Feasible use of recycled CRT funnel glass as heavyweight fine aggregate in barite concrete

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Abstract
The challenge of managing discarded cathode ray tube (CRT) waste has become a major environmental concern in Hong Kong and other cities. Recycled CRT funnel glass with a relatively high density (~3000 kg/m\textsuperscript{3}) can be used as a potential material for the production of heavyweight concrete. This paper aimed to investigate the feasibility of using recycled CRT funnel glass, both treated (lead has been removed from the glass surface) and untreated (without removal of lead) as partial and full replacement of fine aggregate in heavyweight barite concrete. The inclusion of barite aggregate and recycled funnel glass increased the hardened density but reduced the compressive and splitting tensile strengths. The replacement of natural fine aggregate with recycled CRT glass had no significant effect on the elastic modulus but considerably improved the drying shrinkage of the concrete. In conclusion, the overall properties of heavyweight barite concrete made with the treated and untreated recycled CRT funnel glass are comparable, except for lead leaching results. The results show that it is feasible to use the treated CRT glass as 100\% substitution of fine aggregate in making heavyweight concrete. However, the substitution of untreated glass should limit to below 25\% due to its potential lead leaching.

Keywords: Heavyweight concrete, cathode ray tube, recycled glass, barite, mechanical properties

1. Introduction
1.1. Heavyweight concrete
Concrete with a density higher than 2600 kg/m\textsuperscript{3} is classified as heavyweight concrete (HWC) (Başyigit et al., 2010). HWC is one of the common types of concrete used in nuclear power plants, medical units and in structures where radioactive protection is required (Gencel et al., 2010a; Gencel et al., 2010b; Akkurt et al., 2010). This is due to its ability to attenuate radiation (Akkurt et al., 2006). Besides, HWC can also be used for ballasting for pipelines and similar structures for offshore applications.

Previous studies have shown that aggregates which have a density higher than 3000 kg/m\textsuperscript{3} can be considered as heavyweight aggregate for the production of heavyweight
Concrete (Kilincarslan et al., 2006; Sakr and EL-Hakim 2005). Barite has been widely used in making heavyweight concrete because of its high density (4.1 g/cm³). Esen and Yilmazer (2010) investigated some of the physical and mechanical properties of concrete made using barite (BaSO₄) aggregate at different replacement ratios. They found that the unit weight, ultrasound pulse velocity (UPV), modulus of elasticity of barite aggregate concretes increased with an increase of barite aggregate content. In contrast, the tensile and compressive strengths were found to decrease with an increase of barite aggregate content due to the lower mechanical strength of the barite aggregate. Also, Topçu (2003) found that the optimal w/c ratio for heavyweight barite concrete was about 0.4 and the cement content should not be less than 350 kg/m³. Akkurt et al. (2008) investigated the effect of freezing and thawing (F-T) on the properties of concrete made with barite aggregate. The results showed that an F-T cycle had no significant effect on the unit weight and compressive strength of the barite concrete. However, the modulus of elasticity decreased with increase of F-T cycle.

1.2. Research background
The challenge of managing discarded cathode ray tube (CRT) waste has become a major environmental concern in Hong Kong (Poon, 2008). About 490,000 units per year of CRT waste derived from old TV sets and computer monitors is generated in Hong Kong (Ling and Poon, 2011a). A study has shown that over 4 million tonnes of e-waste are generated per year from eight European countries and the amount is kept growing (EA, 2006). According to EPA (2007), almost 175,000 tonnes of products containing CRT is generated in the United States each year and the majority (80-85%) of this waste ends up in landfills. This is undesirable because the lead contained within the CRT glass can leach from the broken glass cullets and contaminate ground water. Thus, special treatment for discarded CRT glass is necessary before it can be reused or disposed of in landfills, mainly because of the high lead content present in the CRT glass (Lee et al., 2004; Lee and His, 2002; Menad, 1999).

A number of studies have been conducted to investigate the effectiveness of different methods to remove the lead present on the surface of CRT crushed glass. Chemical treatment methods by using alkali and/or acid solutions have been studied (Foresman and Foresman 2000; Ioannidis and Zouboulis, 2006). In Hong Kong, a four-step simple recycling method has been developed to remove the surface lead and the method consists of: (i) isolation of the leaded funnel glass from CRT; (ii) crushing the glass into smaller particle sizes of less than 5 mm; (iii) removal of lead from the surface of crushed funnel glass by immersing in 5% nitric acid solution for 3 h; and (iv) rinsing the treated glass using tap water to remove the remaining acid. The details of the recycling process have been reported (Poon, 2008; Ling and Poon, 2011a).

1.3. Motivation of the research
Previous studies have proved that the recycled glass appear to be suitable for use in a wide range of applications including concrete, bricks and road engineering (Lin, 2007; Disfani et al., 2012). Topçu and Canbaz (2004) reported that when 60% of natural aggregates in concrete were substituted by recycled glass aggregate, the overall cost of concrete production can be reduced by 2.8%. Recently, recycled aggregates derived from
various sources with diverse characteristics have been shown to be able to be utilized in concrete. Furthermore, some studies have been done to incorporate recycled rubber aggregate in lightweight concrete for a better functional properties and durability (Pelisser et al., 2012; Ho et al., 2011; Mohammed et al., 2012; Richardson et al., 2012).

The recycled CRT funnel glass can be utilized as a fine aggregate for making concrete. The relatively high density (~3000 kg/m$^3$) of the glass as compared to conventional natural aggregates (~2600 kg/m$^3$) renders it suitable for producing heavyweight concrete. This present study aims to assess the feasibility of using recycled CRT recycled glass as fine aggregate for the production of heavyweight barite concrete. Both treated (lead is removed from the surface of crushed glass) and untreated (glass without removal of lead) crushed CRT glass was used as replacements of natural crushed fine stone at 0%, 25%, 50%, 75% and 100% by volume. The hardened density, compressive strength, tensile splitting strength and elastic modulus of the heavyweight barite concrete were determined. The resistance to carbonation and the drying shrinkage of the concrete were also assessed.

2. Experimental details
2.1. Materials
2.1.1. Cementitious materials
Ordinary Portland cement (OPC) complying with ASTM Type I and Fly ash complying with ASTM class F were used as the cementitious materials. The chemical compositions and physical properties of these cementitious materials are shown in Table 1.

Table 1. The chemical compositions and physical properties of cementitious materials.

<table>
<thead>
<tr>
<th>Chemical compositions (%)</th>
<th>Cement</th>
<th>Fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium oxide (CaO)</td>
<td>63.15</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Silicon dioxide (SiO$_2$)</td>
<td>19.61</td>
<td>56.79</td>
</tr>
<tr>
<td>Aluminium oxide (Al$_2$O$_3$)</td>
<td>7.33</td>
<td>28.21</td>
</tr>
<tr>
<td>Ferric oxide (Fe$_3$O$_5$)</td>
<td>3.32</td>
<td>5.31</td>
</tr>
<tr>
<td>Magnesium oxide (MgO)</td>
<td>2.54</td>
<td>5.21</td>
</tr>
<tr>
<td>Sodium oxide (Na$_2$O)</td>
<td>0.13</td>
<td>0.45</td>
</tr>
<tr>
<td>Potassium (K$_2$O)</td>
<td>0.39</td>
<td>1.34</td>
</tr>
<tr>
<td>Sulfur trioxide (SO$_3$)</td>
<td>2.13</td>
<td>0.68</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>2.97</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Physical properties
Specific gravity 3.16 2.31
Blaine fineness (cm$^2$/g) 3519 3960

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2.1.2. Coarse and fine aggregates
Natural granite and barite aggregates with 5/10 mm and 10/20 mm size were used as coarse aggregates, respectively, in the control-granite and the control-barite mixes. The barite aggregate has a density of 4,200 kg/m$^3$ and can be regarded as a radiopaque material because of its high density.

All fine aggregates used in this study had particle sizes of less than 5 mm. Crushed fine stone (CFS) with a fineness modulus of 1.8 was used as 100% fine aggregate in both the control-granite and the control-barite concrete. The recycled CRT funnel glass was obtained from a local CRT Waste Recycling Centre. In this study, crushed funnel glass (CFG, untreated) and treated funnel glass (TFG, treated with acid to remove lead) were used to replace CFS. The grading curves of the coarse and fine aggregates are shown in Fig. 1. The physical properties of the coarse and fine aggregates are listed in Table 2.

A superplasticizer ADVA-109 containing no added chloride and weighing approximately 1.045±0.02 kg/l was used as a high range water reducer.

2.2. Mix proportions
A total of ten concrete mixes were prepared including two control mixes (control-granite and control-barite). The mixtures were prepared with a cementitious material content of 417 kg/m$^3$ (15% was fly ash), water-to-cementitious material (w/c) ratio of 0.48 and the ratio of fine-to-total aggregates was kept at 0.42. For comparison, granite and barite aggregates were used as 100% coarse aggregate to prepare the control-granite and the control-barite mixes, respectively. Crushed fine stone (CFS) was used as the fine aggregate. In order to assess the feasibility of using recycled CRT funnel glass in heavyweight barite concrete, crushed funnel glass (CFG) and treated funnel glass (TFG) were used respectively to replace 25%, 50%, 75% and 100% of equal volumes of CFS. The details of the mix proportions of the concrete mixes are shown in Table 3.

Table 2. Physical properties of coarse and fine aggregates

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Coarse aggregates</th>
<th>Fine aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Granite 10/20</td>
<td>Granite 5/10</td>
</tr>
<tr>
<td>Fineness modulus</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Saturated-surface-dry (SSD) density (g/cm$^3$)</td>
<td>2.62</td>
<td>2.62</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>10% fine value (kN)</td>
<td>159.0</td>
<td>40.7</td>
</tr>
</tbody>
</table>

*First author: t.ling.1@bham.ac.uk; tcling611@yahoo.com
Fig. 1. Grading curves of coarse and fine aggregates.

Table 3. Mix proportions of heavyweight barite concrete

<table>
<thead>
<tr>
<th>Notation</th>
<th>w/c</th>
<th>Proportions (kg/m³)</th>
<th>Coarse aggregates</th>
<th>Fine aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cement</td>
<td>PFA</td>
<td>Granite</td>
</tr>
<tr>
<td>Granite concrete</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>669</td>
</tr>
<tr>
<td>Barite concrete</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>CFG-25</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>CFG-50</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>CFG-75</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>CFG-100</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>TFG-25</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>TFG-50</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>TFG-75</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>TFG-100</td>
<td>0.48</td>
<td>355</td>
<td>62</td>
<td>-</td>
</tr>
</tbody>
</table>

2.3. Sample preparation
The concrete mixtures were prepared using a pan mixer with a capacity of 100 L. The mixing sequence consisted of mixing cementitious materials, and coarse and fine aggregates together with ½ of the mixing water. After mixing for 3 min, the remaining

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mixing water (with the superplasticizer pre-mixed in it) was introduced into the mixer, and the concrete was mixed for another 2 min.

Immediately after the end of mixing, the fresh concrete mix was cast into different types of steel moulds. A mechanical vibrating table was used to compact the fresh concrete. After the samples were initially set (observed by usual inspection), the samples were covered with a thin plastic sheet and stored in a laboratory environment at a temperature of 23±3°C for 24 hours. After one day, the samples were demoulded and then water cured at a controlled temperature of 25±3°C until the day of testing.

2.4. Test methods
2.4.1. Hardened density
100 mm concrete cube samples were used for determining the hardened density according to ASTM C 642 (2006).

2.4.2. Compressive strength
The compressive strength of 100 mm concrete cube samples was determined at 1, 7, 28, 90 days according to BS 1881: Part 116 (1983). A testing machine with a load capacity of 3000 kN and loading rate of 0.6 kN per second was used for the test. The results reported are the average values of three cube samples for each mix proportion.

2.4.3. Tensile splitting strength
Cylinder samples with dimensions of Φ100 × 200 mm were used for performing a tensile splitting strength test according to BS EN 12390: Part 6 (2000). The loading rate was set at 0.06 MPa per second. For each mix proportion three samples were tested at 1, 7, 28 and 90 days.

2.4.4. Static elasticity modulus
Three Φ100 × 200 mm cylinder samples were used to determine the 28-day static elasticity modulus of the concrete in accordance with ASTM C 469 (2002).

2.4.5. Carbonation
A carbonation test was conducted in accordance with Building Research Establishment, BRE Digest 45. To accelerate the carbonation process, three 100 mm cube samples cured underwater for 28 days were placed in an accelerated carbonation chamber that was set at a 4% CO₂ concentration with a 25 °C constant temperature and 60% relative humidity. The concrete samples were placed in the test chamber for a selected period of 28 and 90 days. Then, the samples were split into two halves and a 1% phenolphthalein solution (pH indicator) was sprayed onto the fractured surface. The depth of the colourless part from the edge of the specimen was measured as the carbonation depth. Four readings were measured in each fractured surface of the specimens.

2.4.7. Dry shrinkage
A modified British standard (BS ISO, Part 8) method was used for the drying shrinkage test (2009). After demoulding, the initial lengths of three 75×75×285 mm prism samples were recorded using a calibrated dial gauge. After the initial readings, the specimens were
conveyed to an environmental chamber with a temperature of 23°C and a relative humidity of 50% until further measurements at the 56th and 112th day.

2.4.8. Toxicity characteristic leaching procedure (TCLP)
All the ten designed concrete mixes sample were tested for lead (Pb) and Barium (Ba) leachability using the toxicity characteristic leaching procedure (TCLP) in accordance to the US Environmental Protection Agency method 1311 (1992). An extraction solution with a pH value of 2.88 was prepared using glacial acetic acid. For each test, 20 g of crushed concrete samples passing through a 10 mm sieve was added in 400 mL extraction solution within plastics containers. The containers were tumbled for 18 h by a rotary shaker. The leachable heavy metals were then analyzed using ICP-MS method.

3. Results and discussion
3.1. Hardened density
3.1.1. Effect of barite aggregate
Fig. 2a shows the results of the hardened density of the control-granite and the control-barite concrete. By keeping the mixing proportion constant, it was able to compare the effect of the use of the two types of coarse aggregate on the hardened density. As indicated in the figure, a density value of 2.607 kg/m³ was recorded for the control-barite (100% replacement of total volume of granite aggregates), which was about 16.2% higher than that of the control-granite. Hence, the control-barite produced in this study can be treated as a heavyweight concrete (with a hardened density >2600 kg/m³). The increase in the concrete density can be attributed to the relatively higher density of barite aggregate (4.1 g/cm³) when compared to natural granite aggregate (2.6 g/cm³). This result is consistent with the results reported by Esen and Yilmazer (2010).

3.1.2. Effect of using CFG and TFG to replace CFS
Fig. 2b shows the effect of replacing CFS by CFG and TFG on the hardened density of heavyweight barite concrete (HWBC). It can be seen that the density of HWBC increased with an increase of the replacement content due to the CRT glass having a higher density than that of CFS. The average percentage increase was about 0.8%, 1.2%, 1.9% and 2.4% at a replacement content of 25%, 50%, 75% and 100%, respectively. It was also noted that the hardened density of the TFG concrete was slightly less than that of the CFG concrete probably because of the removal of lead on the surface of the CRT glass.

3.2. Compressive strength
3.2.1. Effect of barite aggregate
The results of the compressive strength tests of the control-granite and control-barite are shown in Fig. 3a. The use of barite aggregate reduced the compressive strength of the concrete. The reason for this is related to the lower crushing strength of barite. As referred to in Table 2, the determined ten percent fine values of the barite aggregate (40.7 kN) were much lower than that obtained for the granite aggregate (159.0 kN). Similar observations reported by Esen and Yilmazer (2010), showed that there was an 11.7% decrease in compressive strength of the concrete prepared with 50% replacement of granite by barite. However, results reported by Sakr and EL-Hakim (2005) indicate an opposite trend (see Table 4).
Fig. 2. Effect of (a) barite aggregate and (b) replacement content of CFG and TFG on the hardened density of concrete.
Fig. 3. Effect of (a) barite aggregate and (b) replacement content of CFG and TFG on the compressive strength of concrete.
### Table 4. Comparison results of concrete properties between current work and pervious studies

<table>
<thead>
<tr>
<th>Properties</th>
<th>Author</th>
<th>Current work</th>
<th>Sakr and EL-Hakim (2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix ratio</td>
<td>Cementitious content, kg/m³</td>
<td>3</td>
<td>417</td>
</tr>
<tr>
<td></td>
<td>Water-to-cement ratio, w/c</td>
<td>0.48</td>
<td>0.40</td>
</tr>
<tr>
<td>Coarse agg. (5-20mm), kg/m³</td>
<td>Granite=1004 Barite=1570</td>
<td>Barite=1570</td>
<td>Gravel=1125  Barite=1510</td>
</tr>
<tr>
<td>Fine agg. (&lt;5mm), kg/m³</td>
<td>CFS=727</td>
<td>CFS=727</td>
<td>TFG=830      Gravel=750  Barite=1236</td>
</tr>
<tr>
<td>Properties</td>
<td>Density, Kg/m³</td>
<td>2244</td>
<td>2607</td>
</tr>
<tr>
<td></td>
<td>Compressive strength, Mpa</td>
<td>45.9</td>
<td>42.1</td>
</tr>
<tr>
<td></td>
<td>Tensile splitting strength, MPa</td>
<td>3.71</td>
<td>2.51</td>
</tr>
<tr>
<td>Flexural strength, MPa</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Elastic modulus, GPa</td>
<td>29.8</td>
<td>20.5</td>
<td>21.0</td>
</tr>
</tbody>
</table>

**3.2.2. Effect of CFG and TFG**

Fig. 3b shows the results for the compressive strength of HWBC prepared by using different content of CFG and TFG to replace CFS. It can be seen that the compressive strength gradually decreased with an increase in replacement content. A similar trend can be observed for concrete prepared with CFG and TFG. At the 28th day, the compressive strength was decreased from 42.1 MPa (control-barite) to 36.5 MPa and 35.1 MPa when crushed fine stone was fully replaced by CFG and TFG, respectively. This might be explained by the smoother surface of the glass aggregate, thus affecting the bonding between the glass particles and cement paste.

**3.3. Tensile splitting strength**

#### 3.3.1. Effect of barite aggregate

Fig. 4a shows the results of the development of the tensile splitting strength of the control-granite and the control-barite over time. The results show that the control-barite has a lower tensile splitting strength than that of the control-granite. Also, the reduction in tensile splitting strength due to the use of barite was more noticeable than the reduction in compressive strength. For example, when barite was used instead of granite in the concrete, there was about 32.3% reduction in tensile splitting strength, while only 8.3% reduction in compressive strength was noted at the curing age of 28 days. This can be attributed to the high brittleness of the barite aggregate and the initiated cracks propagated along the longitudinal direction of the specimen, resulting in weaker tension as the loading was continually applied in the middle of the specimen during the tensile splitting strength test.

#### 3.3.2. Effect of replacement content of CFG and TFG

The tensile splitting strength decreased as the replacement ratio of CFS by both CFG and TFG increased. For example, the tensile splitting strength decreased by 4.6%, 6.8%, 18.5% and 25.7% on average as the replacement ratio was increased from 0 to 25%, 50%, 75% and 100%, respectively. Similar to the case of barite, the negative influence of CFG
and TFG in concrete is more obvious in tension than in compression. This can be understood by the fact that the adhesion between the aggregates and the cement paste play a more dominant role in affecting the tensile properties of the concrete specimens.

**Fig. 4.** Effect of (a) barite aggregate and (b) replacement content of CFG and TFG on the tensile splitting strength of concrete.
3.4. Elasticity modulus

3.4.1. Effect of barite aggregate

As shown in Fig. 5a, the average 28-day elastic modulus of the control-granite and the control-barite were 29.8 GPa and 20.5 GPa, respectively. In other words, as the granite coarse aggregate was totally replaced by barite, a 31.0\% reduction in elastic modulus resulted. Interestingly, Sark and El-Hakim (2005) reported that the use of barite aggregate for total volume of gravel aggregate replacement noticeably improved the elastic modulus by 39.6\% (see Table 4), although the barite aggregate used also had lower mechanical properties than that of gravel aggregate.

![Diagram showing the effect of barite aggregate and replacement content of CFG and TFG on the elastic modulus of concrete.](a)

![Diagram showing the percentage of volume replacement vs. elastic modulus.](b)

**Fig. 5.** Effect of (a) barite aggregate and (b) replacement content of CFG and TFG on the elastic modulus of concrete.
3.4.2. Effect of replacement content of CFG and TFG
The influence of using CFG and TFG on the elastic modulus is illustrated in Fig. 5b. The results show only an insignificant effect. Moreover, in some cases, the use of CFG and TFG to replace CFS can cause an increase in the elastic modulus of concrete. A study by Topçu and Canbaz (2004) reported that the elastic modulus of concrete increased with increasing use of glass as the aggregate. As for a study by Taha and Noum (2008), they found that it was difficult to identify the difference in elastic modulus of concrete prepared with 50% and 100% recycled fine glass aggregate. The reason was thought to be that the type of fine aggregate used in concrete does not play an important part in affecting the elastic modulus.

3.5. Carbonation
3.5.1. Effect of barite aggregate
Requirement of a concrete durability depending on the exposure environment and the properties desired. Durability of concrete can be assessed by means of accelerated carbonation depth. The carbonation depth results of the two control concrete samples are shown in Fig. 6a. It can be seen that the carbonation depth of the control-barite concrete was lower than that of the control-granite concrete, which may be due to the better packing density of barite aggregate, resulting in lower pore structures in the concrete.

3.5.2. Effect of replacement content of CFG and TFG
Fig. 6b shows the carbonation depth values of the HWBC prepared with CFG and TFG at different replacement ratios. The results indicate that the substitution of CFS by CFG and TFG decreased the carbonation resistance of HWBC. This is because the carbonation resistance is generally associated with the voids present in the concrete and the impermeable surface of recycled funnel glass aggregate might have trapped more air in the concrete matrix, consequently permitting more carbon dioxide to penetrate into the concrete (Ling and Poon, 2011b).
3.6. Dry shrinkage
Concrete shrinkage has become an increasingly important issue to be understood because the potential of drying shrinkage as a function of moisture loss can lead to cracking and contribute to decreased serviceability. Fig. 7 shows the dry shrinkage results. All samples had shrinkage below 0.075% at 56th day and therefore, according to the Australian Standard AS 3600 (2004), the shrinkage was within an acceptable limit. Comparing the results, control-barite concrete showed the highest drying shrinkage value at both 56th and
112\textsuperscript{th} days. It is clearly observed that the incorporation of CFG and TFG has a beneficial effect in reducing the drying shrinkage of HWBC. The decrease in drying shrinkage with the presence of recycled funnel glass aggregates may be attributed to the low water absorption values of the glass. This is in agreement with previous study done by Kou and Poon (2009). They results also show that the concrete with 45\% recycled glass used as fine aggregate had less drying shrinkage (0.031\%) than that of control mix (0.037\%).

![Graph showing the effect of replacement content of CFG and TFG on the drying shrinkage of concrete.](image)

**Fig. 7.** Effect of replacement content of CFG and TFG on the drying shrinkage of concrete.

### 3.7. Lead and Barium leaching

The lead and barium leaching results obtained using TCLP method for all the control and heavyweight barite concretes are summarized in Table 5. The results indicated that all the concrete mixes satisfied the TCLP permitted limit (100 mg/L) for barium. With the exception of CFG-50, CFG-75 and CFG-100, the lead concentrations in the leachate were also below the acceptable limit of 5.0 mg/L. This would suggest that TFG can be used as a substitution for fine aggregate up to 100\% but the use of CFG should to below 25\% due to its higher leachable content.
<table>
<thead>
<tr>
<th>Notation</th>
<th>Barium (mg/L)</th>
<th>Lead (mg/L)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite concrete</td>
<td>0.84</td>
<td>0.09</td>
<td>4.84</td>
</tr>
<tr>
<td>Barite concrete</td>
<td>0.14</td>
<td>0.02</td>
<td>4.49</td>
</tr>
<tr>
<td>CFG-25</td>
<td>0.28</td>
<td>2.20</td>
<td>4.75</td>
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<tr>
<td>CFG-50</td>
<td>0.34</td>
<td>20.69</td>
<td>4.50</td>
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<td>CFG-75</td>
<td>0.34</td>
<td>28.19</td>
<td>4.53</td>
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<td>CFG-100</td>
<td>0.47</td>
<td>84.36</td>
<td>4.38</td>
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<tr>
<td>TFG-25</td>
<td>0.32</td>
<td>0.53</td>
<td>4.32</td>
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<td>TFG-50</td>
<td>0.27</td>
<td>0.76</td>
<td>4.45</td>
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<td>TFG-75</td>
<td>0.29</td>
<td>1.81</td>
<td>4.48</td>
</tr>
<tr>
<td>TFG-100</td>
<td>0.26</td>
<td>1.84</td>
<td>4.54</td>
</tr>
<tr>
<td>TCLP limit</td>
<td>100</td>
<td>5.00</td>
<td>-</td>
</tr>
</tbody>
</table>

4. Conclusion
This study investigated the feasibility of using recycled CRT funnel glass (both crushed funnel glass (CFG) and treated funnel glass (TFG)) as fine aggregates in the production of heavyweight barite concrete (HWBC). Based on the experimental results, the following conclusions can be drawn:

- In general, the overall performance of HWBC prepared with CFG and TFG are comparable.
- The hardened density of the concrete was increased from 2244 kg/m$^3$ to 2672 kg/m$^3$ as the natural coarse and fine aggregates were respectively fully replaced by barite aggregate and recycled funnel glass. This is because the barite aggregate and recycled funnel glass had higher density values than those of natural coarse and fine aggregates.
- The use of barite aggregate and recycled funnel glass decreased both the compressive and tensile splitting strengths of HWBC. This can be attributed to the lower crushing strength of the barite aggregate and smoother surface of the glass aggregate.
- Use of barite aggregate in concrete reduced the elastic modulus by 31%. But no significant difference was observed when the natural fine aggregate was replaced by the recycled CRT glass. It seems that the types of coarse aggregate used affected the elastic modulus more than the types of fine aggregate used in the concrete.
- Heavyweight barite concrete had a better resistance to carbonation than the control-granite concrete, whereas the resistance to carbonation was gradually decreased with increasing use of the CRT glass to replace CFS.
- Inclusion of recycled CRT glass in HWBC can help to reduce the drying shrinkage.
- All the concrete mixes showed lead and barium leaching level below the
permissible limits, except for the HWBC mixes containing high (>25%) CFG content.

The above results suggest that it is feasible to use barite aggregate and TFG up to 100% as replacements of natural coarse and fine aggregates for the production of heavyweight concrete, especially for applications in radiation shielding construction. As for CFG, it is suggested that the percentage used should be less than 25% due to its leachable lead content.

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References


