Study of using recycled glass cullet as an engineering fill in reclamation and earthworks in Hong Kong

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ABSTRACT

Waste recycling has become a worldwide trend to reduce waste generation as a means to help alleviate pollution and impede depletion of natural resources. In Hong Kong, approximately 90,000 tonnes of waste glass, the majority of which contains beverages, are disposed of every year. As glass is chemically inert, instead of burying them in the landfills, the feasibility of recycling waste glass as an engineering fill material in reclamation works and earthworks has been studied. A series of laboratory tests have been conducted on crushed pure glass samples of sizes of 3 mm minus and 20 mm minus to investigate their physical and engineering properties. The results of the study have indicated that with proper engineering control, it is technically acceptable to use glass cullet as an engineering fill in both reclamation and earthworks. Technical requirements for using glass cullet as engineering fill have been developed. This paper presents the feasibility study undertaken and discusses their results. It also highlights the major technical requirements proposed for the use of glass cullet in reclamation and earthworks.

Keywords: glass cullet, engineering fill, reclamation, earthworks, compaction, specification

1 INTRODUCTION

Waste recycling is a contemporary worldwide trend to conserve the environment by reducing waste generation which in turn lessens loading on landfills. Hong Kong has been relying on burying waste in landfills at various locations of the territories since 1960. While the landfill space is limited and waste is still generated at a high rate as a result of rapidly increasing population, it is necessary to efficiently use the landfill space. Annually, approximately 90,000 tonnes of waste glass are disposed of in Hong Kong and beverage bottles account up to 63% of this number (EPD, 2013). As there are large voids in their bodies, it is envisaged that recycling waste glass could save a lot of landfill space. To re-use waste glass in a large amount, a feasible option is to transform it to engineering fill materials by crushing. A study has been launched to evaluate the engineering properties of glass cullet produced in Hong Kong and assess the feasibility of using it as an engineering fill material in reclamation and earthworks.

2 LITERATURE REVIEW

Glass generally consists of 70% or more silica (SiO$_2$) and a small percentage of soda ash (Na$_2$CO$_3$), potash (K$_2$CO$_3$) and lime (CaO). It is chemically inert and does not release any toxic substance into the environment (EPD, 2014). Glass cullet is a mixture of different glass fragments resulting from crushing of waste glass (predominately food and liquor containers) collected from different sources.

2.1 Overseas Experience

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 been widely used in many construction applications in the USA, 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). Glass
cullet has also been used in earthworks for supporting facilities with different loading conditions. However, there has been no record of using glass cullet as reclamation fill.

2.2 Physical and Engineering Properties of Glass Cullet based on Overseas Studies

Clean Washington Centre (CWC) carried out a series of laboratory tests to determine the physical and engineering properties of glass cullet (CWC, 1993 & 1998). 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 overseas are summarized 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 angles ranging from 40° to 50°;
(c) under normal compaction and loading conditions (e.g. Standard Proctor test), there is little grading change on glass cullet. However, notable 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 (percentage of debris content estimated using visual classification method was about 2.5 to 5 times greater than that measured by weight) (CWC, 1993 & 1998). No long-term settlement of the compacted glass cullet is expected if the debris content is limited to 5% to 10%;
(f) permeability of glass cullet is similar to that of medium sand and gravel which are commonly used as filter materials; and
(h) glass cullet is durable and mechanically sound.

A summary of the physical properties of glass cullet as reported by CWC (1993 & 1998) is given in Table 1. In addition, the engineering properties of 100% glass cullet and mixture of glass cullet and soil are presented in Table 2.

2.3 Grading and Testing Requirements on Fill Materials

CWC proposed gradings for glass cullet as structural and drainage fills, which are shown in Table 3 and Fig. 1.

| Property                     | ¾ inch minus | ¾ inch | No. 10 | No. 40 | No. 200 |
|------------------------------|--------------|--------|--------|--------|--------|
| Sieve Size                   | (19 mm)      | (6.35 mm) | (2 mm) | (425 μm) | (75 μm) |
| Percent Passing              | 100          | 100    | 0-50   | 0-25   | 0-5    |
| (Structural Fill)            |              |        |        |        |        |
| Percent Passing              | 100          | 100    | 0-100  | 0-50   | 0-5    |
| (Drainage Fill)              |              |        |        |        |        |

Table 1. Physical Properties of Glass Cullet (CWC 1993 & 1998).

Table 2. Engineering Properties of Glass Cullet (CWC 1993 & 1998).

Table 3. Gradings of Glass Cullet as Structural and Drainage Fills Proposed by CWC (1993 & 1998).

In Hong Kong, the requirements on the grading and testing for fill materials in earthworks and reclamation are documented in the General Specification for Civil Engineering Works (HKSAR, 2006) and guidelines published by the relevant authorities. The specification covers particle size distribution (PSD), in particular the maximum size and percentage of fines by mass (< 10% for hydraulic fill), and coefficient of uniformity (> 5 for
reclamation in general). It is also required that the fill materials should be free of any material susceptible to volume change and other foreign materials. If vibrocompaction is to be used, it is recommended that the PSD of the fill material should fall within a particular grading zone (CEO, 2002) in order to achieve effective compaction, as shown in Fig. 1.

![Fig. 1. Particle Size Distributions of 3 mm Minus and 20 mm Minus Glass Cullet Samples.](image)

### 3 Glass Cullet in this Study

Glass cullet samples in this feasibility study were obtained from two local suppliers. 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 into small particles by crushing machines. The study covered 3 mm minus glass cullet as well as 20 mm minus glass cullet. Results of the study are reported in GEO (2014) and they are summarized in the following sections.

### 4 Testing Programme

A series of laboratory tests were conducted to examine the physical and engineering properties of the two types of glass cullet. Samples of 100% glass cullet were tested. The tests were conducted according to GEOSPEC3 (GEO, 2001) as far as practicable.

#### 4.1 Grading

Particle size distribution (PSD) of 3 mm minus and 20 mm minus glass cullet samples were determined. The 63μm sieve was replaced by a 75 μm following the PSD procedure in CWC (1998). A summary of PSD plots is given in Fig. 1 and the associated coefficients of uniformity and fines contents are given in Table 4. The limits of coefficient of uniformity and fines contents as reported by CWC (1993) for ¼ inch minus glass cullet are also presented in Table 4 for comparison purpose.

| Grading        | PSD of Uniformity | Fines Content |
|----------------|-------------------|---------------|
| Zone A         | Zone B            | Zone C        |
| 3 mm minus     | 5.9 - 8.0         | 5%            |
| (Hong Kong)    | 2.3 - 16.7        | 1%            |
| 20 mm minus    | 3.3 - 16          | 0.2%          |
| (Hong Kong)    |                   |               |
| ¾ inch minus   |                   |               |
| (CWC, 1993)    |                   |               |

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 a few samples 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 local 3 mm minus samples did not exceed 6%, which satisfied the requirement on fill material for earthworks and reclamation works as stipulated in both GS (HKSAR, 2006) and Port Works Design Manual (CEO, 2002). The coefficients of uniformity of all 3 mm minus samples were found to exceed 5, which would meet the respective requirement for reclamation fill.

Fines contents of the 20 mm minus samples were less than 5%. 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 reclamation fill.

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

#### 4.2 Debris Content

Non-glass debris in glass cullet samples in Hong Kong was found to comprise cork, paper, plastic, metal flakes, etc. Manual separation of the debris from the glass cullet samples was 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 content than that of 20 mm minus samples. This is probably because those non-glass debris is relatively less susceptible to crushing and the 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.
4.3 Particle Shape Analysis

A close examination of the particle form and angularity of glass cullet collected was conducted. The cullet particles were angular in shape and with very sharp, conchoidal fracture surfaces. The particle form was mostly flat and partly equidimensional.

4.4 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.

4.5 Maximum Dry Densities

The maximum dry densities (MDDs) of glass cullet samples determined by Standard and Modified Proctor tests are given in Table 5. The MDDs of ¼ inch minus glass cullet as reported by CWC (1993) are also presented in the Table for comparison purpose. 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 (1.68 – 1.72 Mg/m$^3$) 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.

Table 5. Maximum Densities Based on Proctor Tests.

|                  | 3 mm minus (Hong Kong) | 20 mm minus (Hong Kong) | ¼ inch minus (CWC, 1993) |
|------------------|------------------------|-------------------------|--------------------------|
| **Maximum**      |                        |                         |                          |
| Dry Density      | 1.68–1.72 Mg/m$^3$     | 1.51-1.59 Mg/m$^3$      | 1.59 Mg/m$^3$            |
| **Minimum**      |                        |                         |                          |
| Dry Density      | 1.77-1.79 Mg/m$^3$     | 1.69-1.89 Mg/m$^3$      | 1.78 Mg/m$^3$            |

Similar to the compaction behavior 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 mainly either flat or monotonically ascending (see Fig. 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-draining 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.

![Fig. 2. Proctor Test Results.](image)

A left shift of the PSD curve was noted after Modified Proctor test on 20 mm minus sample, indicating that breakage of flat glass cullet particles would have occurred under heavy impact load. The fines contents of the compacted 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. Trial compactions of 20 mm minus and 3 mm minus glass cullet samples were undertaken and the results indicated that compaction of the glass cullet to a dry density exceeding 95% MDD was rather easy.

4.6 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). It was indicated in CWC’s studies that the permeability of glass cullet sample could be about one order of magnitude higher (i.e. $10^{-4}$ m/s to $10^{-3}$ m/s) if it is compacted to 95% MDD as determined by Standard Proctor test.

4.7 Compressibility

As glass cullet is free draining, only the creep behaviour was studied. Creep compression ratios (α) of 3 mm minus glass cullet samples were determined by conducting laboratory tests using conventional oedometers while those of 20 mm minus samples were determined using large diameter oedometer (see Fig. 3).
and Rowe Cell. The test results are given in Table 6. The samples were initially in a loose state. It was observed that primary consolidation settlement completed shortly after applying the compression load, which was in line with the high permeability determined. The results indicated that 3 mm minus glass cullet samples would have lower compressibility than that of 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 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.

Table 6. Compressibility of Glass Cullet.

| Size       | 3 mm minus | 20 mm minus | 5 – 20 mm |
|------------|------------|-------------|-----------|
| Creep Ratio | $\alpha = 0.057$ | $\alpha = 0.50\%$ | $\alpha = 0.41\%$ |
| Compression | $-0.16\%$ | $-0.50\%$ | $-0.80\%$ |

The samples were then prepared for the oedometer tests, with a view to preparing 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 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.

Table 7. Friction Angles of Glass Cullet.

| Test Methods            | Friction Angle (°) |
|-------------------------|--------------------|
| Direct Shear Test (3mm Minus) | 41.0 - 48.9        |
| Triaxial Test (3mm Minus)  | 40.8 - 44.0        |
| Direct Shear Test (20mm Minus) | 45.0              |
| Triaxial Test (20mm Minus)  | 42.7               |

Development of negative excess pore water pressures were noted in shearing stages of the consolidated undrained triaxial tests, indicating that the compacted glass cullet specimens dilated upon shearing.

4.9 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 lower void ratio as a result of the fines migration at the lower portions is believed to be the causes for the higher CBR values. The CBR values 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.

5 DISCUSSION

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 minus glass cullet produced by the two suppliers in Hong Kong was generally used for
production of concrete paving blocks. The grading of 3 mm minus cullet fell within the envelope specified by CWC (1993) for drainage fill. 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.

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.

Based on the results of the feasibility study, it is considered that glass cullet can be used as fill material in earthworks and reclamation works. Recommended technical requirements for the glass cullet are given in GEO (2014).

6 CONCLUSIONS

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.

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