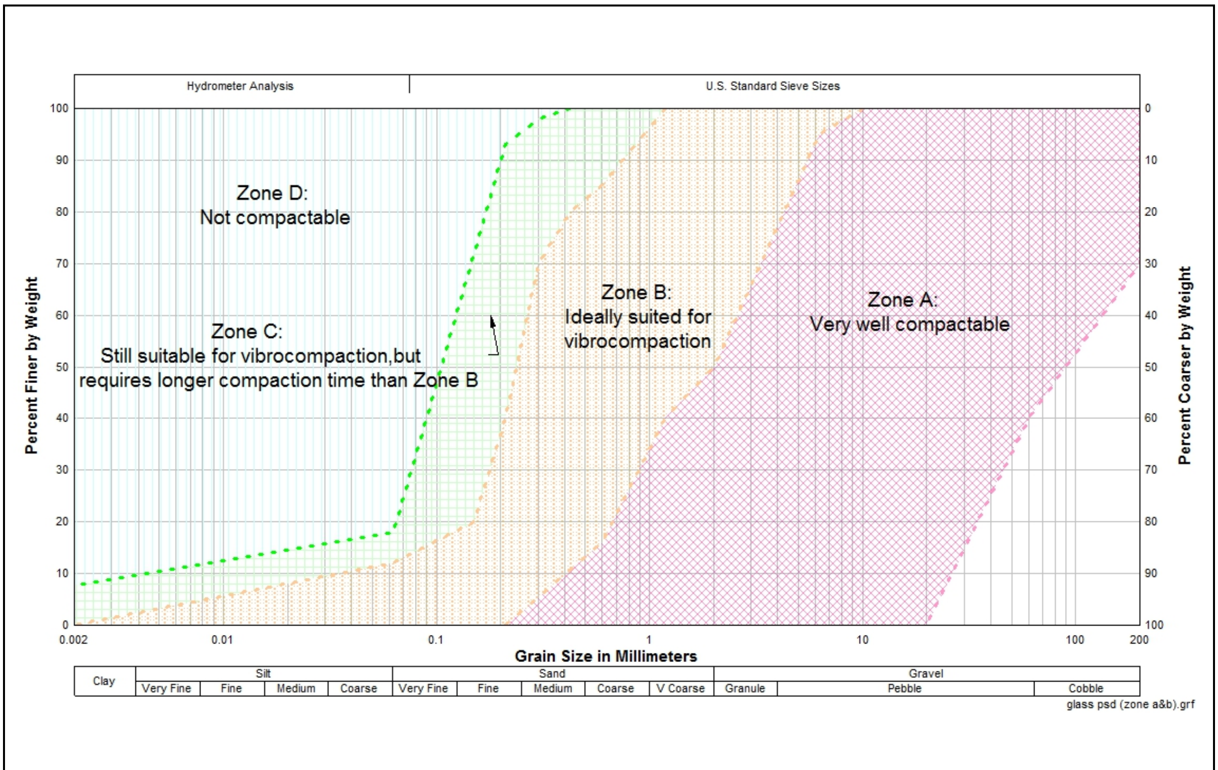

Figure 3.1 Grading of Soils Suitable for Vibrocompaction (CEO, 2002)

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4 Glass Cullet Produced in Hong Kong

4.1 General

In Hong Kong, the composition of waste glass generation in 2011 is shown in Figure 4.1. Glass beverage bottles form the majority (i.e. about 63% or 55,000 tonnes) of waste glass generated in 2011 (EPD, 2013). For the rest, food/sauce and other glass bottles account for about 37%, but they are often "contaminated" and may adversely affect the recycling operations if mixed with used glass beverage bottles without prior intensive cleansing. In addition, many consumer products such as fluorescent lamps and cathode ray tube computers or televisions also contain glass but such glass materials might contain hazardous substances (e.g. lead, mercury). These together with other uncommon glass products (e.g. tempered glass, glass cookware) should not be mixed with glass beverage bottles for recycling.

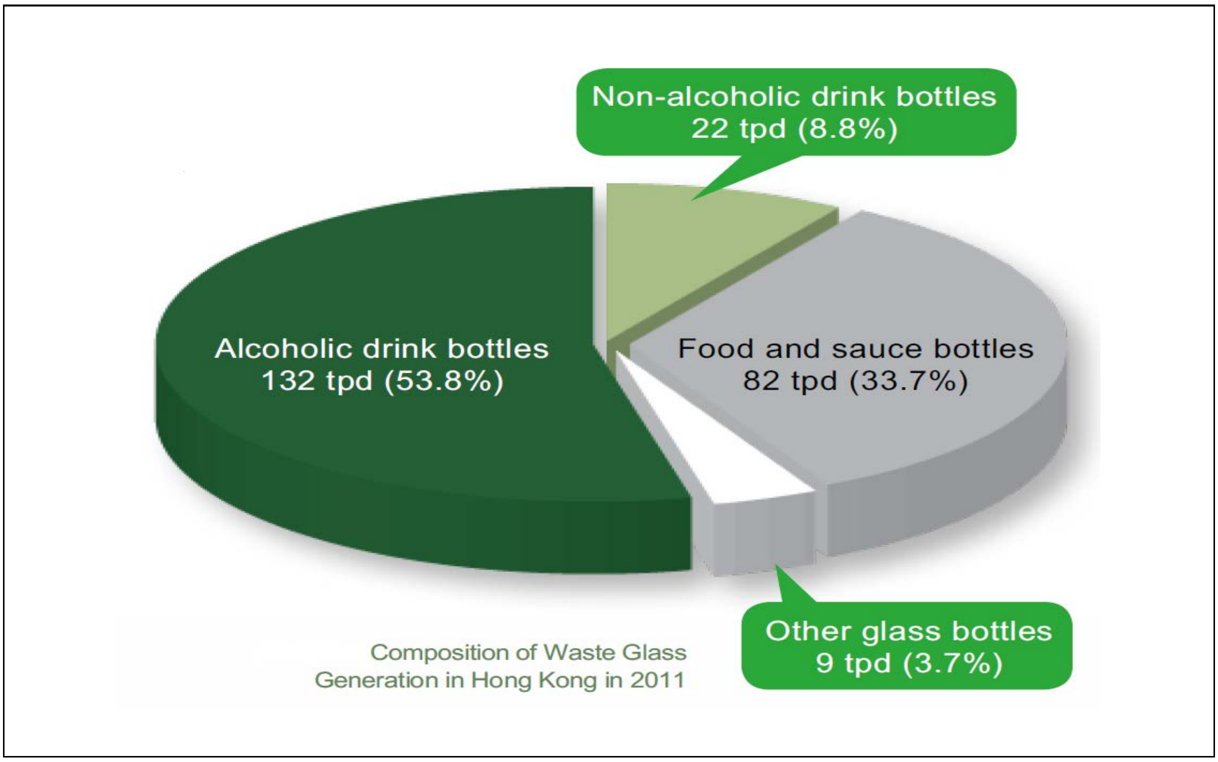

Figure 4.1 Waste Glass Generation in Hong Kong in 2011

Glass cullet samples in this study were obtained from two local suppliers, viz. Laputa Eco-Construction Material Co., Ltd. (Laputa) and Ka Wah Construction Product Ltd. (Ka Wah). The waste glass collected for production of glass cullet was mainly glass beverage bottles and glass panels. In the production process, waste glass was crushed and ground into smaller particles by a crushing machine (see Figure 4.2).

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Figure 4.2 Production of Glass Cullet by Crushing of Waste Glass

The glass cullet produced by the two suppliers is of grading 3 mm or smaller (i.e. 3 mm minus) in size, which would be used for production of paving blocks. The grading of 3 mm minus glass cullet would comply with that for drainage fill (see Figure 2.2) as recommended by CWC (1993). Based on the literature review, there were no previous cases or recommendations of using 3 mm minus glass cullet in backfilling or drainage works. Also, the overseas experience and the related tests were mainly on glass cullet of ¾ inch minus (i.e. maximum size of about 19 mm).

Only Laputa is capable of produceing glass cullet of 20 mm or smaller (i.e. to fit the size of sieving in BS standard). In general, lesser crushing effort and energy would be required for production of coarser glass cullet. This should be welcomed by suppliers. As glass cullet could be used in various applications, it is considered necessary to carry out tests on both 3 mm minus and 20 mm minus samples. In the study in 2012 (GEO, 2013a), six batches totaling 600 kg of 20 mm minus (all from Laputa) glass cullet were collected for testing. In an additional study in 2013 (GEO, 2013b), approximately 1,500 kg of 3 mm minus glass cullet was collected from each of Laputa and Ka Wah for testing.

A close examination of the particle form and angularity of glass cullet collected was conducted in 2012 (GEO, 2013a). The 20 mm minus glass particles were angular in shape and with very sharp, conchoidal fracture surfaces. The particle form was mostly flat and

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partly equidimensional. In the additional study in 2013, the 3 mm minus glass particles were angular in shape, with sharp edges and conchoidal fracture surfaces and particle form mostly equidimensional or flat (see Figure 4.3).

4.2 Debris Content of Glass Cullet in Hong Kong

Non-glass debris that was found in glass cullet samples in Hong Kong comprised cork, paper, plastic, metal flakes, etc. Manual separation of the debris from the glass cullet samples were carried out for determination of debris contents. The total debris contents in all samples were found to be less than 2% by weight and the organic matter contents (e.g. timber) were less than 0.2%. In general, 3 mm minus samples had lower debris contents than those of 20 mm minus samples (Table 4.1). This is probably because those non-glass debris is relatively less susceptible to crushing and use of sieve of a smaller size would have helped to remove them from the bulk mass of glass cullet, thus reducing the debris content.

Assuming that percentage of debris content estimated using visual classification method was about 2.5 to 5 times greater than that measured by weight (see Section 2), the debris contents of glass cullet samples in this study are similar to those reported in the literature (i.e. 5% to 15% by visual classification). Also, it is generally within the limits specified by CWC (1993) (i.e. 5% to 10% by visual classification could be equivalent to 1% to 4% by weight).

4.3 Chemical Tests on Glass Cullet in Hong Kong

Chemical tests were conducted to determine the concentration of some common organic and inorganic chemicals (e.g. arsenic, cadmium, chromium, copper, lead, nickel, zinc and mercury) in the glass cullet samples. The results are summarised in Table 4.1 and only a few chemicals at very low concentrations were detected. The concentrations of all chemical substances were found to be much lower than the limits specified in the Sediment Quality Criteria for the Classification of Sediment as stated in ETWB TCW No. 34/2002 (ETWB, 2002) and the Risk-Based Remediation Goals for Soil & Soil Saturation Limits as stated in the Guidance Note for Contaminated Land Assessment and Remediation (EPD, 2007). Nonetheless, providing guidance on the allowable levels of various chemical substances in glass cullet is outside the scope of this study.

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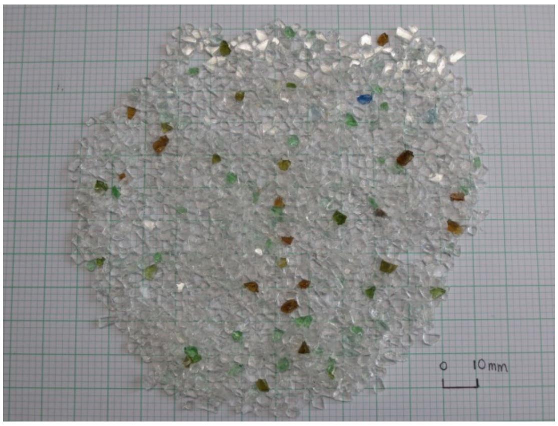
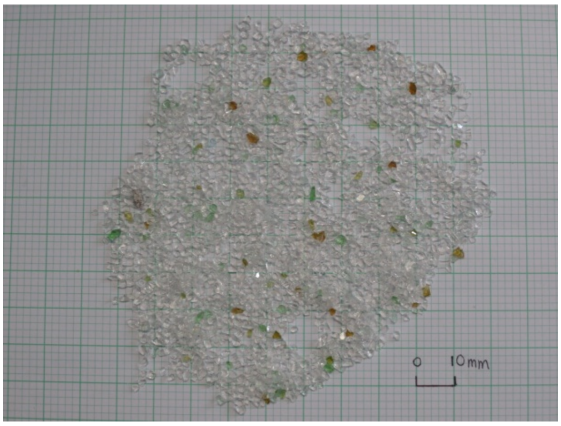
20 mm Minus Glass Cullet in the 2012 Study

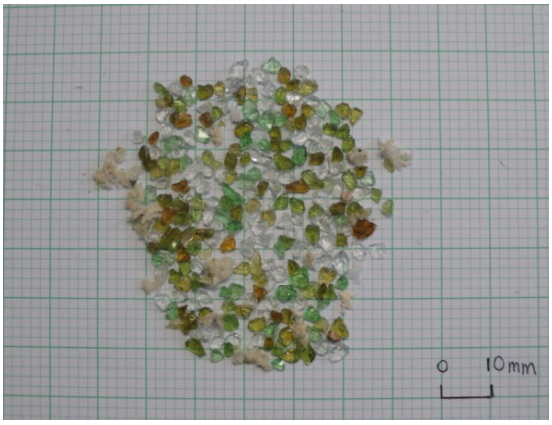


2 mm – 3.35 mm diameter

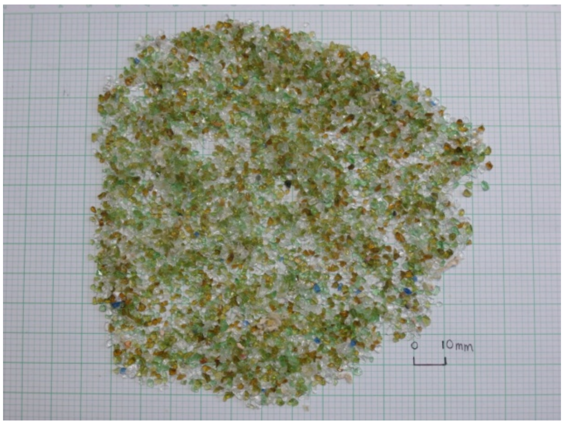


1.18 mm – 2 mm diameter

3 mm Minus Glass Cullet from Laputa in the 2013 Study



2 mm – 3.35 mm diameter



1.18 mm – 2 mm diameter

3 mm Minus Glass Cullet from Ka Wah in the 2013 Study

Figure 4.3 Particle Forms and Angularities of 3 mm and 20 mm Glass Cullet Samples

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Table 4.1 Debris, Metal and Chemical Contents

Sample		Lower Chemical Exceedance Level	3 mm Minus Glass Cullet	20 mm Minus Glass Cullet
Debris Content/Organic Matter Contents				
Debris Content (i.e. non-glass materials)	%	N/A	< 1	< 2
Organic Matter Content (Geospec 3 Test Method 9.1)	%	N/A	0.07 - 0.14	0.14
Metal Content				
Arsenic	mg/kg	12	< 1	< 1
Cadmium	mg/kg	1.5	0.4 - 1.0	0.2 - 0.6
Chromium	mg/kg	80	5 - 7	2 - 6
Copper	mg/kg	65	3 - 10	1 - 9
Lead	mg/kg	75	7 - 8	2 - 6
Mercury	mg/kg	0.5	< 0.05	< 0.05
Nickel	mg/kg	40	< 1	< 1
Zinc	mg/kg	200	< 10	< 20
Chemical Content				
Water-soluble Sulphate (in water-soil extract)	g/L	N/A	0.03	0.01
Water-soluble Sulphate (in soil sample)	%	N/A	0.00005 - 0.006	0.003
Total Sulphate	%	N/A	0.006 - 0.008	0.005
Chloride	%	N/A	0.0004 - 0.0005	0.0005
pH	-	N/A	7.8 - 9.6	8.4

5 Laboratory Testing (Other Than Chemical Tests) and Results

5.1 General

A series of laboratory tests were conducted to investigate the physical and engineering properties of 3 mm minus and 20 mm minus glass cullet. Only samples of 100% glass cullet were tested. No tests were carried out on glass cullet and soil mixture. A summary of the properties together with a comparison with those presented in the literature are given below.

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The tests were conducted according to Geospec 3 (GEO, 2001) as far as practicable unless otherwise stated.

Laboratory tests to determine the physical properties of the 3 mm minus and 20 mm minus glass cullet samples comprise particle size distribution, coefficient of uniformity, specific gravity, maximum and minimum dry densities, Standard and Modified Proctor tests. Laboratory tests to investigate the engineering properties comprise permeability, fines migration and segregation potentials, compressibility and shear strength.

5.2 Physical Properties of Glass Cullet in Hong Kong

Specific Gravity

The specific gravities of both 3 mm and 20 mm minus glass cullet samples were in a narrow range from 2.40 to 2.55, indicating that their material compositions were very similar. The specific gravity of glass cullet is in general lower than that of the soils commonly found in Hong Kong (e.g. weathered granitic and volcanic rocks) of which the average specific gravities are about 2.65.

Particle Size Distribution

Particle size distribution (PSD) tests for 3 mm minus and 20 mm minus glass cullet samples were carried out. It should be noted that the 63μm sieve was replaced by a 75 μm following the PSD procedure in CWC (1998). A summary of PSD plots are given in Figure 5.1 and the associated coefficients of uniformity and fines contents are given in Table 5.1. The limits of coefficient of uniformity and fines contents as reported by CWC (1993) for ¾ inch minus glass cullet are also presented in Table 5.1 for comparison purpose.

The gradings of 20 mm minus glass cullet samples were within the ranges specified by CWC (1993) for structural fill. The grading of 3 mm minus glass cullet samples were generally within the ranges for drainage fill, except that the fines contents of samples from Ka Wah were slightly larger than 5%.

Although higher than those of 20 mm minus glass cullet in Hong Kong and ¾ inch minus glass cullet in the US, the fines contents of the 3 mm minus samples produced by both Laputa and Ka Wah did not exceed 6%, which satisfied the requirement on fill material for earthworks and reclamation works as stipulated in both GS (HKSAR, 2006) and PWDM (CEO, 2002). The coefficients of uniformity of all 3 mm minus samples were found to exceed 5, which would meet the respective requirement for Type 2 underwater fill.

Fines contents of the 20 mm minus samples were less than 5%, which satisfied the requirement on fill material for earthworks and reclamation works as stipulated in both GS (HKSAR, 2006) and PWDM (CEO, 2002). Twelve (12) out of fourteen (14) 20 mm minus samples were found to have the coefficients of uniformity exceeding 5, which met the respective requirement for Type 2 underwater fill.

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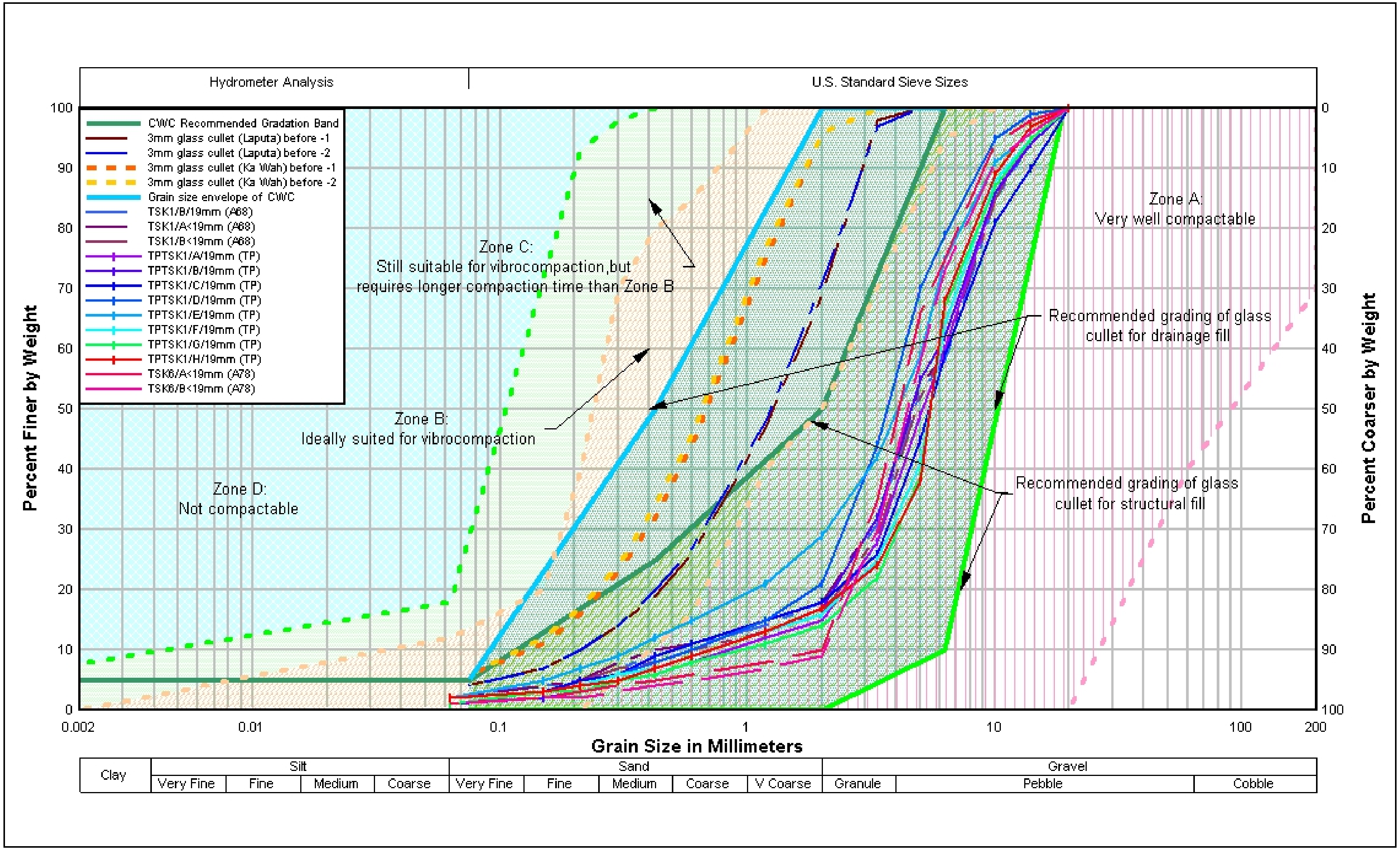

Figure 5.1 Particle Size Distributions of 3 mm Minus and 20 mm Minus Glass Cullet Samples

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Table 5.1 Coefficient of Uniformity and Fines Content of Glass Cullet Samples

	Laputa 3 mm Minus	Ka Wah 3 mm Minus	20 mm Minus	¾ inch Minus (CWC, 1993)
Coefficient of Uniformity (C_u)	7.5 - 8.0	5.9 - 7.4	2.3 - 16.7	3.3 - 16
Fines Content	4%	6%	1% - 2%	0.2% - 1.4%

The PSDs of 3 mm minus glass cullet samples entirely lie within "Zone B" (i.e. "ideally suited for vibrocompaction") and the 20 mm minus samples lie within "Zone A" (i.e. "very well compactable") and Zone B, indicating that both types could be well-compacted using vibrocompaction method.

Maximum and Minimum Dry Densities

The maximum and minimum dry densities of the glass cullet samples were determined by vibrating hammer method (BS 1377: Part 4:1990 Cl. 4.3) (BSI, 1990) and free falling method (BS 1377: Part 4:1990 Cl. 4.5) (BSI, 1990) respectively and the results are given in Table 5.2. The maximum and minimum dry densities of ¾ inch minus glass cullet as reported by CWC (1993) are also presented in Table 5.2 for comparison purpose.

Table 5.2 Maximum and Minimum Dry Densities

	Laputa 3 mm Minus	Ka Wah 3 mm Minus	20 mm Minus	¾ inch Minus (CWC, 1993)
Maximum Dry Density	1.75 - 1.77 Mg/m^3	1.78 - 1.80 Mg/m^3	1.82 - 1.83 Mg/m^3	1.58 - 1.75 Mg/m^3
Minimum Dry Density	1.51 - 1.52 Mg/m^3	1.35 - 1.37 Mg/m^3	1.26 Mg/m^3	1.23 - 1.43 Mg/m^3

The maximum dry densities of the 3 mm minus glass cullet were similar to those of the 20 mm minus glass cullet samples and those of the ¾ inch minus glass cullet reported by CWC (1993) whereas the minimum dry densities were generally higher. It should be noted that the results could be affected by specific gravities and particle size distribution of the samples tested. The difference between the maximum and minimum densities could be considered as the possible range of density under different compaction efforts.

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Standard and Modified Proctor Tests

The maximum dry densities (MDD) of glass cullet samples determined by Standard and Modified Proctor tests are given in Table 5.3. The MDD of ¾ inch minus glass cullet as reported by CWC (1993) are also presented in the Table for comparison purpose.

Table 5.3 Maximum Dry Densities Based on Proctor Tests

	Laputa 3 mm Minus	Ka Wah 3 mm Minus	20 mm Minus	¾ inch Minus (CWC, 1993)
Maximum Dry Density (Standard Proctor)	1.72 Mg/m^3	1.68 - 1.69 Mg/m^3	1.51 - 1.59 Mg/m^3	1.59 - 1.72 Mg/m^3
Maximum Dry Density (Modified Proctor)	1.79 Mg/m^3	1.77 Mg/m^3	1.69 - 1.89 Mg/m^3	1.78 - 1.89 Mg/m^3

The MDDs of the 20 mm minus samples as determined by Standard Proctor tests were relatively low (i.e. < 1.6 Mg/m^3), which were close to the lower bound values of CWC (1993) and weathered saprolites (about 1.5 - 1.9 Mg/m^3) in Hong Kong (GEO, 1993). This indicates that the 20 mm minus glass cullet particles would still have a high void ratio after Standard Proctor test. The MDDs of 3 mm minus glass cullet determined by Standard Proctor tests were higher than those of the 20 mm minus glass cullet. This indicates that the 3 mm minus glass cullet particles would be packed more closely.

Similar to the compaction behaviour of soils, dry density of glass cullet increased with compaction effort. However, the Proctor compaction curves did not take similar shapes of those for typical soils but were either flat or monotonically ascending (see Figure 5.2). This indicated that the compacted dry density of glass cullet was insensitive to the moisture content. This is consistent with the overseas literature (CWC, 1993 & 1998). The insensitivity to moisture content is probably because glass cullet is a free-drainage material, with high permeability and low water retention capacity. Water would flow downward upon compaction. As such, only a small amount of water can be retained in voids between particles for determination of water content.

A shift in the PSD curve was noted after Modified Proctor test on Laputa's 20 mm minus sample, indicating that breakage of flat glass cullet particles would have occurred under heavy impact load (see Figure 5.3). The fines contents of the broken glass cullet samples slightly increased.

There was a notable increase in MDD (i.e. or reduction in void ratio) after Modified Proctor test, when compared with that after Standard Proctor test. The increase was larger for 20 mm minus samples than 3 mm minus samples, likely attributed to the breaking of glass into finer particles. This would have a significant improvement of the shear strength and resistance against compression of glass cullet samples.

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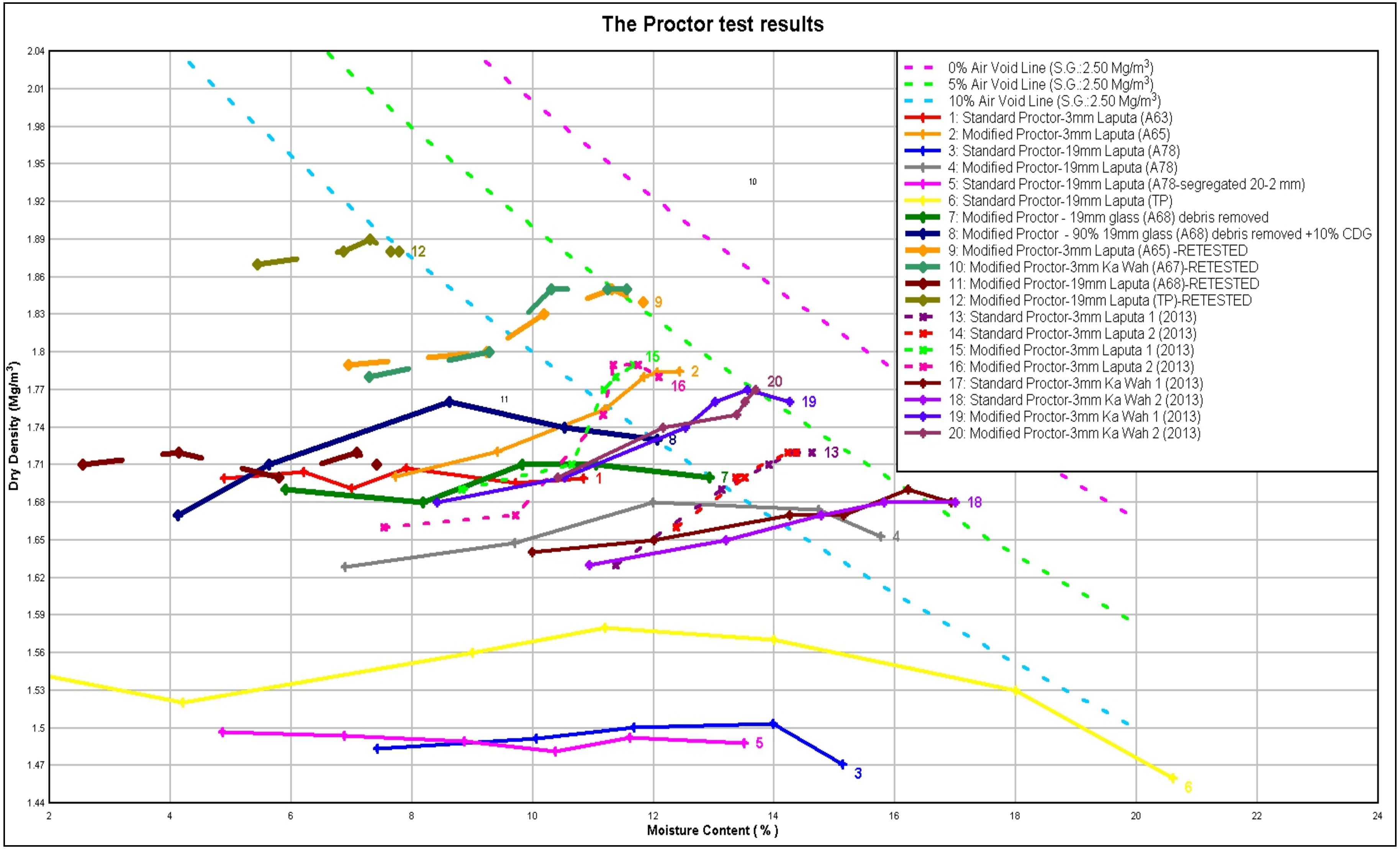

Figure 5.2 Proctor Test Results

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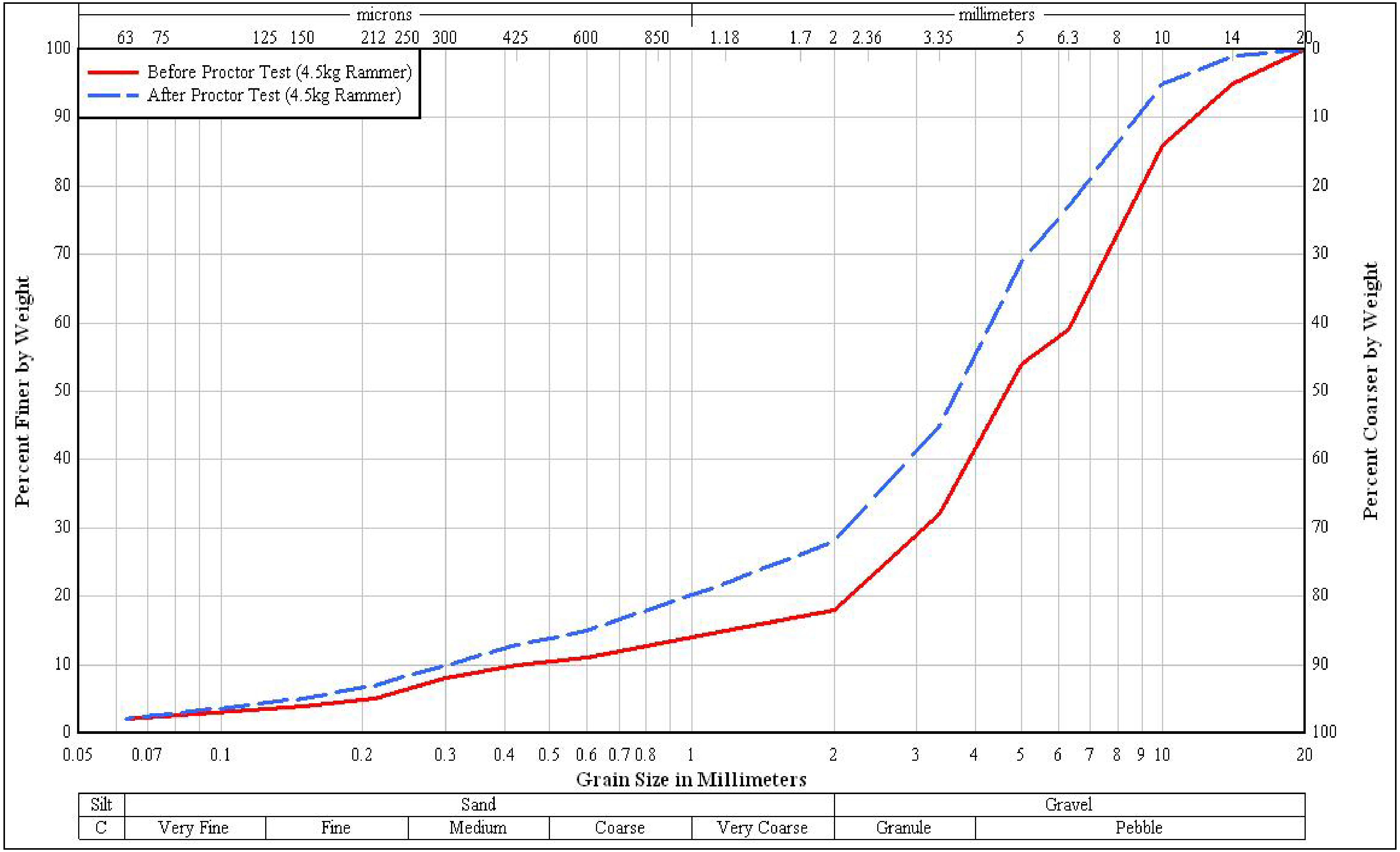

Figure 5.3 Particle Size Distributions before and after Modified Proctor Tests

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Trial compactions of 20 mm minus and 3 mm minus glass cullet samples in an area of 0.8 m $\times$ 1 m were undertaken and then followed by sand replacement tests. Compaction of glass cullet to a dry density exceeding 95% MDD was rather easy, and could be achieved manually using simple tools.

Aggregate Tests

Five types of aggregate tests were carried out to study the dimensional characteristics and susceptibility to crushing, abrasion and impact of 20 mm minus glass cullet. The results are given in Table 5.4. Typical values of laboratory crushed natural aggregates are also given for comparison (Irfan et al, 1992). It is observed that glass cullet has much higher flakiness and elongation indices and is relatively more susceptible to crushing, abrasion and impact when compared with crushed aggregates.

Table 5.4 Aggregate Tests on 20 mm Minus Glass Cullet

<table>
<tr><th>Tests</th><th colspan="3">Glass Cullet
(20 mm Minus)</th><th>Natural Aggregates (Irfan et al, 1992)
(10 - 20 mm)</th></tr>
<tr><td rowspan="2">Flakiness Index
(BS812:Section 105.1:1989)</td><td>20 - 14 mm</td><td>14 - 10 mm</td><td>10 - 6.3 mm</td><td rowspan="2">7 - 28%</td></tr>
<tr><td>97 - 99%</td><td>97 - 98%</td><td>87%</td></tr>
<tr><td rowspan="2">Elongation Index
(BS812:Section 105.2:1990)</td><td>20 - 14 mm</td><td>14 - 10 mm</td><td>10 - 6.3 mm</td><td rowspan="2">28 - 52%</td></tr>
<tr><td>64 - 65%</td><td>70 - 72%</td><td>27 - 29%</td></tr>
<tr><td rowspan="2">10% Fines Value
(BS812:Part 111:1989)</td><td>20 - 14 mm</td><td colspan="2">14 - 10 mm</td><td rowspan="2">104 - 215 kN</td></tr>
<tr><td>20 - 25 kN</td><td colspan="2">40 - 45kN</td></tr>
<tr><td rowspan="2">Los Angeles Abrasion Value
(ASTM C131-81 and C535-81 with modification)</td><td>20 - 14 mm</td><td colspan="2">5 - 2.36 mm</td><td rowspan="2">21.5 - 43%</td></tr>
<tr><td>48%</td><td colspan="2">33%</td></tr>
<tr><td rowspan="2">Aggregate Impact Value
(BS812:Part 112:1990)</td><td colspan="3">14 - 10 mm</td><td rowspan="2">12 - 33%</td></tr>
<tr><td colspan="3">45%</td></tr>
</table>

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5.3 Engineering Properties of Glass Cullet in Hong Kong

Permeability

Permeability tests were conducted on both 3 mm minus and 20 mm minus glass cullet samples which were compacted to 95% MDD as determined by Modified Proctor test using triaxial test apparatus. The results indicated that permeability of glass cullet ranged from 10^{-5} m/s to 10^{-4} m/s, which are similar to that of clean sand (Holtz & Kovac, 1981). CWC (1993) study shows that the permeability of glass cullet sample could be increased by about one order of magnitude (i.e. 10^{-4} m/s to 10^{-3} m/s) if it is compacted to 95% MDD as determined by Standard Proctor test.

Fines Migration and Segregation Potential

The test for fines migration was conducted using custom-made apparatus. 20 mm minus and 3 mm minus glass cullet specimens of known PSD, each loosely filled in a 74 mm diameter plastic tube (see Figure 5.4), were subjected to a constant water flow under various heads of 5 cm to 10 cm for 3 hours and later extracted for PSD determination. For the 20 mm minus specimen, there were measurable decreases in the relatively fine portion (mass retained on 0.3 mm or finer sieves) up to a maximum amount of 2.6% by weight. For the 3 mm minus specimen, there were measurable decreases in the fine portion (mass passing 0.075 μm) up to a maximum amount of 4% by weight. Both results indicated that there was a slight migration of fines under constant water flow.

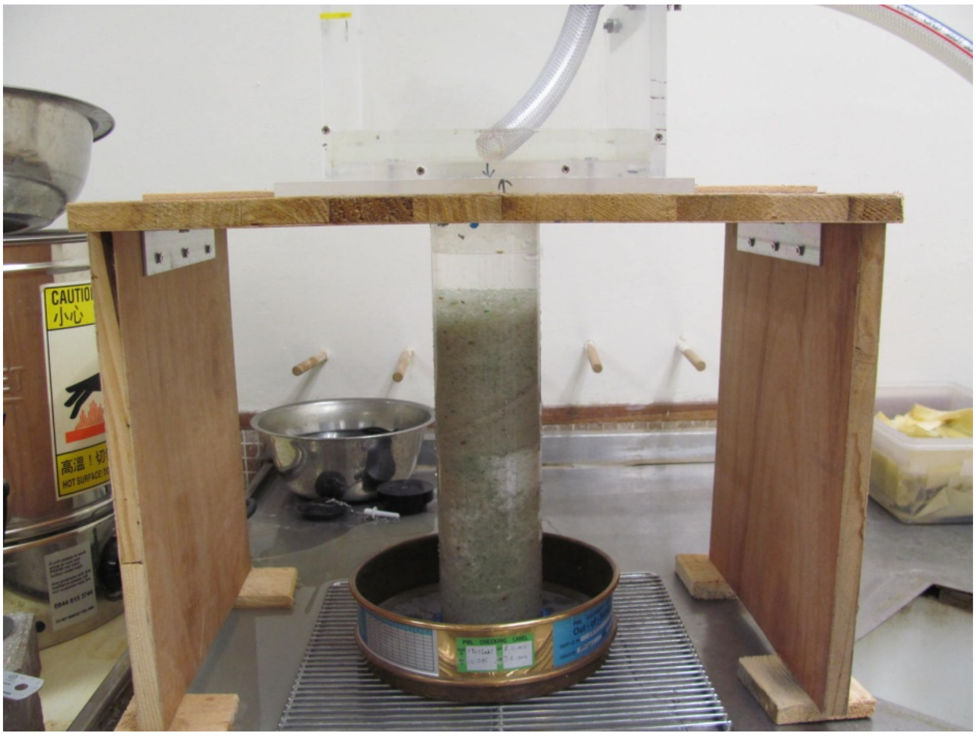

Figure 5.4 Fines Migration Test

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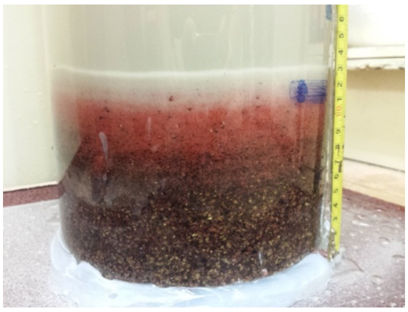
Segregation of glass cullet in water was studied by observing the settling time of a mixture of glass cullet of different sizes (for 3 mm minus samples - particles retained on 1.18 mm (gold), 0.6 mm (black), 0.3 mm (red) and passing 0.3 mm (white) sieves; for 20 mm minus samples - particles retained on 10 mm (black), 6.3 mm (red), 3.35 mm (blue) and 1.18 mm (yellow) sieves) in a 2 m high custom-made water column. The results of the experiment showed a general trend that coarser particles settled faster for both sources. It is evidenced by the layers of glass cullet of different sizes formed at the bottom of the water column. A typical result is shown in Figure 5.5.

Before mixing

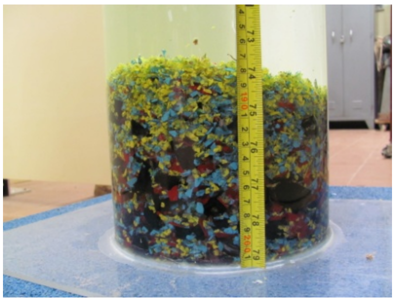
After mixing



After settling

3 mm Minus Glass Cullet

Before settling



After settling

20 mm Minus Glass Cullet

Figure 5.5 Segregation of Glass Cullet

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Compressibility

Compression indices (C_c), re-compression indices (C_r) and creep compression ratios (α) of 3 mm minus glass cullet samples were determined by conducting laboratory tests using conventional oedometers. C_c, C_r and α of 20 mm minus samples were determined using large diameter oedometer (see Figure 5.6) and Rowe Cells (See Figure 5.7). The test results are given in Table 5.5.

Figure 5.6 250 mm Diameter Oedometer and Dead-load Loading Frame

Figure 5.7 250 mm Diameter Rowe Cell

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Table 5.5 Compressibility of Glass Cullet

	3 mm Minus Specimens	20 mm Minus Specimens	5 - 20 mm Specimens
Compressibility Index	C_c = 0.126 - 0.219	C_c = 0.37	C_c = 0.38 - 0.56
Re-compression Index	C_r = 0 - 0.008	C_r = 0.018	C_r = 0.023 - 0.05
Creep Compression Ratio	α = 0.057 - 0.16 %	α = 0.50%	α = 0.41% - 0.80%

The samples were initially in a loose state. It is observed that primary consolidation settlement completed shortly after applying the compression load (see Figure 5.8), which was in line with the high permeability determined. The results indicated that 3 mm minus glass cullet samples would have lower compressibility than 20 mm minus samples. Samples of particle sizes between 5 to 20 mm (i.e. gravel) were specifically prepared for the oedometer tests, with a view to investigating the effect of possible segregation on the compressibility behaviour of the segregated coarse part of glass cullet. The results indicated that gravel size glass cullet samples would have higher compressibility (i.e. higher values of C_c, C_r and α) than 20 mm minus samples. Nonetheless, the compression creep ratios of all samples were still less than those for granular fill (1% - 2%) as given in PWDM (CEO, 2002). No obvious PSD change was observed after the compression tests.

Shear Strength

Shear strengths of 3 mm minus glass cullet compacted to 95% MDD based on Modified Proctor test were determined by direct shear tests (see Figures 5.9 and 5.10) and consolidated undrained (CU) triaxial tests (see Figures 5.11 and 5.12). The friction angle derived from the tests ranged between 40.8° and 48.9° (see Table 5.6). Shear strengths of 20 mm minus glass cullet compacted to 95% MDD based on Modified Proctor test were determined by large shear box tests (i.e. 300 mm × 300 mm) (see Figure 5.13) and consolidated undrained triaxial tests (see Figure 5.14). The friction angle derived from the tests ranged between 42.7° and 45.0° (see Table 5.6). The friction angles of both types of samples resembled the range for crushed rock fill (GEO, 1993) and were in agreement with the values reported in the literature.

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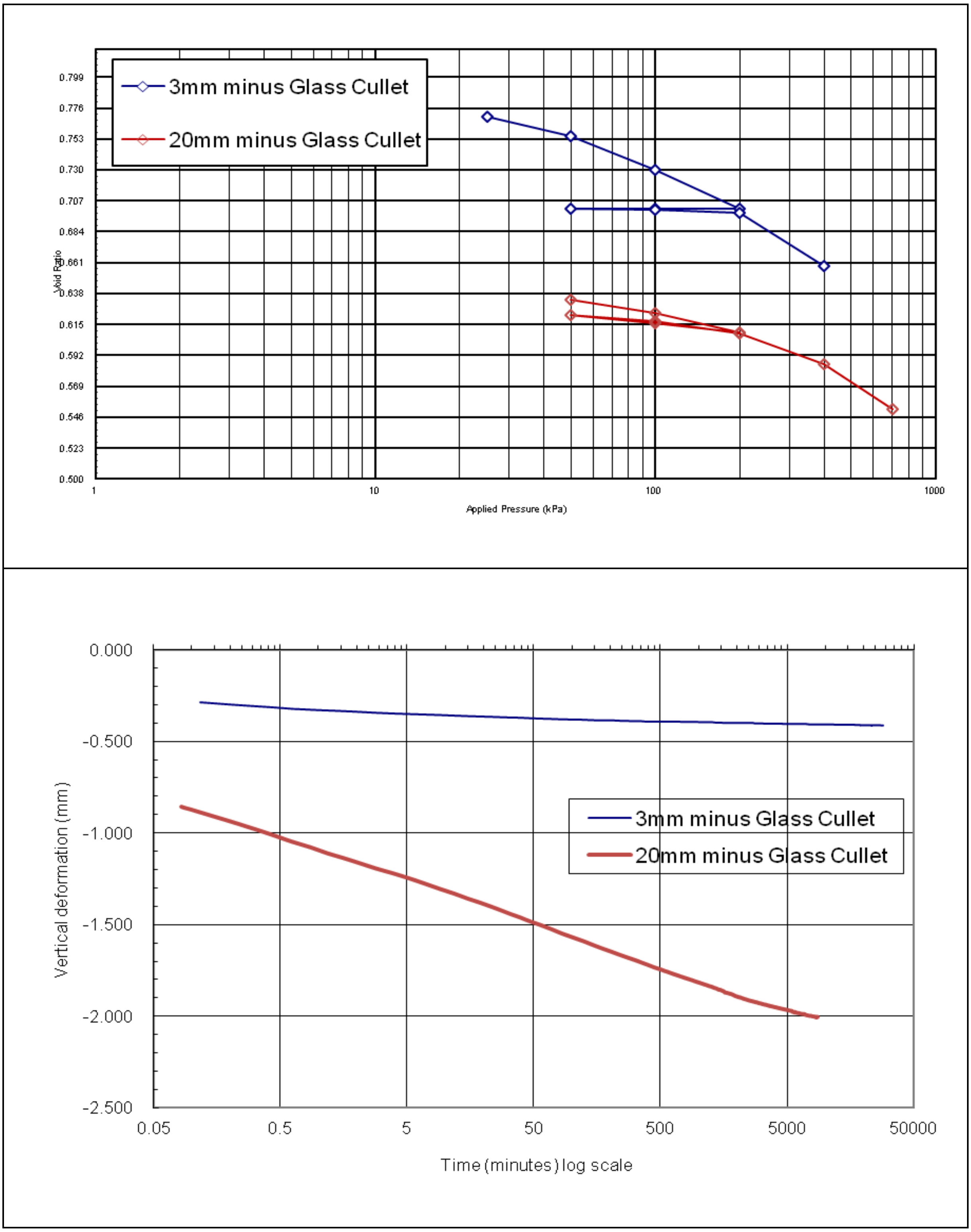

Figure 5.8 Typical Results of Oedometer Tests

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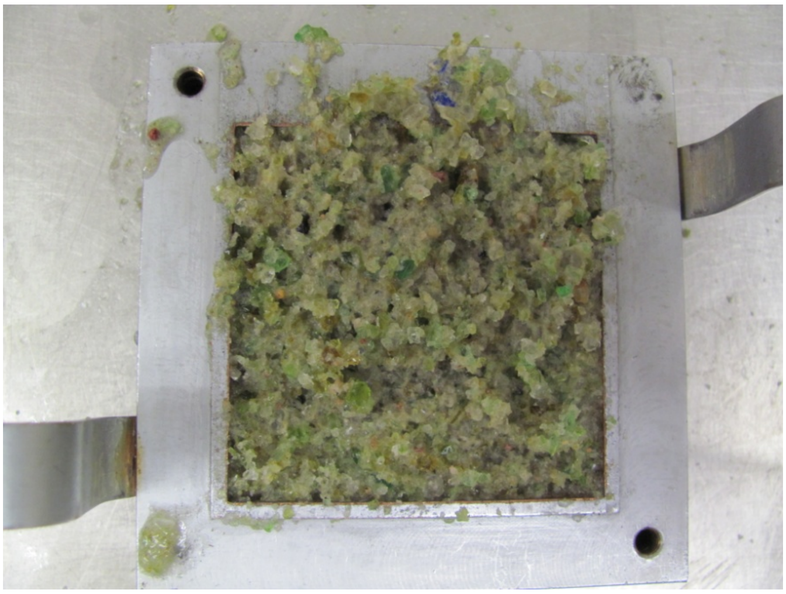

Figure 5.9 Direct Shear Test on 3 mm Minus Glass Cullet

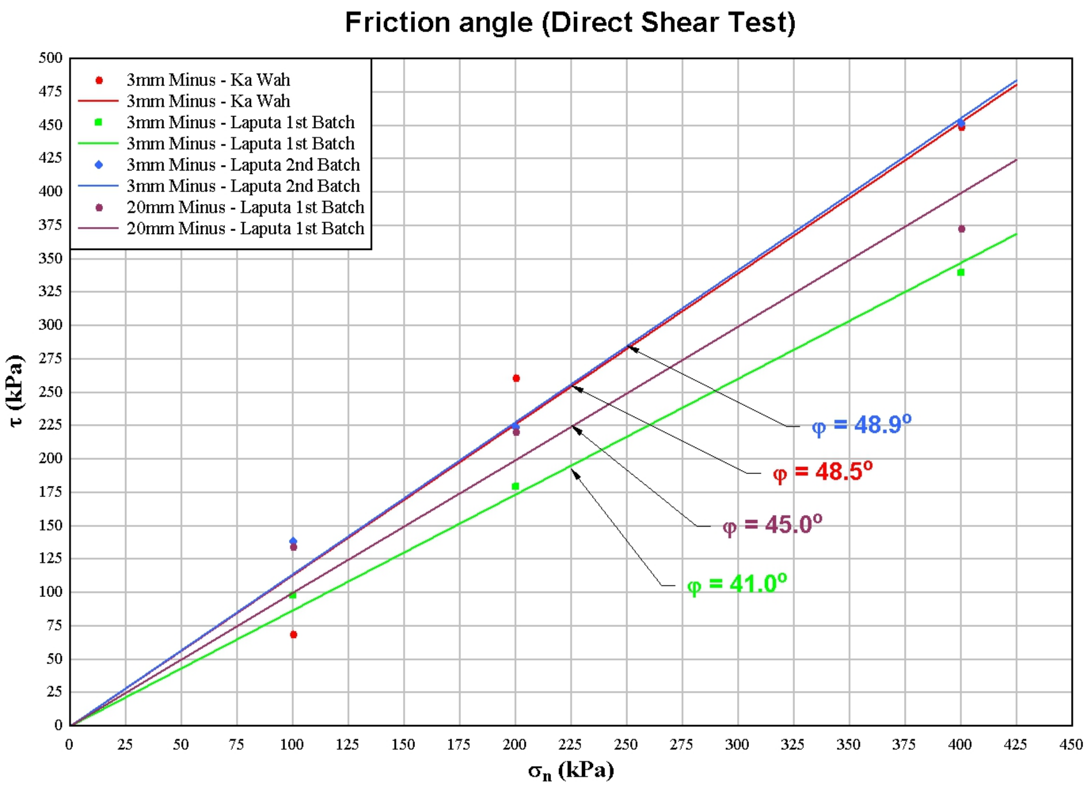

Figure 5.10 Friction Angles of Glass Cullet Determined by Direct Shear Tests

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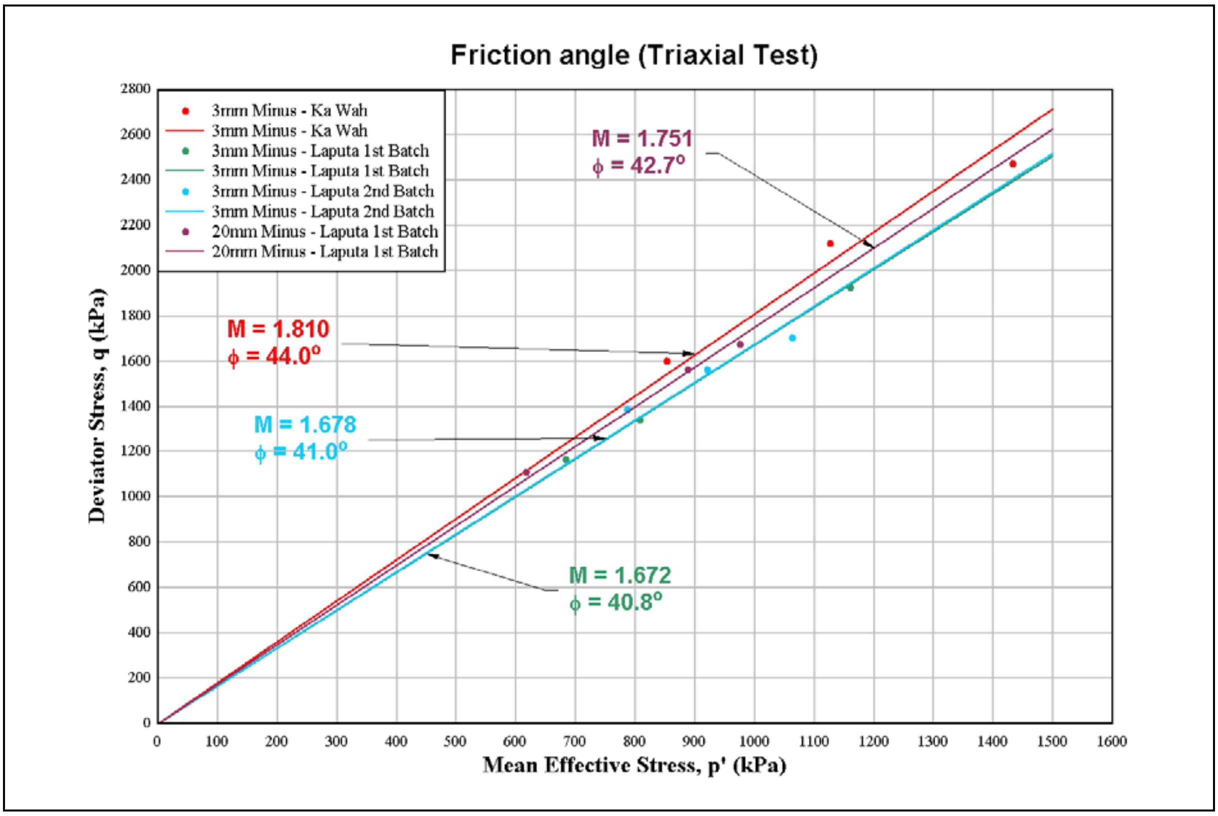

Figure 5.11 Friction Angles of Glass Cullet Determined by Consolidated Undrained Triaxial Tests

Figure 5.12 75 mm Diameter 3 mm Minus Glass Cullet Triaxial Test Specimen

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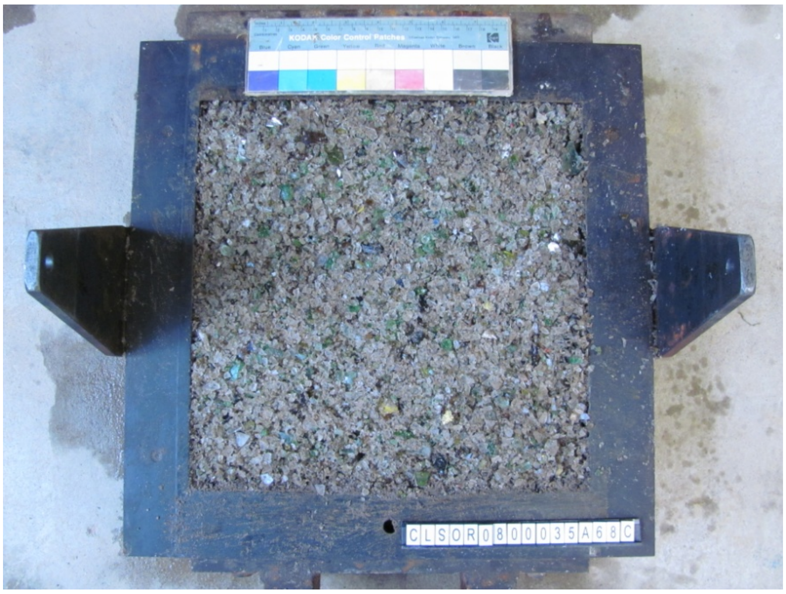

Figure 5.13 Direct Shear Test on 20 mm Minus Glass Cullet

Figure 5.14 100 mm Diameter 20 mm Minus Glass Cullet Triaxial Test Specimen

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Table 5.6 Friction Angle of Glass Cullet

Friction Angle (°)	Laputa (1st Batch)	Laputa (2nd Batch)	Ka Wah
Direct Shear Test (3 mm Minus)	41.0	48.9	48.5
Triaxial Test (3 mm Minus)	40.8	41.0	44.0
Direct Shear Test (20 mm Minus)	45.0		
Triaxial Test (20 mm Minus)	42.7		

Development of negative excess pore water pressures were noted in shearing stages of the consolidated undrained triaxial tests (see Figures 5.15 and 5.16), indicating that the compacted glass cullet specimens dilated upon shearing (see Figures 5.17 and 5.18).

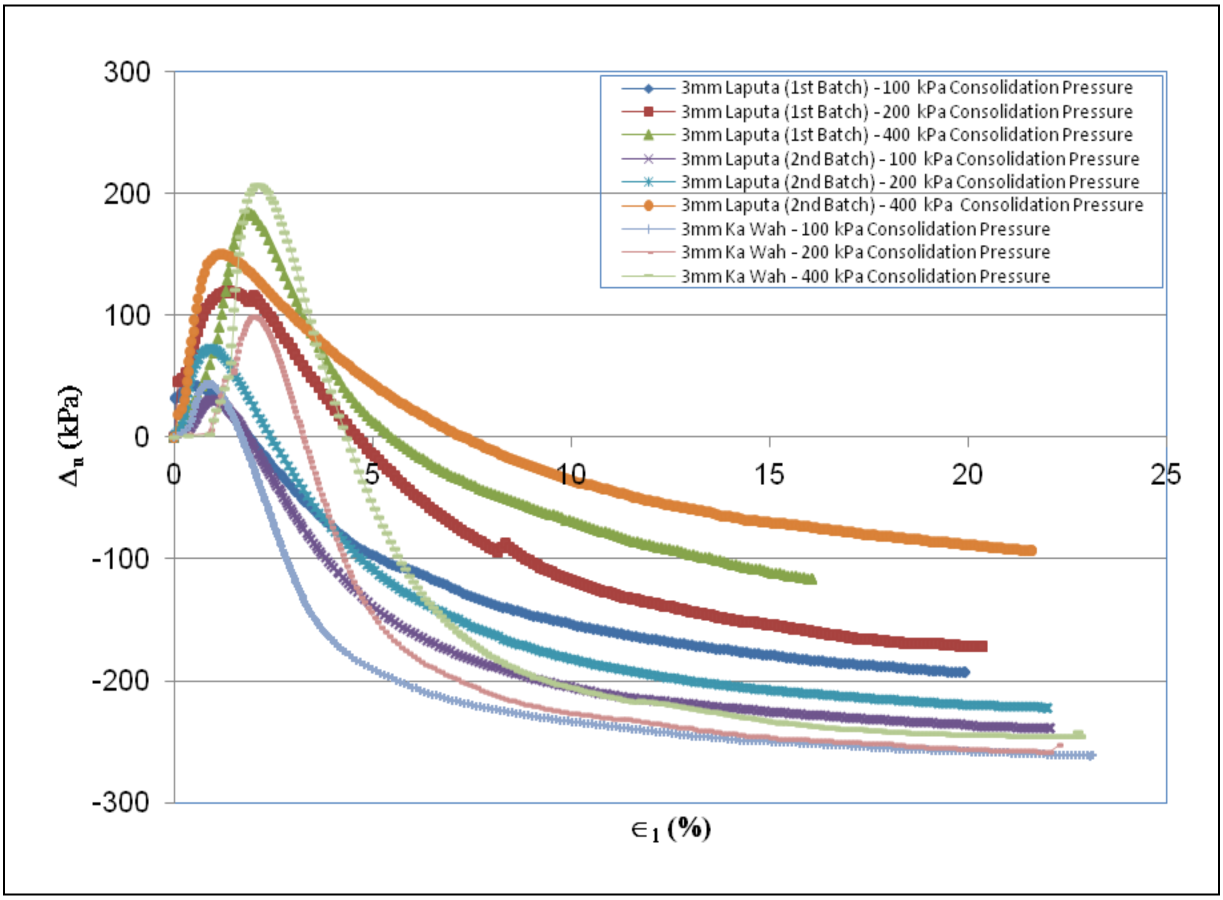

Figure 5.15 Change of Excess Pore Water Pressure in 3 mm Minus Glass Cullet Specimen during Shearing Stage of CU Triaxial Test

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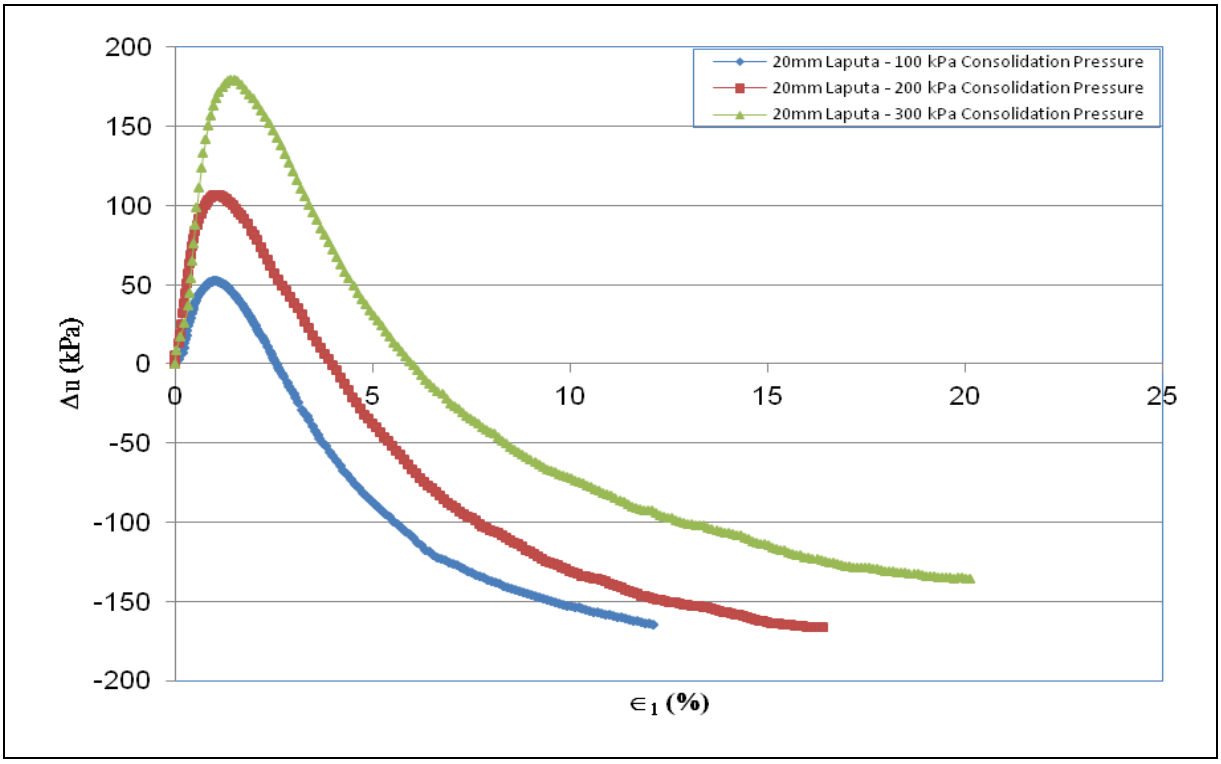

Figure 5.16 Change of Excess Pore Water Pressure in 20 mm Minus Glass Cullet Specimen during Shearing Stage of CU Triaxial Test

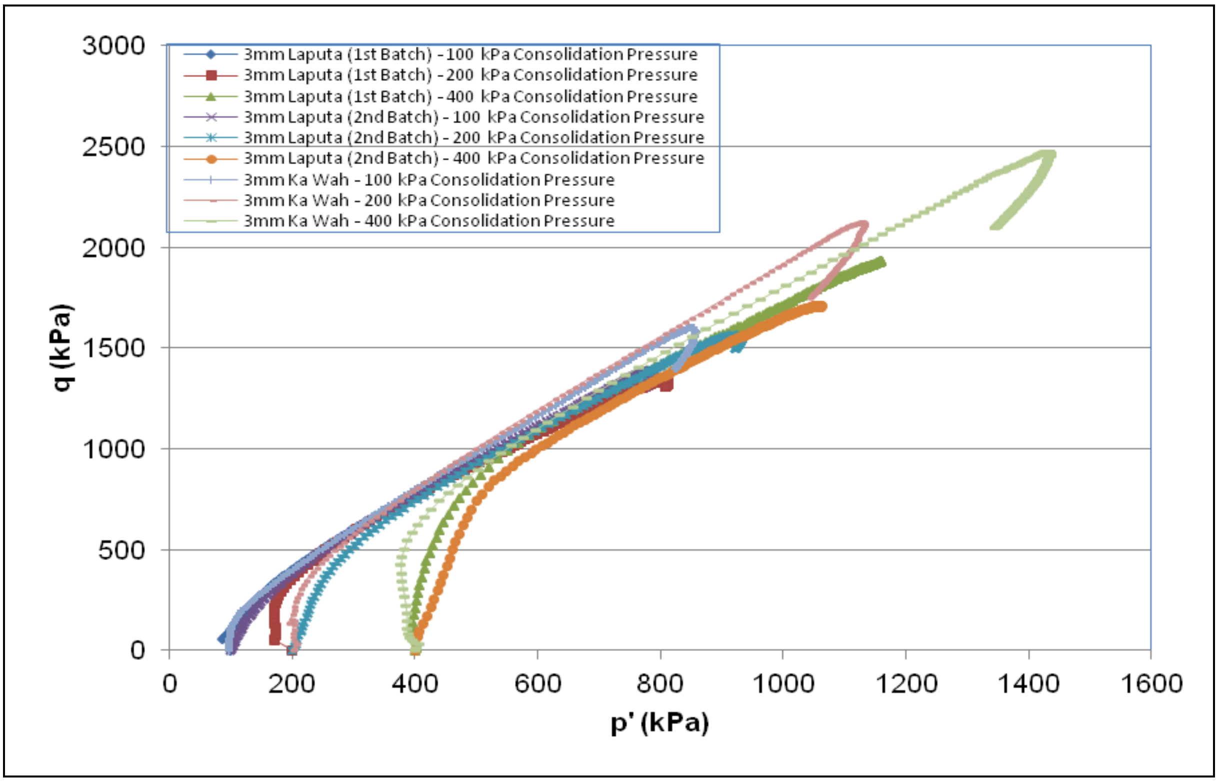

Figure 5.17 Stress Path in Shearing Stage of CU Triaxial Test on 3 mm Minus Glass Cullet

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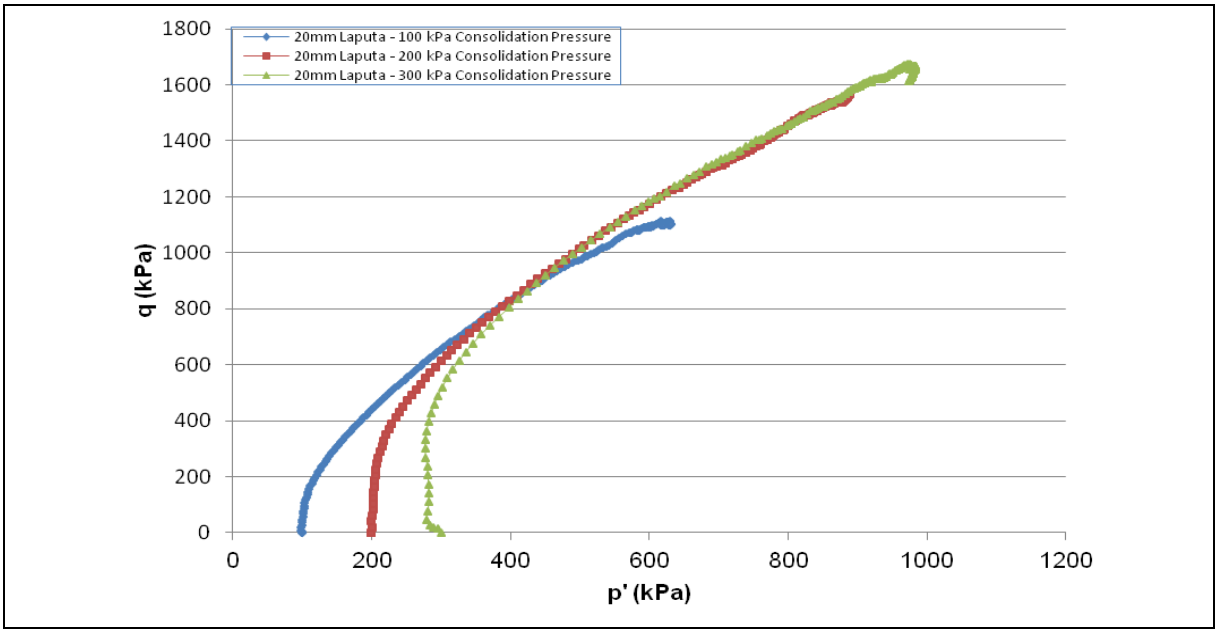

Figure 5.18 Stress Path in Shearing Stage of CU Triaxial Test on 20 mm Minus Glass Cullet

No obvious changes in PSD curves were observed after direct shear test on 3 mm minus samples and all triaxial tests. However, a shift of PSD curves of 20 mm minus samples were noted after large shear box test (see Figure 5.19), indicating that breakage of glass cullet particles occurred upon shearing.

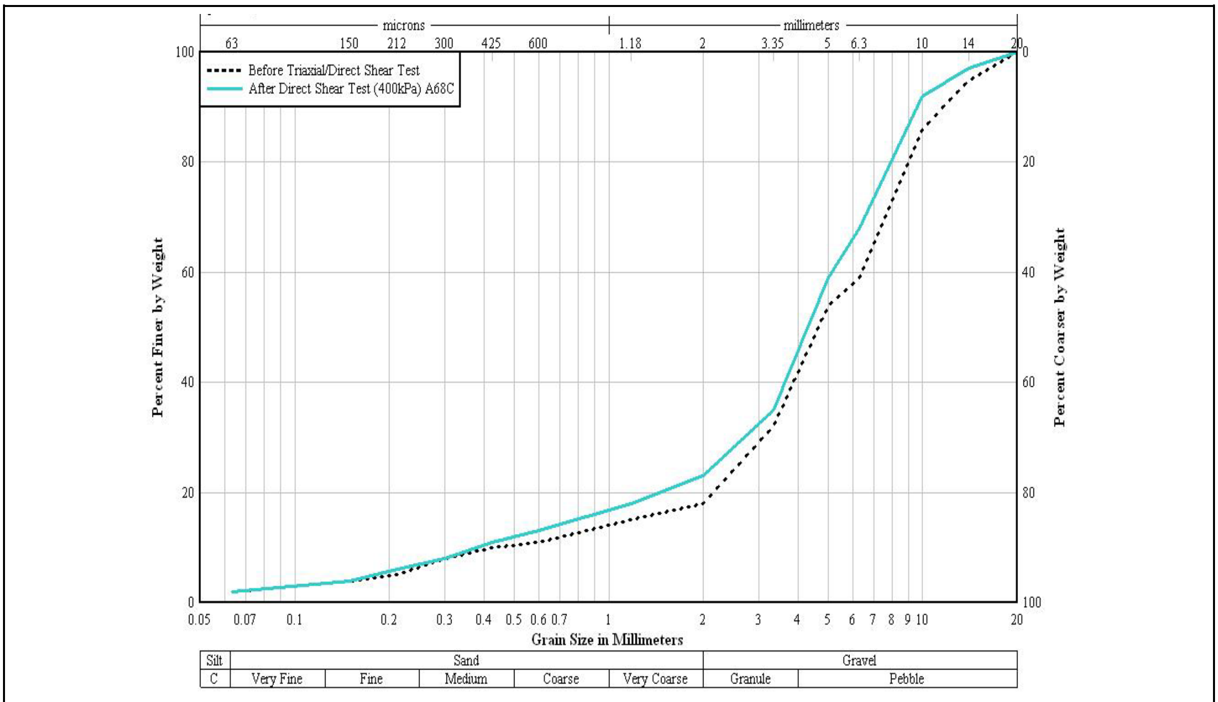

Figure 5.19 Shift of PSD after Large Shear Box Test on 20 mm Minus Glass Cullet

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It is worth noting that punctures of membranes were encountered during consolidation and shearing stages in the triaxial tests on the 20 mm minus samples. This was overcome by applying multiple layers of membranes with suitable corrections. No punctures were encountered for the 3 mm minus samples.

California Bearing Ratio

The California Bearing Ratios (CBR) of the 3 mm minus glass cullet were determined to be 8.1 - 20.3% (upper face of mould) and 53.7 - 97.6% (lower face of mould). The difference between the two faces was probably due to migration of fines from the top of the specimen to the lower portion when the specimen was compacted during preparation. The higher fines content and thus lower void ratio at the lower portions are believed to be the causes for the higher CBR values. The California Bearing Ratios of the 20 mm minus glass cullet were determined to be 6.5 - 9.0% (upper face of mould) and 22.5 - 27.1% (lower face of mould).

A shift of PSD curves of 3 mm minus and 20 mm minus samples were observed after CBR tests as shown in Figures 5.20 and 5.21.

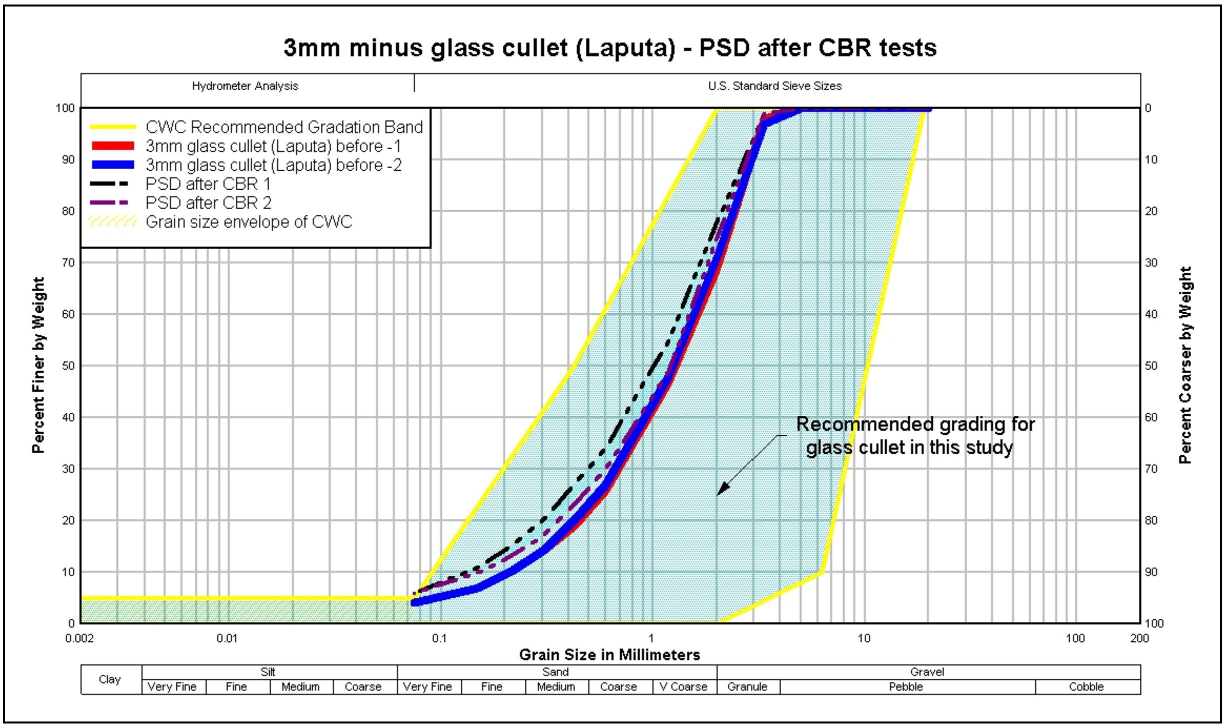

Figure 5.20 Shift of PSD after CBR Test on 3 mm Minus Glass Cullet

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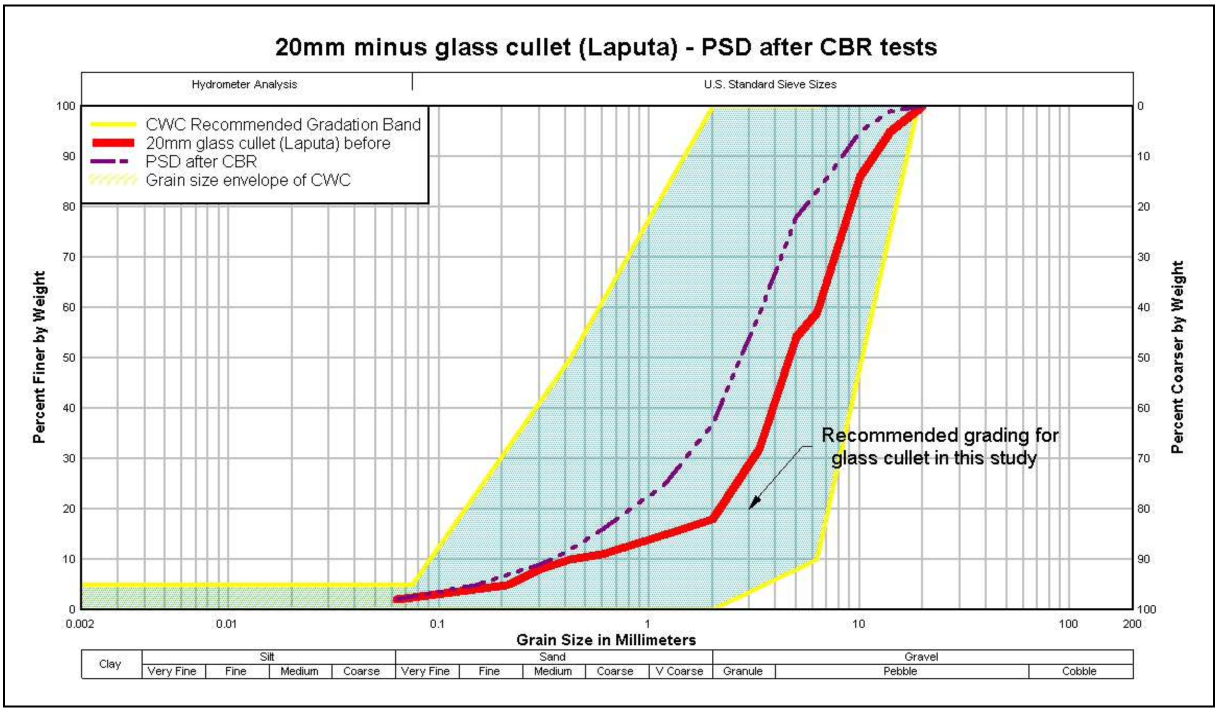

Figure 5.21 Shift of PSD after CBR Test on Laputa's 20 mm Minus Glass Cullet

6 Discussion

6.1 General Properties of Glass Cullet

The main raw material for glass is quartz which is the crystal form of silica (SiO_2). Glass cullet is chemically inert and does not release any toxic substance into the environment. Glass cullet is not as mechanically sound as rock (CWC, 1998), as revealed by the aggregate tests. The physical durability of the glass cullet samples could be inferred from the observations that the grading of samples remained virtually the same after light impact and vibratory compaction. The lower water absorption of glass cullet renders it not susceptible to volume change upon compression whereas its lower specific gravity would result in lower active pressure on the back of retaining structures.

The 3 mm glass cullet produced by the two suppliers in Hong Kong was generally used for production of concrete paving blocks. The grading of 3 mm cullet fell within the envelope specified by CWC (1993) for drainage fill (see Figure 2.2). Samples of 20 mm minus glass cullet were prepared specifically for this study and their gradings fell within the range specified by CWC (op cit) for structural fill (see Figure 2.1). All the laboratory tests carried out in this study are on samples of 100% glass cullet. No tests have been conducted on soil-glass mixtures.

Based on results of the laboratory tests, glass cullet has quantifiable engineering properties similar to those of granular soils. The review of the overseas experience, mainly in North America, has not found any reported cases of using glass cullet for reclamation. This is probably due to the fact that reclamation is relatively less popular in those countries. With proper engineering control, glass cullet is considered to be a suitable fill material for both reclamation and earthworks.

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7 Recommendations

7.1 Technical Requirements for Use of Glass Cullet in Reclamation Works

7.1.1 Recommended Grading and Testing Requirements

Grading Requirements

All the 3 mm minus and 20 mm minus glass cullet samples have gradings in compliance with those specified in CWC (1993) for drainage fill and in Section 21 of GS (HKSAR, 2006) for Type 2 underwater fill. Also, the maximum fines content of all glass cullet samples is less than 6%, which is much lower than 25% specified in GS for Type 2 underwater fill and 10% in PWDM (CEO, 2002) for hydraulically placed fill. As the laboratory testing has established that both types of glass cullet have engineering properties, i.e. shear strength, compressibility, permeability, segregation potential, etc., similar to those of coarse natural soils and that the fines content can be controlled by, for example, sieving, to below 5% as recommended by CWC (op cit), the glass cullet is considered suitable for reclamation. The grading of glass cullet for reclamation works should follow that for drainage fill specified in CWC (op cit). The respective details are given in Appendix B.

The minimum coefficient of uniformity (C_u) of glass cullet for reclamation works is recommended to be 5, which is consistent with that specified in GS for marine works. This requirement would help reduce the void ratio of glass cullet after placement, resulting in higher density and lower compressibility. Only two out of fourteen 20 mm minus samples tested in this study were found to have the value of C_u less than 5. The low C_u value was probably due a significant high percentage of coarse content (i.e. > 80% by weight are gravel size or larger) in those samples. It is considered that the requirement on C_u (i.e. > 5) could be achievable by increasing the crushing effort in order to produce a more well-graded material.

Debris Contents

Organic debris may decay and result in volume change, whereas other debris (e.g. metal, ceramics, plastic), if present in large quantities, can affect the overall engineering properties of the glass cullet. Visual classification method is recommended by CWC (1993) to estimate quantitatively the percentage of debris content in the glass cullet. The percentages produced by the visual classification method are neither mass nor volume percentages, but an indicator of the relative level of contamination in a glass sample on an area basis. Calibration exercises conducted by CWC (op cit) indicated that percentage of debris content estimated using the visual classification method was about 2.5 to 5 times greater than that measured by weight.

CWC (1998) recommends that the maximum debris contents in glass cullet for various applications should generally range from 5% to 10%, which may be equivalent to 1% to 4% by weight. However, there are no specific requirements for the maximum organic debris content. According to CWC (1998), no long-term deformation is expected if the debris content is limited to less than 5% to 10% as determined by visual classification method.

The debris contents of all the glass cullet samples collected in this study were less than 2% by weight and the organic matter contents were less than 0.2%. Organic debris would

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generally be separated from the bulk mass of the glass cullet after deposition in water, owing to its low density. As such, the effect of organic debris on the compression behaviour of glass cullet should be relatively minor. It is recommended that the total debris content and organic matter content of glass cullet for reclamation works should be limited to 2% and 0.2% by weight respectively.

Testing Requirements

The use of glass cullet as fill material for reclamation works is new to Hong Kong. In the absence of precedent local experience, a higher testing frequency is recommended. Hence, the minimum testing frequency for glass cullet is recommended to follow that for special fill in earthworks. The tests should include PSD, C_u, debris contents, etc. The recommended frequency is the same as that for backfilling works behind retaining walls (GEO, 1993).

7.1.2 Design Considerations

Fill Treatment

Treatment of marine fill is normally required with a view to reducing the residual settlement after placement. Figure 5.1 shows that the gradings of all the 3 mm minus and 20 mm minus glass cullet samples and that recommended by CWC (1993) for drainage fill fall within the zones of "ideally suited for vibrocompaction" and "very well compactable".

Segregation of glass cullet may occur after deposition in water and this would result in larger particles lying in the bottom of a layer. Given that glass cullet should be deposited in batches, the effect of segregation would be localized. Where vibrocomapction is used for treatment of glass cullet, the high frequency vibration and high pressure water jet in the course of compaction would mix the glass particles to form a denser matrix. The use of vibrocompaction for treatment of glass cullet fill should be favourable and is recommended for compaction of glass cullet under water.

The degree of fill densification could be checked by in-situ tests such as Cone Penetration Test (CPT) and Standard Penetration Test (SPT) (CEO, 2002). CPT has been used in a trial embankment construction using 80% glass cullet and 20% fine-grained soil (Lee, 2007). Hence, it is considered that CPT or SPT is applicable to areas of glass cullet fill.

Creep Settlement

Owing to its high permeability and low water absorption characteristic, the primary consolidation settlement of glass cullet would be completed within a short period of time after placement, as revealed by the oedometer and Rowe Cell tests.

Particle crushing at contact points may cause creep settlement of glass cullet. According to CEO (2002), the creep compression rate (α) of granular fill would be about 1% to 2%. The value of α is sensitive to fill treatment and it could be reduced by 50% after treatment.

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The results of oedometer and Rowe Cell tests on 3 mm minus and 20 mm minus samples of different gradings (see Section 5.3) indicate the values of α for all samples are in the range from 0.1% to 0.8% Taking into consideration of sample variation and other uncertainties, the value of α may be conservatively assumed to be 1.5% (i.e. about two times of the maximum value) for preliminary estimation of creep settlement. Site-specific tests should be carried out in detailed design stage to investigate the compression characteristics of glass cullet.

If all glass cullet generated from crushing of waste glass beverage bottles (i.e. about 55,000 tones per year) is used for reclamation, the thickness of glass cullet would be about 1 m for a 200 m square filling area. A rough estimation indicates that the residual settlement of the 1 m thick glass cullet would be about 25 mm. This accounts for a relatively small portion of the limits of 500 mm and 300 mm for areas designated for roads and drains respectively, as stipulated in CEO (2002).

Migration of Fines

The limit of fines contents of all glass cullet samples is less than 5%, and is lower than that of special fill or Type 2 underwater fill. However, water flow can cause finer particles to migrate to the bottom of each layer. As a result, the void space increases in the upper portion of the layer and the density increases toward the bottom of the layer. Although the migration of fines may occur at a slow rate, it may have an adverse effect on the long-term settlement behaviour of glass cullet.

In order to minimize the effect of the migration of fines, it is recommended that the maximum upper level of the glass cullet fill should be set at 1 m below the lowest sea tide level of the site, below which the water should be relatively calm without being significantly affected by the tidal current.

The recommended grading, sampling and testing requirements for glass cullet and the design considerations for reclamation works using glass cullet are given in Appendix B.

7.2 Technical Requirements for Use of Glass Cullet as Fill Material in Earthworks

7.2.1 Grading and Testing Requirements

In order to facilitate the use of glass cullet, it is recommended that technical requirements of glass cullet for different applications be consistent where possible. The gradings and fines contents of all 3 mm minus and 20 mm minus glass cullet samples are generally in compliance with those specified for granular fill given in Section 6 of GS (HKSAR, 2006) Aligning with the recommendations for reclamation works, the grading of glass cullet for drainage fill as specified in CWC (1998) is considered appropriate for earthworks. Also, given that no specific requirements for the minimum value of C_u for granular fill are given in GS, such requirement is considered not necessary for earthworks using glass cullet.

The discussion on the requirements of debris contents in glass cullet is given in Section 7.1.1. Similar to reclamation works, the maximum total debris content and organic

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debris content in glass cullet for earthworks are recommended to be 2% and 0.2% respectively. Given that only a small amount of organic debris is allowed to be present in glass cullet, the organic debris is not expected to cause significant settlement.

The minimum sampling and testing frequencies of glass cullet for earthworks are recommended to be the same as those for special fill in earthworks. The tests should include PSD, debris contents, sulphate contents, etc.

7.2.2 Design Considerations

Glass cullet for supporting loads must be strong, with minimal settlement potential under material self-weight and applied loads. These requirements could be achieved by controlling of debris content, specifying the maximum content of glass cullet in a mixture and compacting the material to a pre-determined density.

Compaction

Trial compaction and sand replacement tests (SRT) on 3 mm minus and 20 mm minus glass cullet were carried out in this study. The procedure and process of compaction and SRT for glass cullet were similar to those for granular fill. These are consistent with those reported by NSRA (1997) and CWC (1998).

The degree of compaction should be field-verified by SRT. CWC (1993) recommended that the frequency of testing should typically be one per 1,000 square feet (i.e. about 100 m^3) of fill but not less than one per lift of fill. This is consistent with that given in Table 3 of Geoguide 1 (GEO, 1993) for compaction control tests on backfill behind retaining walls.

According to CWC (1993), compaction of glass cullet should be carried out in layers of not exceeding 8 inch (i.e. about 200 mm) in loose thickness for each layer. The performance of compaction on glass cullet is insensitive to the moisture content, indicating that the material could be placed and compacted without being affected by wet weather. This will help expedite the compaction process.

Potential safety hazards identified during compaction and testing of glass cullet mainly comprised cutting and skin irritation. Direct skin contact with glass cullet should be avoided. Adequate safety equipment (e.g. gloves, goggles, mask) and measures (e.g. dust control measures) should be provided when working with glass cullet.

It is recommended that glass cullet should not be placed within 2 m from the face of any slope and the last 1 m below the final grade that supporting utilities. Also, glass cullet should not be in direct contact with unprotected synthetic liners or geogrids (NSRA, 1997).

Shear Strength Parameters

Results of the direct shear and triaxial tests indicated that the shear strengths of the 3 mm minus and 20 mm minus glass cullet samples were similar to that of natural aggregates, with friction angle ranging from 40° to 49°. No tests have been carried out in this study to

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determine the engineering properties of soil-glass cullet mixture.

CWC (1993) conducted a series of direct shear and triaxial tests on aggregate-glass cullet mixtures with different mixing ratios (i.e. glass cullet of 15%, 50% and 100% by weight). Similar to the observation in this study, the shear strength of 100% glass cullet was found to be similar to that of the natural aggregates. The test results also indicated that percentage content of glass cullet and debris level would not have significant effect on the shear strength of the mixtures, and only a slight reduction (i.e. about 2°) in the friction angle was noted for the mixtures with 50% glass cullet.

The shear strength of a soil-glass cullet mixture would be dependent on, *inter alias*, stress range, strength of each type of material and mixing ratio. In general, the shear strength of glass cullet is higher than that of typical soil fill in Hong Kong. The lower bound shear strength parameters of the compacted completely decomposed volcanic (i.e. $c' = 0$ kPa and $\phi' = 35°$, see Table 8 of Geoguide 1 (GEO, 1993)) could be conservatively assumed in the preliminary design of earthworks involving compacted soil-glass cullet mixtures.

When carrying out triaxial tests on glass cullet specimen, crushed glass particles may cause small punctures in membranes surrounding the specimen. It is recommended that a layer of grease should be applied to the external surface of the inner membrane and if needed, additional layers of membranes may be used to reduce the chance of puncture during the test.

Bearing Capacity - Light Load Conditions

According to CWC (1998), 100% glass cullet compacted to 95% maximum dry density as determined using Standard Proctor test is typically used in lightly loaded or non-loading applications, such as pedestrian sidewalks. Also, for small load areas such as footings, typical bearing capacities of 48 kPa to 72 kPa can be considered for glass cullet (CWC, 1996). These could be equivalent to the allowable bearing capacities of about 16 kPa to 24 kPa if a factor of safety of 3 is applied.

The Standard Proctor tests on 20 mm minus glass cullet samples indicated that the respective MDDs were relatively low when compared with that of compacted CDG and CDV. Also, glass cullet could be compacted to 95% of MDD as determined by both Modified Proctor test and Standard Proctor test using simple tools.

A notable increase in MDD was observed when Modified Proctor test was used. In order to ascertain that glass cullet particles are closely packed and would exhibit dilative behaviour upon shearing, the determination of MDD is recommended to be based on Modified Proctor test.

Results of oedometer and Rowe Cell tests on glass cullet indicated that over a wide stress range, the settlement caused by an imposed load of 20 kPa would be minimal. Hence, the use of glass cullet for supporting lightly loaded facilities of static load less than 20 kPa should be acceptable, especially for facilities with high tolerability to settlement.

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Bearing Capacity - Heavy Load or Fluctuating Load Conditions

Glass cullet could be susceptible to breakage under heavy or fluctuating loads. Notable changes in grading were observed on 3 mm minus and 20 mm minus glass cullet samples after Modified Proctor test, but not after Standard Proctor test. This indicates that Modified Proctor test could relatively better reflect the effects of heavy or fluctuating loads than Standard Proctor test.

It is recommended by CWC (1998) that the maximum glass cullet contents of 30% and 15% by weight be allowed for sites subject to heavy stationary loads and fluctuating loads respectively. Mixing soil with glass cullet could render the mixture having a better resistance to heavy load or fluctuating load. The soil-glass mixture should be compacted to 95% of maximum dry density based on Modified Proctor test (NSRA, 1997).

The grading, sampling and testing requirements for glass cullet and the design considerations for earthworks using glass cullet are given in Appendix C.

8 Conclusions

In general, glass cullet has quantifiable engineering properties similar to those of granular soils. With proper engineering control, the use of glass cullet as fill material in both reclamation and earthworks should be acceptable. Recommendations on grading and testing requirements of glass cullet for reclamation and earthworks, together with an executive summary of design considerations and applications, are given in Appendices B & C.

Since the laboratory tests under this study were carried out on samples of 100% glass cullet and no tests were conducted on glass-soil mixtures, the recommendations in respect of material and construction control requirements and design considerations are confined to the use of 100% glass cullet only. Futher study and tests would be needed if the application of glass cullet is extended to cover glass-soil mixtures.

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Appendix A

Study on Particle Form and Angularity of 20 mm Minus and 3 mm Minus Crushed Glass Sam

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Mr. Patrick C.S. Ho
Geological Survey Section, Planning Division, Geotechnical Engineering Office,
Civil Engineering and Development Department

November 2012

1 Introduction

Mr Sunny T.C. So (GE1/Lab1) from Standard and Testing Division sent us an email by Lotus Notes on 24 October 2012, requesting us to provide assistance to a study on the properties of crushed glass. In particular, the Planning Division was asked to investigate the particle form and angularity of a few crushed glass samples (see attached email).

The samples were received by Planning Division on 30 October 2012. There are totally five samples. Each of them were further separated by sieving, with diameters ranging from < 0.063 mm to 3.35 mm.

The form and angularity of particles were described with reference to the Geoguide 3 (Figures 1 & 2). A stereo-microscope was used to inspect the smaller sized particles in detail (Plate 1).

2 Sample Description

2.1 CLSOR0800035A63 (Tap Shek Kok 3 mm glass cullet)

The sample contains broken glass shards that are translucent white, green or brown (Plate 2). The particles are angular and with very sharp edge (Plate 3). Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original smooth surfaces preserved on some particles. Most of the particles are either equidimensional or flat, and elongated particles are rare. Rust flakes are present at the smaller sized portion (< 0.6 mm) of the sample (Plate 4).

2.2 CLSOR0800035A65 (Tap Shek Kok 3mm glass cullet)

The sample contains broken glass shards that are translucent white, green or brown (Plate 5). The particles are angular and with very sharp edge. Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original smooth surfaces preserved on some particles. Most of the particles are either equidimensional or flat, and elongated particles are rare. The sample also contains contaminants including paper/plastic, rock and rust flakes.

2.3 CLSOR0800035A67 (Ka Wah 3mm glass cullet)

The sample contains broken glass shards that are translucent white, green or brown (Plate 6). The particles are angular and with very sharp edge. Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original

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smooth surfaces preserved on some particles. Most of the particles are either equidimensional or flat, and elongated particles are rare. The sample also contains contaminants including paper/plastic and rock.

2.4 CLSOR0800035A68 (Tap Shek Kok 19 mm glass cullet)

The sample contains broken glass shards that are translucent white, green or brown, occasionally blue (Plate 7). The particles are angular and with very sharp edge. Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original smooth surfaces preserved on some particles. Most of the particles are flat, some are equidimensional, and elongated particles are rare. The sample also contains contaminants including paper/plastic and rock.

2.5 CLSOR0800035A78 (Tap Shek Kok 19 mm glass cullet)

The sample contains broken glass shards that are translucent white, green or brown, occasionally blue (Plate 8). The particles are angular and with very sharp edge. Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original smooth surfaces preserved on some particles. Most of the particles are flat, some are equidimensional, and elongated particles are rare. The sample also contains contaminants including paper/plastic and rock.

3 Conclusions

It is concluded that:

(i) The glass particles in all samples are angular.

(ii) The particle form of the 3 mm glass cullet samples (CLSOR0800035A63, CLSOR0800035A65 and CLSOR0800035A67) are mostly equidimentional or flat, while the particle form of the 19mm glass cullet samples (CLSOR0800035A68 and CLSOR0800035A78) are mostly flat, partly equidimentional.

4 References

Geotechnical Control Office (1988). *Guide to Rock and Soil Descriptions. Geoguide 3*. Geotechnical Control Office, Hong Kong.

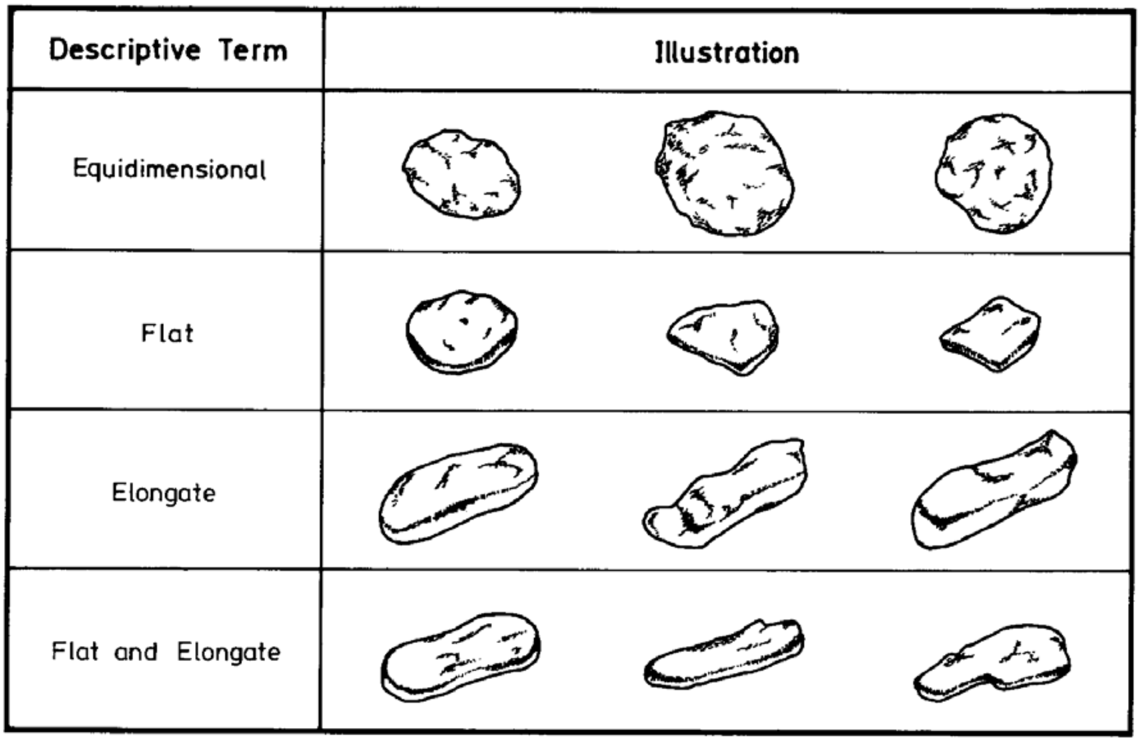

Figure 1: Classification of Particle Form (GEO, 1988)

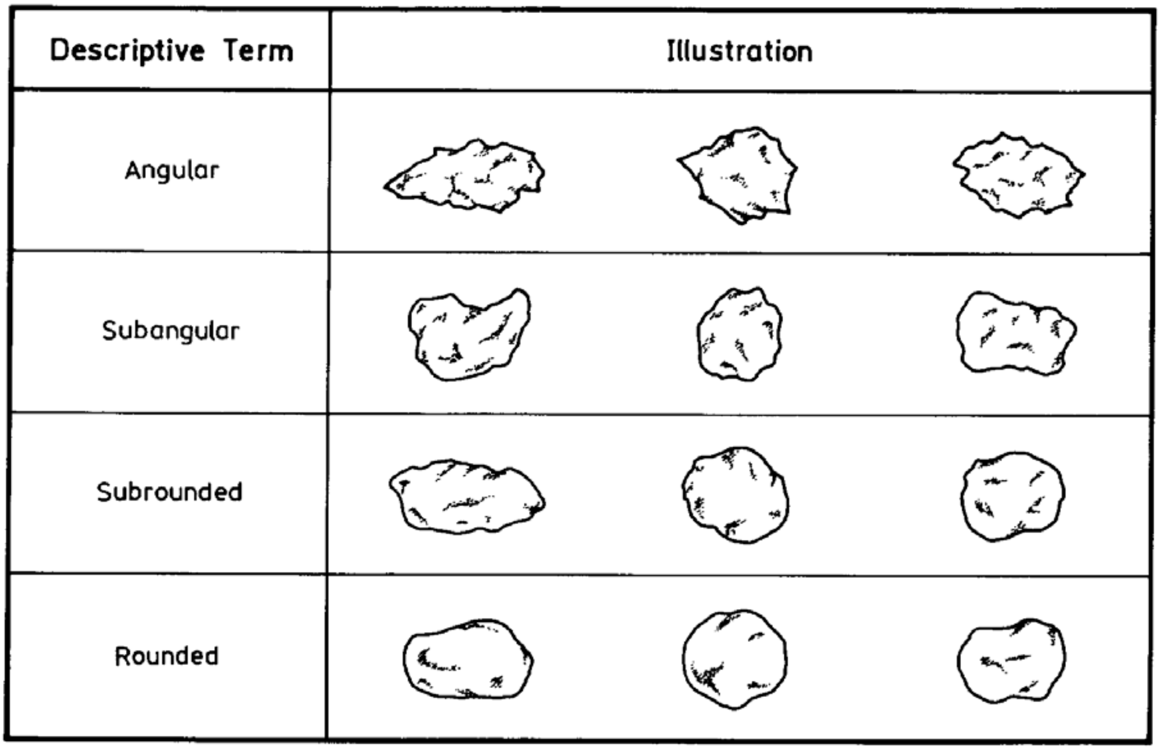

Figure 2: Classification of Particle Angularity (GEO, 1988)

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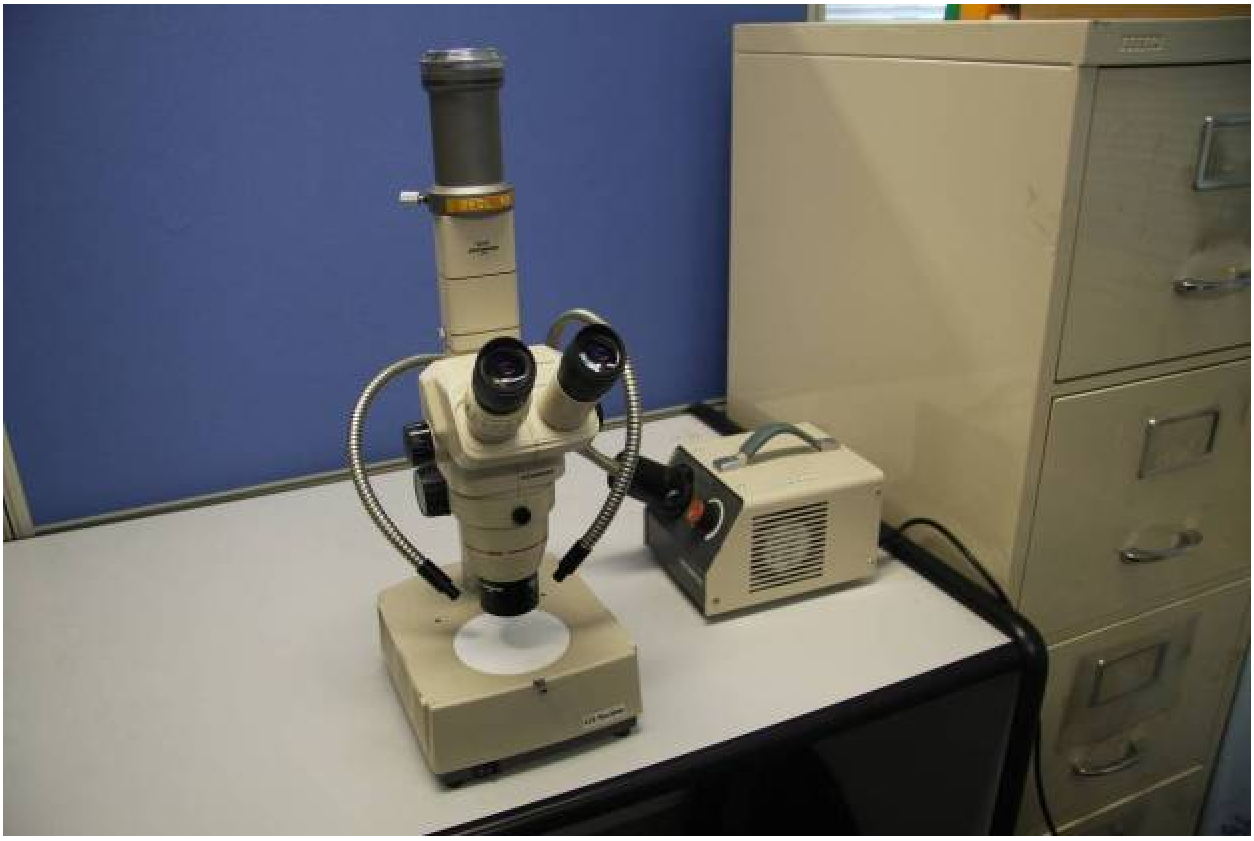

Plate 1: The Stereo-microscope (Olympus SD-ILK) Used for this Study

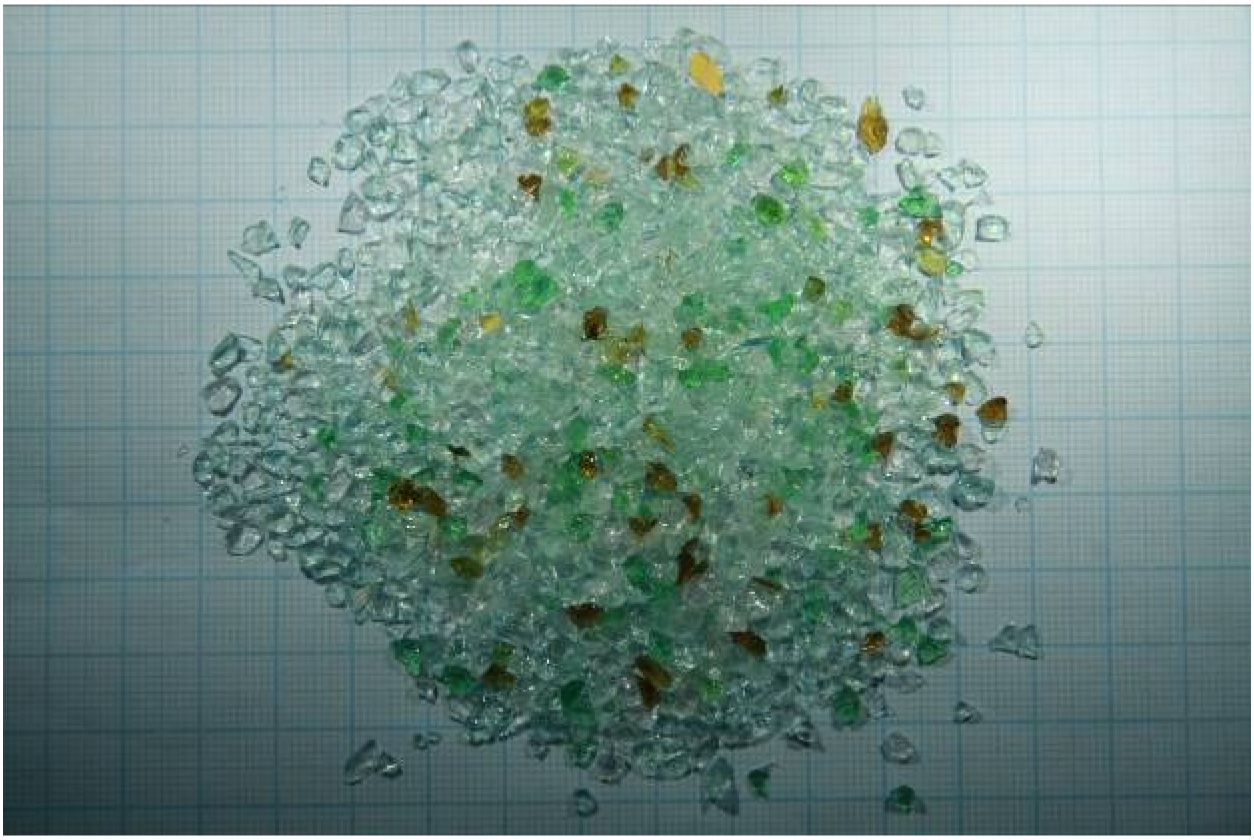

Plate 2: Photo of Sample CLSOR0800035A63 (2 mm - 3.35 mm Diameter)

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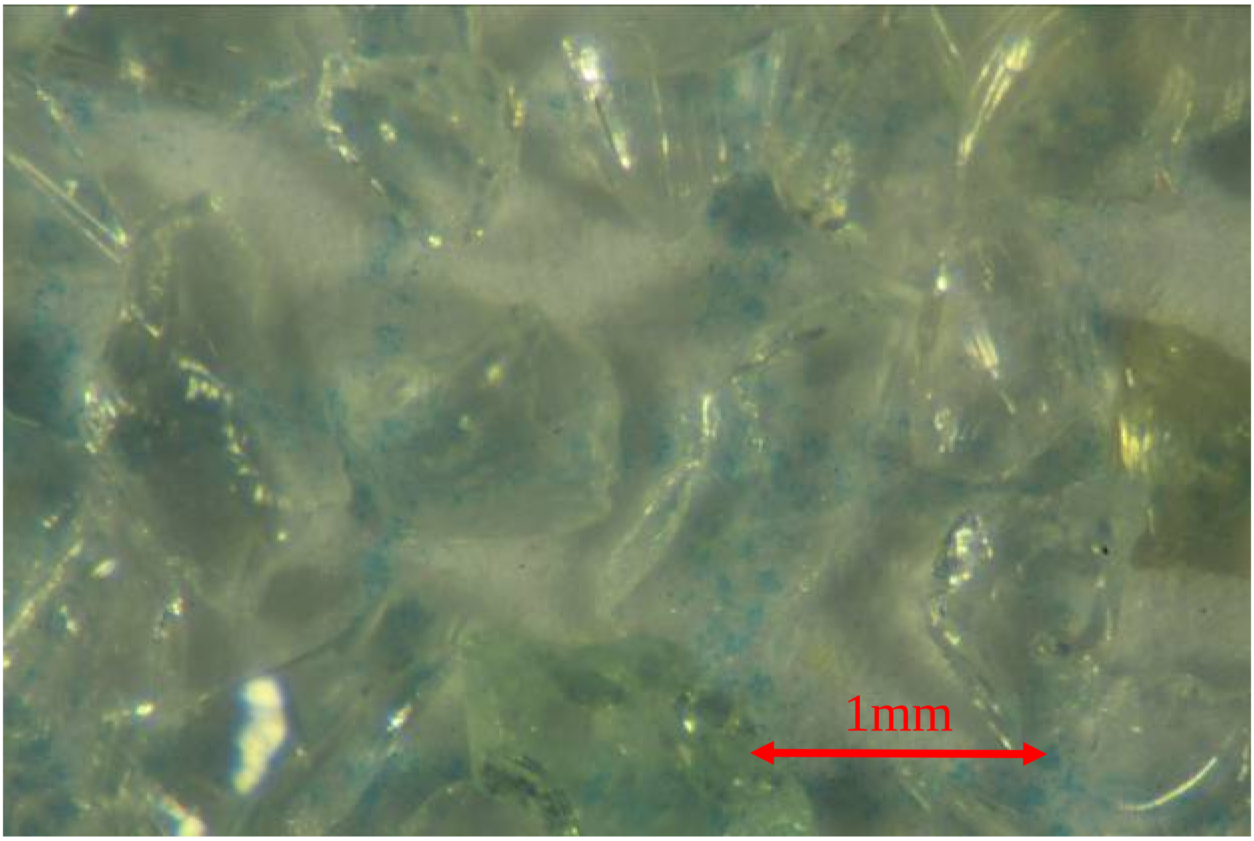

Plate 3: View of Sample CLSOR0800035A63 (0.425-0.6 mm Diameter) under Microscope

Plate 4: A Rust Flake with Metallic Luster Found in Sample CLSOR0800035A63

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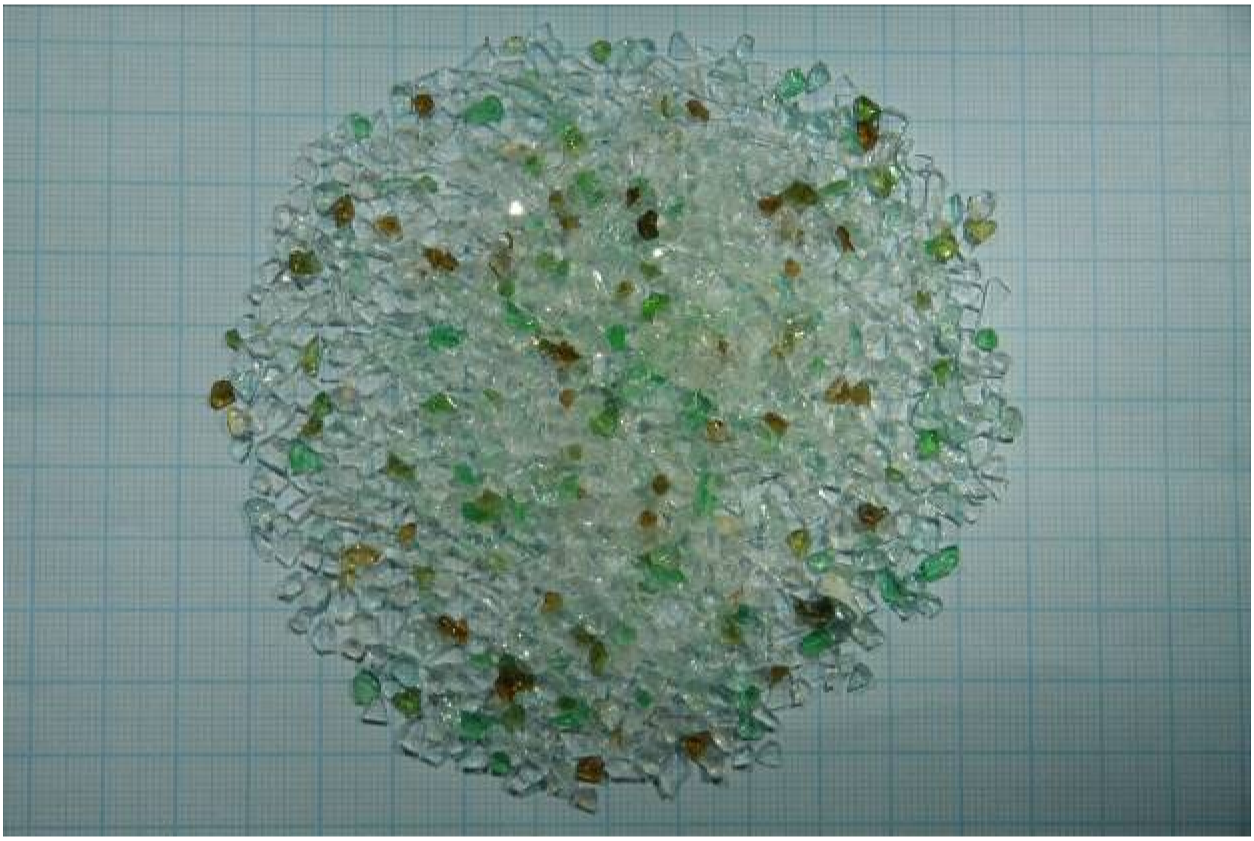

Plate 5: Photo of Sample CLSOR0800035A65 (2 mm - 3.35 mm Diameter)

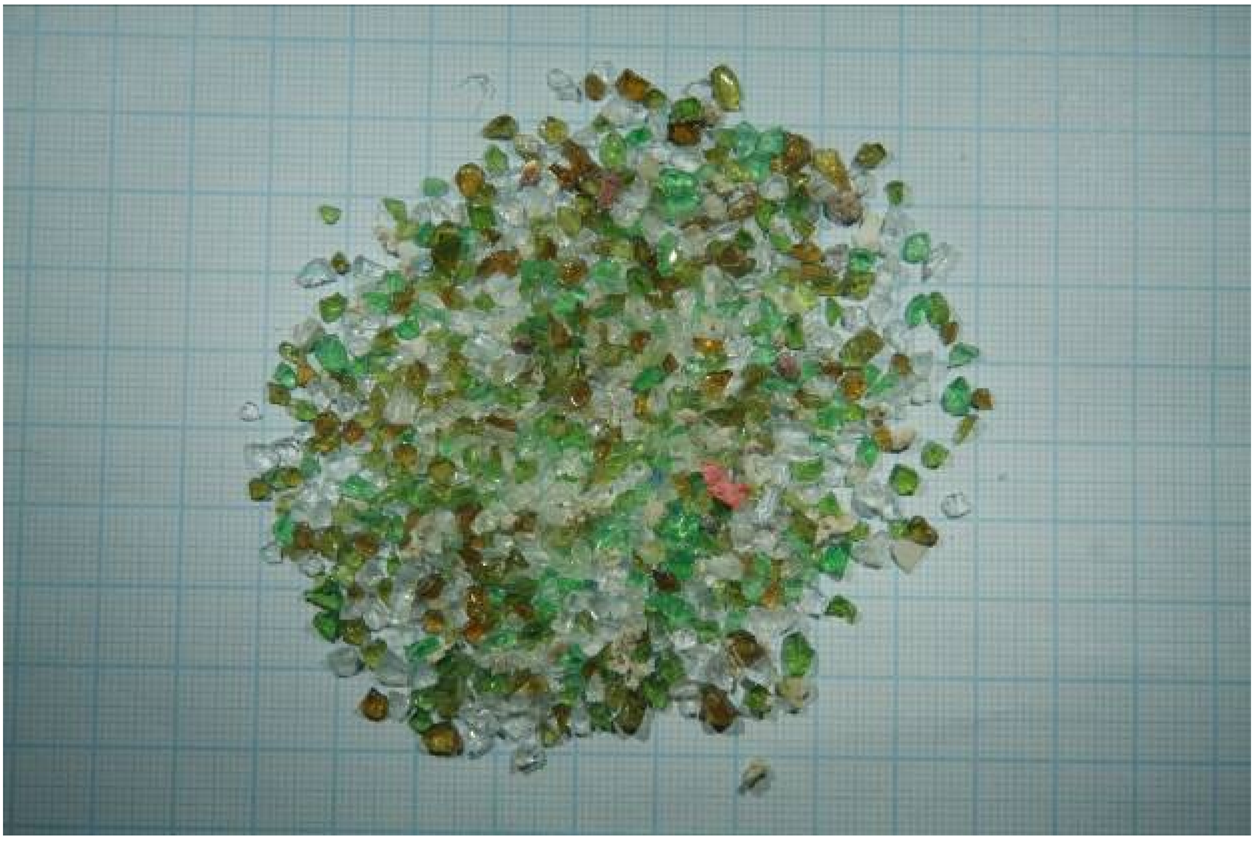

Plate 6: Photo of Sample CLSOR0800035A67 (2 mm - 3.35 mm Diameter)

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Plate 7: Photo of Sample CLSOR0800035A68 (2 mm - 3.35 mm Diameter)

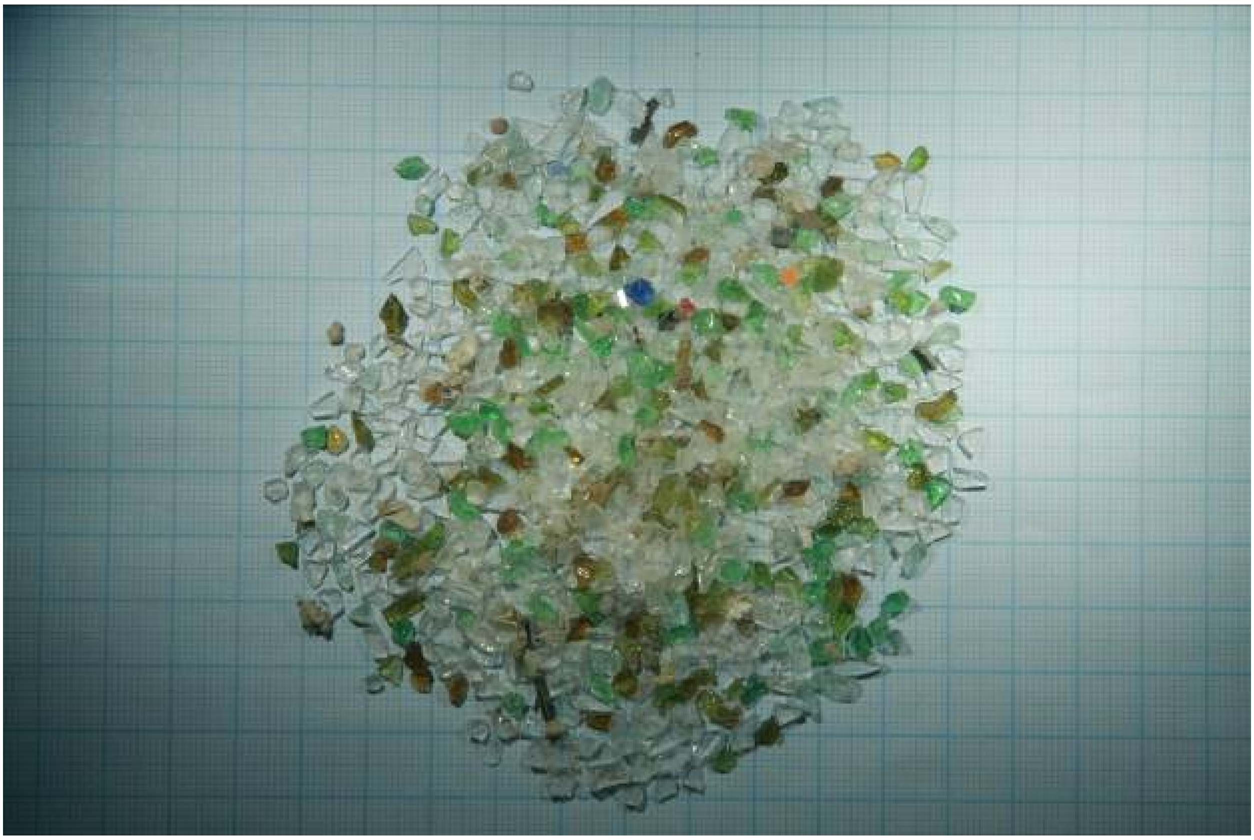

Plate 8: Photo of Sample CLSOR0800035A78 (2 mm - 3.35 mm Diameter)

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Mr. Kay S.C. Mok
Geological Survey Section, Planning Division, Geotechnical Engineering Office, Civil Engineering and Development Department

November 2013

1 Introduction

Mr. Sunny T.C. So (GE1/Lab1) from Standard and Testing Division sent an email by Lotus Notes on 6 November 2013, requesting Planning Division to provide assistance to a study on the properties of crushed glass, in particular, the particle form and angularity of some crushed glass samples.

The samples were received by Planning Division on 6 November 2013. There are two samples in total. Each of them were further separated by sieving, with diameters ranging from < 0.075 mm to 3.35 mm.

The form and angularity of particles were described with reference to the Geoguide 3 (Figures 1 & 2). A stereo-microscope (Olympus SD-1LK) was used to inspect the smaller-sized particles in detail (Plate 1). Typical equidimensional and flat particles are shown in Plate 2 and Plate 3 respectively.

2 Sample Description

2.1 CLSOR1300012A12 (Laputa 3 mm glass cullet)

The sample contains broken glass shards that are mostly translucent white, partly green or brown, occasionally blue (Plates 4 to 6). The particles are angular and with very sharp edges. Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original smooth surfaces preserved on some particles. Most of the particles are flat, while some are equidimensional and, elongate particles are rare. Most of the flat particles are translucent white. The sample also contains contaminants, including rock and wood.

2.2 CLSOR1300012A13 (Ka Wah 3 mm glass cullet)

The sample contains broken glass shards that are translucent white, green or brown, occasionally blue or dark grey (Plates 7 to 9). The particles are angular and with very sharp edges. Most of the particles have conchoidal fractures developed on the rough, broken surfaces, but there are also original smooth surfaces preserved on some particles. Most of the particles are either equidimensional or flat, and elongate particles are rare. The sample also contains contaminants, including paper/plastic and rock.

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3 Conclusions

It is concluded that:

(i) The glass particles in all samples are angular.

(ii) The particle form of Laputa 3 mm glass cullet samples (CLSOR1300012A12) is mostly flat, with some equidimensional particles, whereas the particle form of Ka Wah 3 mm glass cullet samples (CLSOR1300012A13) is mostly equidimensional or flat.

4 References

Geotechnical Control Office (1988). *Guide to Rock and Soil Descriptions. Geoguide 3.* Geotechnical Control Office, Hong Kong.

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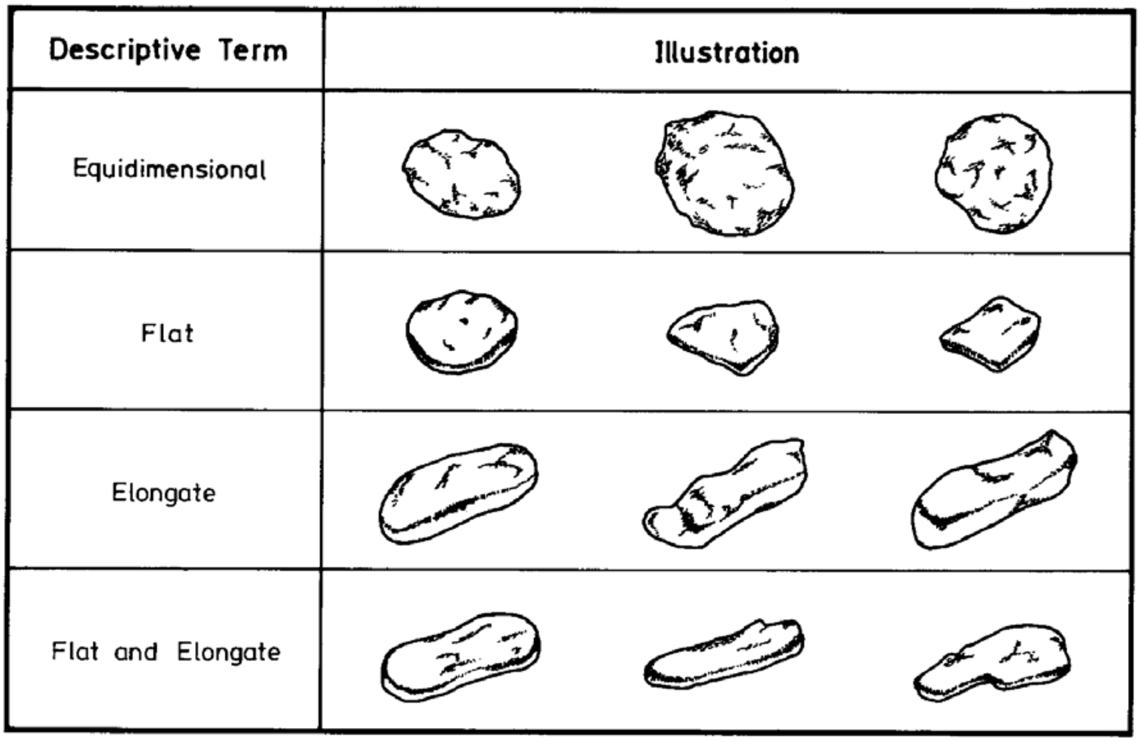

Figure 1: Classification of Particle Form (GEO, 1988)

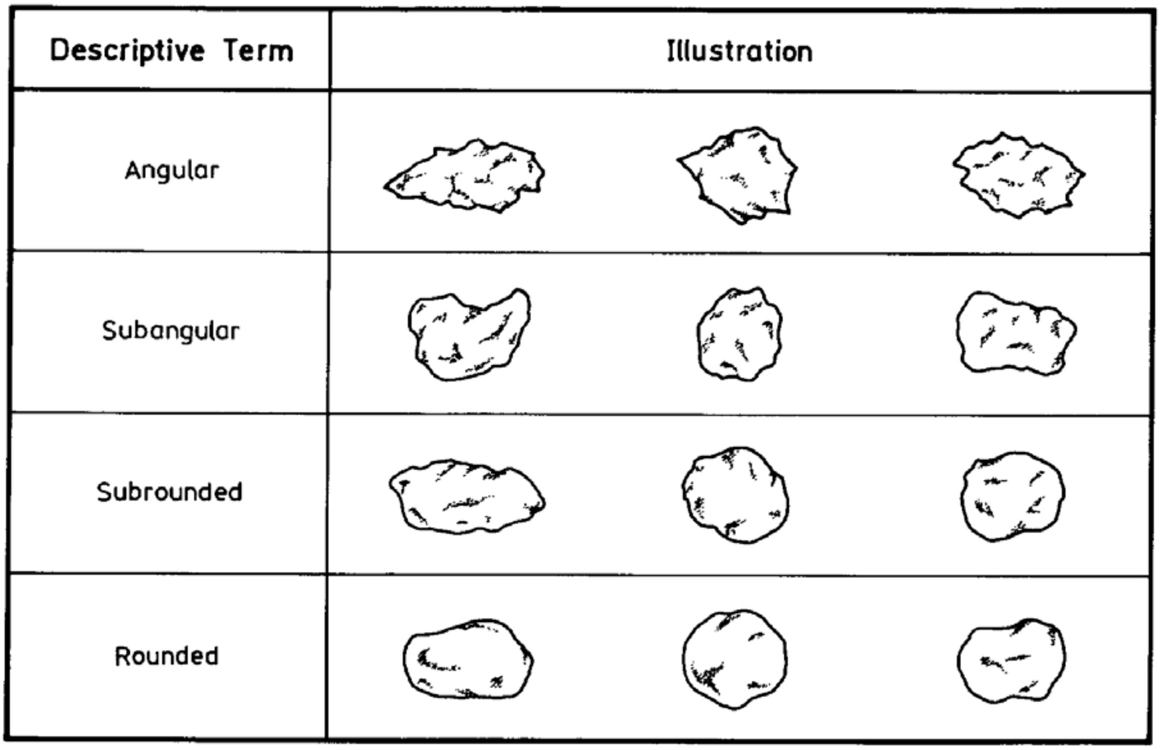

Figure 2: Classification of Particle Angularity (GEO, 1988)

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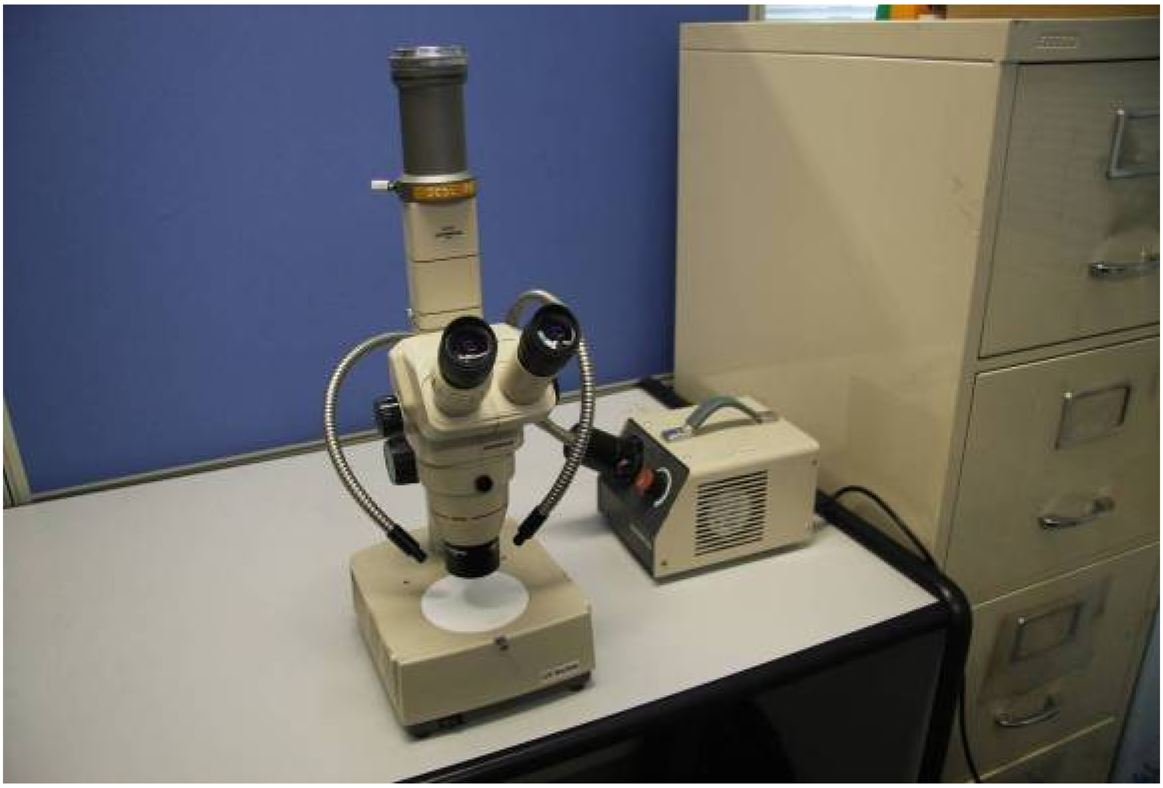

Plate 1: The Stereo-microscope (Olympus SD-ILK) Used for This Study

Plate 2: Typical Equidimensional Particle

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Plate 3: Typical Flat Particle

Plate 4: Photo of Sample CLSOR1300012A12 (2 mm - 3.35 mm Diameter)

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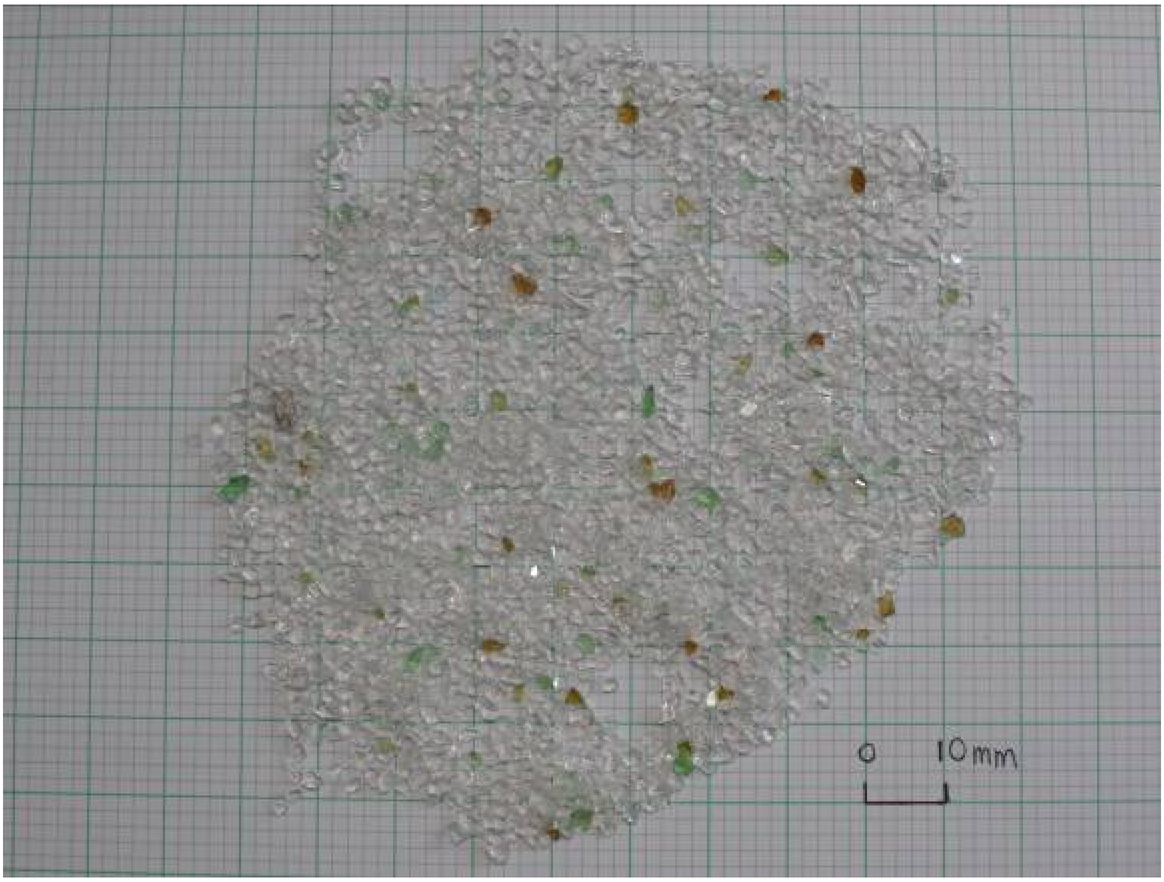

Plate 5: Photo of Sample CLSOR1300012A12 (1.18 mm - 2 mm Diameter)

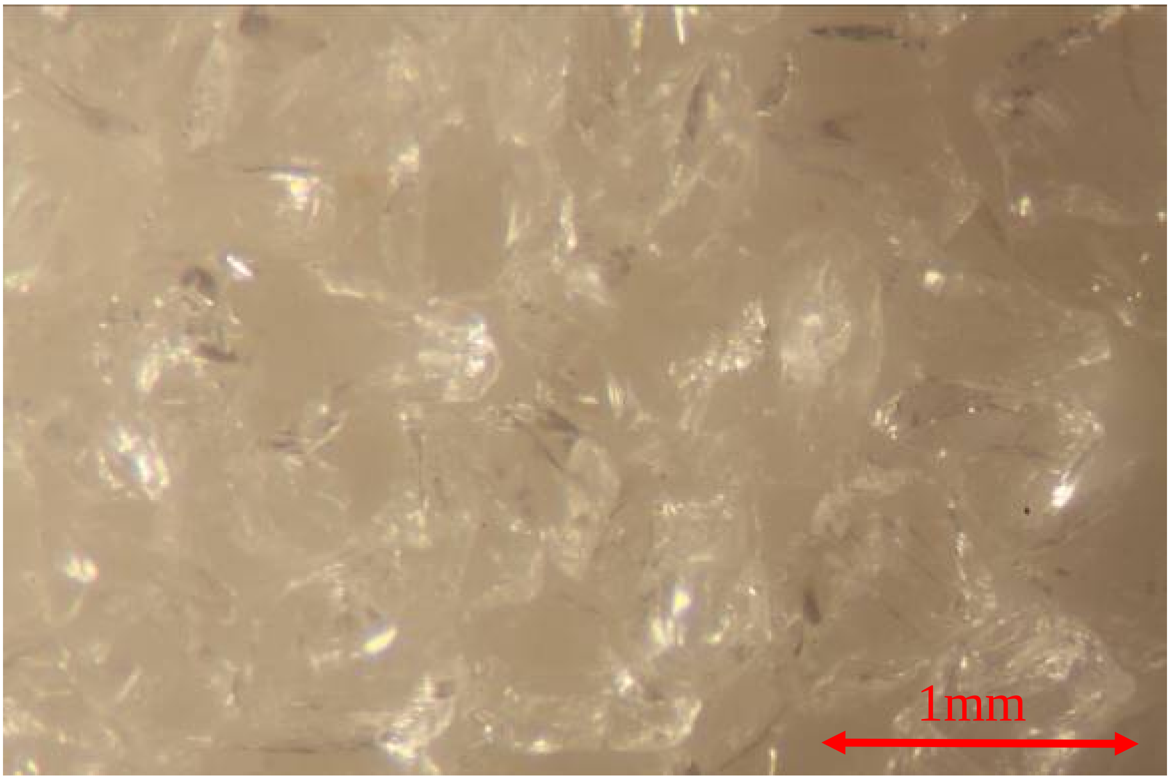

Plate 6: View of Sample CLSOR1300012A12 (0.425 mm - 0.6 mm Diameter) under Microscope

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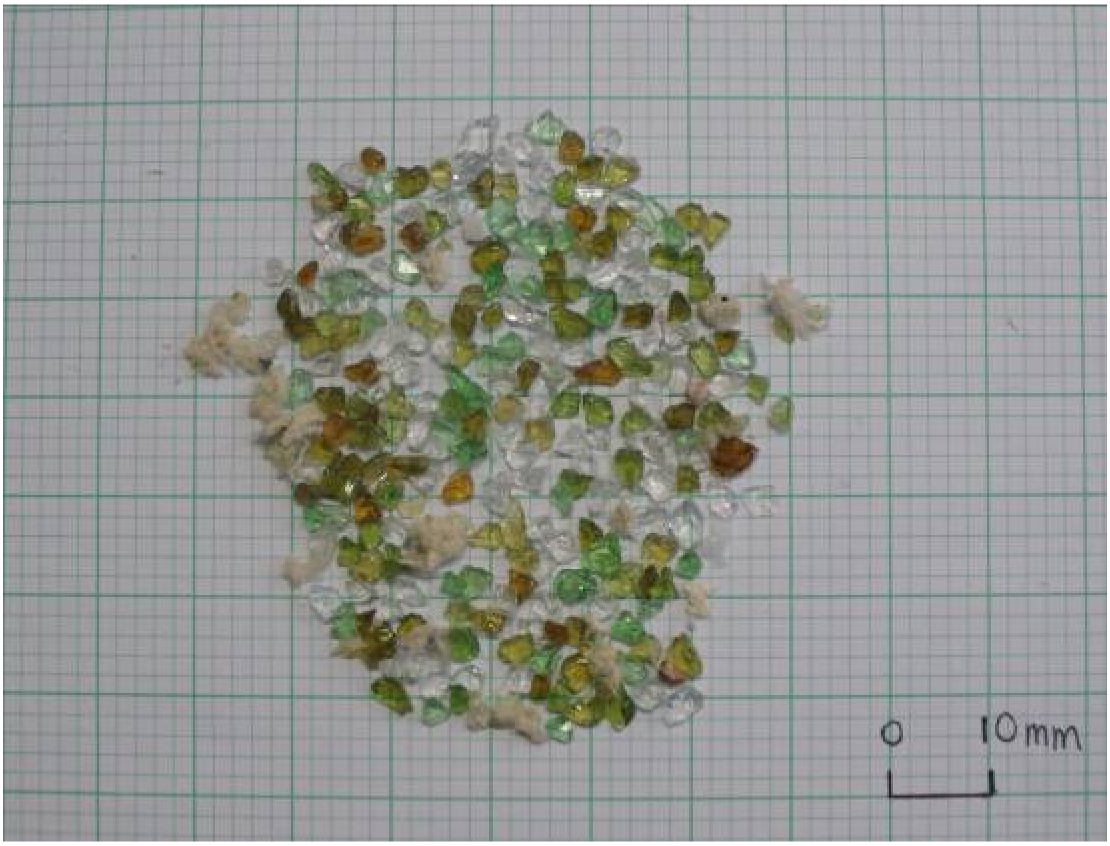

Plate 7: Photo of Sample CLSOR1300012A13 (2 mm – 3.35 mm Diameter)

Plate 8: Photo of Sample CLSOR1300012A13 (1.18 mm - 2 mm Diameter)

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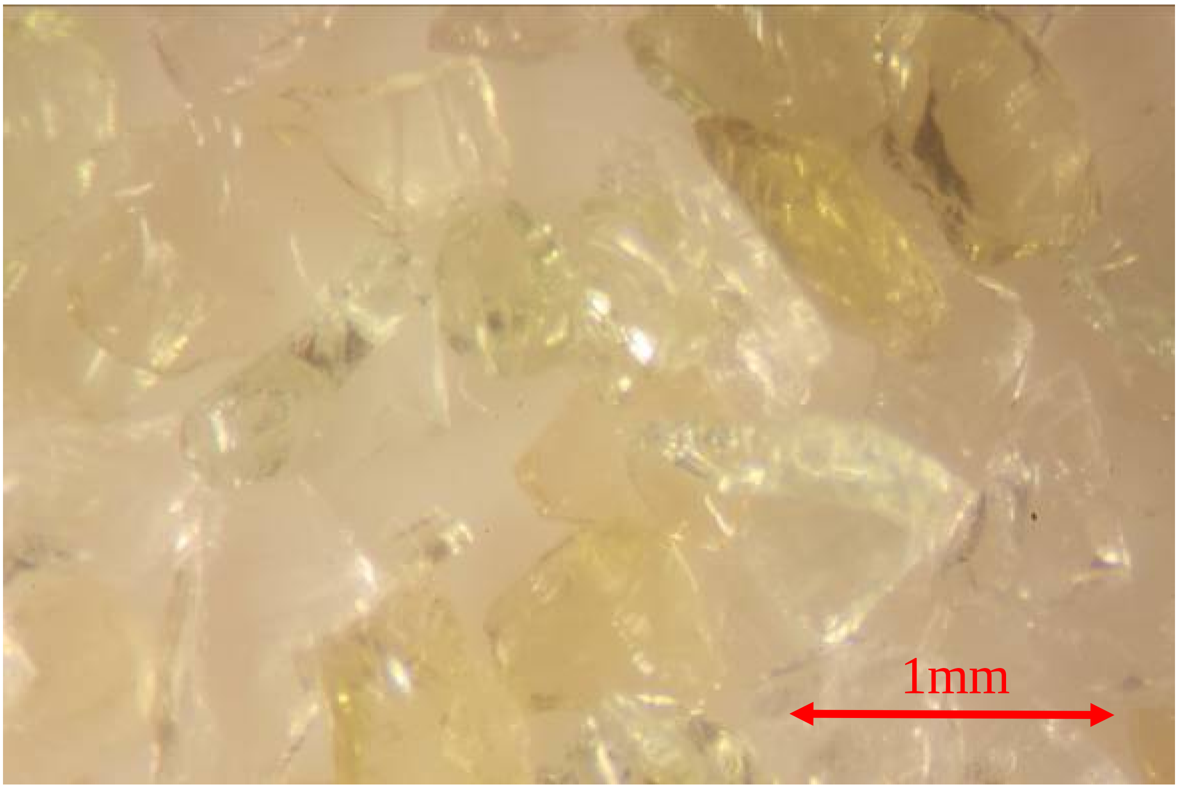

Plate 9: View of Sample CLSOR1300012A13 (0.425 mm - 0.6 mm Diameter) under Microscope

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Appendix B

Technical Requirements for Use of Glass Cullet in Reclamation Works

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B.1 Proposed Grading Requirements

The proposed grading requirements of glass cullet for reclamation works should comply with the following requirements:

Type of Fill Material	Percentage by Mass Passing				
	BS Test Sieve				
	20 mm	6.3 mm	2 mm	425 μm	75 μm
Glass cullet	100	10 - 100	0 - 100	0 - 50	0 - 5

Note : The 75 μm sieve is a BS sieve for aggregate.

Title	Clause in GS	Requirements
Glass cullet for reclamation works	21.12	(9) Glass cullet shall consist of material that has a coefficient of uniformity exceeding 5.

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B.2 Proposed Material Requirements

The proposed material requirements of glass cullet for reclamation works should follow those stipulated in Clause 21.12 of GS (HKSAR, 2006), together with the following additional specific requirements:

Title	Clause in GS	Requirements
Glass cullet for reclamation works	21.12	(10) Glass cullet for reclamation works shall consist of glass particles generated from crushing of glass beverage bottles or other glass products as approved by the Engineer, excluding other glass products such as tempered glass, glass cookware, fluorescent lamps, cathode ray tubes, etc. (11) The debris content (non-glass materials) of glass cullet shall be less than 2% by weight. (12) The organic matter content of glass cullet shall be less than 0.2% by weight.

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B.3 Proposed Testing Requirements

The proposed testing requirements of glass cullet for reclamation works should follow those stipulated in Clauses 21.89 - 21.92 of GS (HKSAR 2006), together with the following additional specific requirements:

Title	Clause in GS	Requirements
Samples: fill materials for reclamation works	21.90	(4) The sampling frequency for testing shall be the same as that for special fill as stipulated in Table 6.4 in GS.
Samples: glass cullet for reclamation works	21.91	(3) Each sample of glass cullet shall be tested in accordance with Section 21 of GS. Tests to be deleted : plasticity index Tests to be added : Debris content and organic matter content. (4) The methods of additional tests shall be in accordance with the following: Debris content[1] : Manual separation Organic matter content : Test Method 9.1 of Geospec 3

Note: (1) Debris to be separated manually from the bulk mass of glass cullet.

B.4 Guidance Notes

Other than specific requirements on grading and testing, other salient issues related to the use of glass cullet in reclamation works are summarized below.

Design

(a) Unless specified in Section B.1, B.2 and B.3 above, the grading, materials and testing requirements for glass cullet shall follow those specified in Section 21 of GS.

(b) Site-specific tests should be carried out in detailed design stage to investigate the engineering properties of glass cullet, including compression characteristics and shear strength as appropriate.

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(c) Maximum upper level of the glass cullet fill should be set at 1 m below the lowest sea tide level of the site.

Construction

(d) Treatment of glass cullet using vibrocompaciton is recommended.

(e) The degree of improvement of glass cullet after treatment could be checked by in-situ tests such as Cone Penetration Test (CPT) or Standard Penetration Test (SPT).

(f) Direct skin contact with glass cullet should be avoided. Adequate safety equipment (e.g. gloves, goggles, mask) and measures (e.g. dust control measures) should be provided when working with glass cullet.

B.5 References

HKSAR (2006). *General Specification for Civil Engineering Works*. Volumes 1 & 2. Hong Kong Special Administration Region, Hong Kong.

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Appendix C

Recommended Technical Requirements for Use of Glass Cullet in Earthworks

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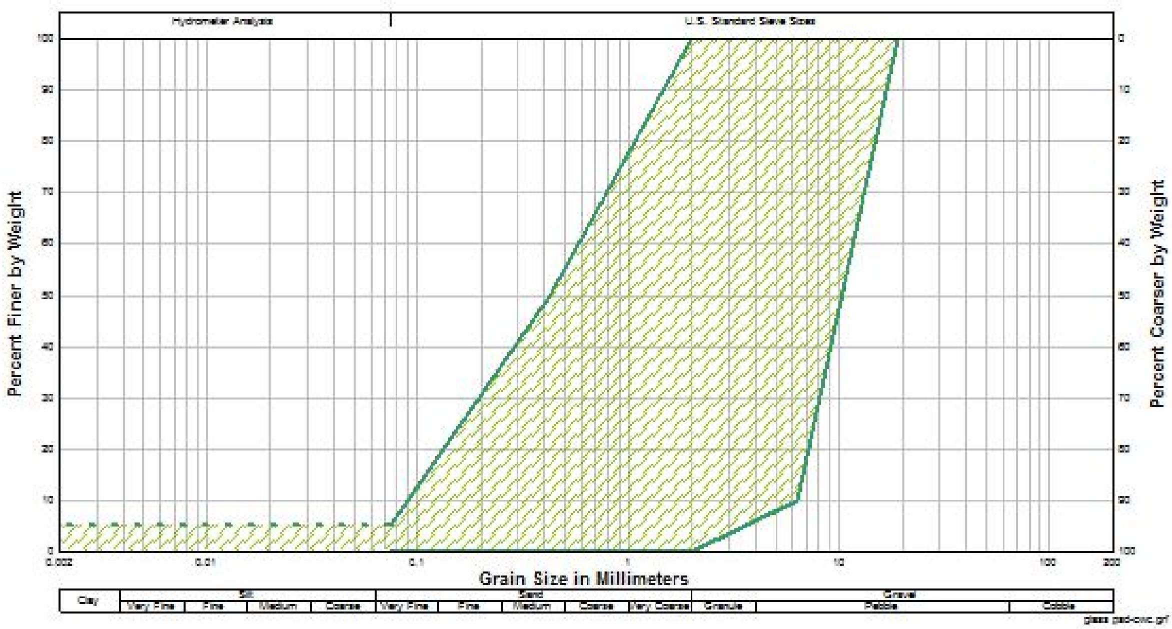
C.1 Proposed Grading Requirements

The proposed grading requirements of glass cullet for earthworks should follow those stipulated in Clause 6.09 of GS (HKSAR, 2006), together with the following specific requirements:

Type of Fill Material	Percentage by Mass Passing				
	BS Test Sieve				
	20 mm	6.3 mm	2 mm	425 µm	75 µm
Glass cullet	100	10 - 100	0 - 100	0 - 50	0 - 5



Note: The 75 µm sieve is a BS sieve for aggregate.

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C.2 Proposed Material Requirements

The proposed material requirements of glass cullet for earthworks should follow those stipulated in Clause 6.09 of GS (HKSAR, 2006), together with the following additional specific requirements:

Title	Clause in GS	Requirements
Glass cullet for earthworks	6.09	(13) Glass cullet for earthworks shall consist of glass particles generated from crushing of glass beverage bottles or other glass products as approved by the Engineer, excluding other glass products such as tempered glass, glass cookware, fluorescent lamps, cathode ray tubes, etc. (14) The debris content (non-glass materials) of glass cullet shall be less than 2% by weight. (15) The organic matter content of glass cullet shall be less than 0.2% by weight.

C.3 Proposed Testing Requirements

The proposed testing requirements of glass cullet for earthworks should follow those stipulated in Clauses 6.69 - 6.83 of GS (HKSAR, 2006), together with the following additional specific requirements with respect to Clauses 6.71 & 6.72:

Title	Clause in GS	Requirements
Samples: fill materials for earthworks	6.71	(2) The sampling frequency for testing on glass cullet shall be the same as that for special fill as stipulated in Table 6.4 in GS.
Samples: glass cullet for earthworks	6.72	(5) Each sample of glass cullet shall be tested in accordance with Section 6 of GS. Tests to be deleted : liquid limit and plasticity index Tests to be added : Debris content and organic matter content. (6) The methods of additional tests shall be in accordance with the following: Debris content[(1)] : Manual separation Organic matter content : Test Method 9.1 of Geospec 3

Note: (1) Debris to be separated manually from the bulk mass of glass cullet.

C.4 Guidance Notes

Other than specific requirements on grading and testing, other salient issues related to the use of glass cullet in earthworks are summarized below.

Design

(a) Unless specified in Section C.1, C.2 and C.3 above, the grading, materials and testing requirements for glass cullet shall follow those specified in Section 6 of GS.

(b) 100% glass cullet could be used for supporting facilities

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with stationary load not exceeding a pressure of 20 kPa.

(c) Glass cullet should not be placed within 2 m below any slope surface or 1 m below utilities, and should not be in direct contact with unprotected synthetic liners or geogrids.

Construction

(d) The performance of compaction on glass cullet is insensitive to the moisture content. Hence, compaction of glass cullet is not required to be at moisture content close to OMC.

(e) Compaction of glass cullet should be carried out in layers of not exceeding 200 mm in loose thickness for each layer.

(f) Test Method 10.8 (i.e. Modified Proctor Test) in Geospec 3 should be used to determine the maximum dry density of glass cullet.

(g) Frequency of in-situ density test to verify the degree of compaction should follow that specified in Table 6.5 of GS for "areas of fill in excavations for structures, pits and trenches and on formations".

(h) Direct skin contact with glass cullet should be avoided. Adequate safety equipment (e.g. gloves, goggles, mask) and measures (e.g. dust control measures) should be provided when working with glass cullet.

C.5 References

HKSAR (2006). *General Specification for Civil Engineering Works*. Volumes 1 & 2. Hong Kong Special Administration Region, Hong Kong.

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土力工程處刊物及訂購資料

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MAJOR GEOTECHNICAL ENGINEERING OFFICE PUBLICATIONS
土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 302 p. (English Version), (Reprinted, 2011).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2007).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.
Geoguide 7	Guide to Soil Nail Design and Construction (2008), 97 p.

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

GEO PUBLICATIONS

GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/2006	Foundation Design and Construction (2006), 376 p.
GEO Publication No. 1/2007	Engineering Geological Practice in Hong Kong (2007), 278 p.
GEO Publication No. 1/2009	Prescriptive Measures for Man-Made Slopes and Retaining Walls (2009), 76 p.
GEO Publication No. 1/2011	Technical Guidelines on Landscape Treatment for Slopes (2011), 217 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

TGN 1	Technical Guidance Documents

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