Mix Design of High-Strength Concrete Incorporating Spherical and Crushed CRT Funnel Glass Waste

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Abstract. Cathode ray tube (CRT) funnel glass, due to its high content of lead oxide (PbO), is considered as hazardous waste. The growing volume of the disposed CRTs technology presents a risk of environmental contamination owing to the potential of toxic Pb metals leaching from glass. A typical way of recycling CRT funnel glass waste is by crushing it and partially replaced the cement and fine aggregates. However, this approach has been facing serious issues in terms of leaching of Pb. Hence, a new recycling method has been developed, that is by performing proper melting and annealing operations in producing the spherical CRT funnel glass (GS). GS does not show any harmful risk of the release of Pb to the environment. The Pb leaching value of CRT concrete specimens with GS is significantly lower than the allowable limit although it contains high concentration of PbO, 25%. While the performance of GS in leaching aspects have been determined, the optimum mix designs of high-strength concrete incorporating both GS and crushed CRT funnel glass (GC) as coarse aggregates yet remains to be investigated. Predominantly to provide a safe method of recycling CRT funnel glass as aggregate and to increase the confidence level of the industries, this paper addresses the mix design of high-strength concrete with GS and GC as coarse aggregates. Given the importance of selecting the materials and its contents, the influence of five parameters, i.e. water/binder (w/b) ratio, coarse aggregate (CA) content, superplasticizers (SP) dosage, and silica fume (SF) content were evaluated. It was found that the incorporating of GS and GC that differ in terms of morphologies (size, shape, texture) and water absorption rate than the natural rock have led to the increase of workability of CRT concrete mixtures, however, decrease the compressive strength. But the results also have highlighted that the CRT specimens that were designed with w/b ratio 0.31, 43% content of CA, 2% SP, and 10% SF were able to achieve the highest strength of 61 MPa, which was only 9% lower than control specimens. The optimum mix design of CRT concrete has greatly improved the strength of concrete and enhance its potential for future applications.

1. Introduction

The technology cathode ray tube (CRT) has been used as oscilloscope to transmit and receive image electronically. It is widely used in television (TV) and monitors. In this era of globalization, the amount of CRT waste has been reported increasing. In United States, it is estimated around 232.2 million tons monitors and televisions with CRT tube require proper recycling from 2013 to 2033 [1,2].
increasing amount of disposed CRT tube has become a major concern in many countries, since it was classified as hazardous waste due to its high concentration of lead oxide (PbO), especially in funnel component is around 15% to 25% [3]. Thus, if the CRT glass is disposed at the landfill sites, the toxic Pb may leach out, which will pollute the groundwater and affect human health [4]. Therefore, past studies [5-8] using the crushed CRT glass as a replacement of natural sand. Generally, the use of milled waste glass results in improved particle packing and stronger interfacial transition zone [6,8]. In addition, due to the nearly zero water absorption rate, the use of crushed CRT glass able to increase the resistance of concrete in the aspect of shrinkage, abrasion, and creep. However, the use of crushed CRT funnel glass at a size smaller than 4.75 mm, which is used to partially replace the natural fine aggregates has caused the Pb leaching value higher than the allowable limit. It is because of increasing the surface area exposed to acid by decreasing the size of CRT funnel glass, will lead to the higher Pb leaching rate [9,10]. Even so, the author’s recent work [11] proved that the use of bigger-sized crushed glass of range 4.75 mm to 19 mm, i.e. crushed CRT funnel glass (GC) has significantly reduced the Pb leaching rate. Moreover, the annealed glass namely spherical CRT funnel glass (GS) does not show any harmful risk of Pb leaching. It is because of the annealing process could reduce the internal pressure and subsequently strengthens the final product of waste CRT glass [12]. Furthermore, the studies done on the use of CRT funnel glass as a replacement of natural rock are very limited. It is estimated about 3000 million metric tons of natural aggregates i.e. rock and sand were extracted every year [13]. Excessive use of natural rock can cause extinction of natural resources as it affects the ecosystem, causing soil structure to be instable, and quality of water resources to be low [14]. Therefore, there is a pressing need to use the waste CRT glass as a replacement of natural rock, acts as coarse aggregate in concrete productions. The features of coarse aggregates would affect the concrete performance. Past studies [6,9] claimed that the smooth surface texture of the CRT glass has weaken the bonding between cement paste and aggregates. Thus, in order to use the CRT funnel glass as coarse aggregates effectively, it is necessary to produce a stronger cement matrix, which subsequently develop a high strength concrete (HSC). The production of HSC is very important move towards the development of glass concretes, hence certainly requires the waste CRT funnel glass be utilized to their full potential as aggregates. Therefore, the focus of the present work is to determine the potential of using two products of waste CRT funnel glass, namely as GS and GC as a substitute to use of natural rock, which is assessed in the aspect of workability and compressive strength. Given the importance of selecting the materials and its contents, the mix design of high strength CRT concrete (K-CRT) were evaluated based on the ratio of w/b, the percentage content of CA, the dosage of SP, and percentage of SF. The optimum mix design that is specific for K-CRT is necessary to ensure the best performance of this type of concrete structure.

2. Experimental Investigations
Materials used in this study included ordinary Portland cement (OPC), SF, tap water, polycarboxylate ether SP, river sand as fine aggregate, gravel and CRT glass products, i.e. GS and GC as CA. Both were collected from the company of Nippon Electric Glass (NEG), Malaysia (Figure 1). GS (spherical glass particles) was prepared through the processes of melting, annealing and cooling, while GC (angular glass particles) was prepared through the processes of crushing and grading. The different production methods of GS and GC have caused them to have their own characteristics. GS has the lowest specific gravity, unit weight, and percentage absorption as compared to GC and natural aggregate. The total of eighteen concrete mixtures were prepared for this study (Table 1). The proportions of those materials were designed based on the absolute volume method [15]. Generally, the concrete mixtures were designed with the aim of ensuring that the K-CRT reaches its best potential despite the expected variations between GS, GC, and natural rock properties. Therefore, there are four parameters investigated, which are w/b ratios (0.35, 0.31, 0.29), CA content (48%, 45%, 43%), SP dosage (2.3%, 2.0%, 1.8%), and SF percentage (12%, 10%, 8%). The optimum mix design for K-CRT were selected based on the aspects of workability [16,17] and compressive strength [18].
Figure 1. Products of CRT funnel glass (a) spherical glass (GS) and (b) crushed glass (GC)

Table 1. Material proportions of concrete specimens

| Mix notation | C   | SF  | FA  | NCA | GS  | GC  | Water | SP  |
|--------------|-----|-----|-----|-----|-----|-----|-------|-----|
| CRT concrete (K-CRT) |     |     |     |     |     |     |       |     |
| 1a           | 435.1 | 48.3 | 582.7 | 0   | 405.9 | 724.2 | 169.2 | 8.7 |
| 2a           | 491.2 | 54.6 | 524.5 | 0   | 405.9 | 724.2 | 169.2 | 9.8 |
| 3a           | 525.1 | 58.3 | 489.4 | 0   | 405.9 | 724.2 | 169.2 | 10.5 |
| 2a-1         | 491.2 | 54.6 | 582.8 | 0   | 385.6 | 688.0 | 169.2 | 9.8 |
| 2a-2         | 491.2 | 54.6 | 641.2 | 0   | 365.3 | 651.8 | 169.2 | 9.8 |
| 2a-2a        | 491.2 | 54.6 | 638.5 | 0   | 365.3 | 651.8 | 169.2 | 10.9 |
| 2a-2b        | 491.2 | 54.6 | 634.4 | 0   | 365.3 | 651.8 | 169.2 | 12.6 |
| 2a-2a1       | 502.1 | 43.7 | 642.5 | 0   | 365.3 | 651.8 | 169.2 | 10.9 |
| 2a-2a2       | 480.3 | 65.5 | 634.4 | 0   | 365.3 | 651.8 | 169.2 | 10.9 |
| Control (K-N) |     |     |     |     |     |     |       |     |
| 1a           | 435.1 | 48.3 | 582.7 | 1130.0 | 0 | 0 | 169.2 | 8.7 |
| 2a           | 491.2 | 54.6 | 524.5 | 1130.0 | 0 | 0 | 169.2 | 9.8 |
| 3a           | 525.1 | 58.3 | 489.4 | 1130.0 | 0 | 0 | 169.2 | 10.5 |
| 2a-1         | 491.2 | 54.6 | 582.8 | 1073.6 | 0 | 0 | 169.2 | 9.8 |
| 2a-2         | 491.2 | 54.6 | 641.2 | 1017.1 | 0 | 0 | 169.2 | 9.8 |
| 2a-2a        | 491.2 | 54.6 | 638.5 | 1017.1 | 0 | 0 | 169.2 | 10.9 |
| 2a-2b        | 491.2 | 54.6 | 634.4 | 1017.1 | 0 | 0 | 169.2 | 12.6 |
| 2a-2a1       | 502.1 | 43.7 | 642.5 | 1017.1 | 0 | 0 | 169.2 | 10.9 |
| 2a-2a2       | 480.3 | 65.5 | 634.4 | 1017.1 | 0 | 0 | 169.2 | 10.9 |

3. Results and Discussion

3.1. Workability

Figure 2 and Figure 3 shows the slump value and slump flow of K-CRT and K-N specimens. Generally, the use of GS and GC as coarse aggregates has increased the workability of the concrete mixtures. The highest slump value of K-CRT specimens was shown by mix 2a-2a2 at 180 mm, up to 38% higher than the K-N specimens. Meanwhile, the highest slump flow of the K-CRT specimens is indicated by mix 2a-2b at 400 mm, where up to 25% higher than K-N specimens. This is attributed to the smooth surface texture of GS and GC causing weaker cohesion between the coarse aggregates and the mortar. Besides that, the nearly zero water absorption rate of the glass has led to the higher free water content and subsequently increase the fluidity of K-CRT mixtures. In addition, the results also demonstrated that the workability of K-CRT mixtures were influenced by the aspects of w/b ratios, percentage content of CA, dosage of SP, and percentage of SF. It is found that the slump value of K-CRT increased with the increased of w/b ratio [19]. However, based on the observation during the mixing process of K-CRT, the mix K-CRT 3a designed with w/b ratio 0.29 was found to cause the mixture to be difficult to place.
and consolidate. Other than that, the mixtures of K-CRT 1a and K-CRT 2a indicated a segregation problem between CRT glass particles and cement paste. This is due to the different density of GS and GC.

The total content of GS and GC as CA for all the three mixes (K-CRT 1a, K-CRT 2a, K-CRT 3a), were higher which was about 48%, whereas the coarse aggregate content for conventional concrete is normally between 45% and 46% [20]. Meddah et al. [20] claimed that the percentage content of CA can also affect the concrete performance. Aggregates and cement particles that consist of wider range of sizes can increase the concrete density and compactness [21,22]. Therefore, the segregation problem of K-CRT mix could be overcome by reducing the content of GS and GC as coarse aggregates and increasing the content of cement paste. Figure 2 shows that the slump value of K-CRT increased with the reduction in the percentage content of GS and GC as CA. The K-CRT mix containing lowest percentage of CA that was only 43% (K-CRT 2a-2) has shown higher slump value than the mix containing 45% CA (K-CRT 2a-1). It indicated that the reduction of GS and GC content in the K-CRT mixtures has improved their workability performances from medium to high category of workability, as its slump values were ranged from 100 mm to 150 mm [23]. Besides that, the reduction of the percentage content of CA in K-CRT mixture had also increased the content of fine materials. Thus, it was able to lower the tendency of segregation problem. However, the K-CRT mixtures required at least 18 seconds of vibration in producing compact specimens. The longer the vibration time, the more it would affect the homogeneity of GS and GC in K-CRT specimens. Normally, the vibration time for conventional
concrete is between 5 and 15 seconds only. If it is longer than 15 seconds, it will cause the segregation of CA [19]. Therefore, the segregation problems may be overcome by increasing the flowability of K-CRT mixtures, so that the vibration time in producing compacted K-CRT specimens could be reduced. The figures demonstrate that the increase of SP dosage has increased the fluidity of K-CRT mixes. The increase of SP dosage was able to shorten the vibration time in consolidating the K-CRT mixtures, which then reduced the tendency of segregation problem between the GS, GC, and cement paste. Past studies [24,25] have reported that the polymer bond in SP can increase the dispersing action of cement particles uniformly, due to the steric hindrance and electrostatic repulsive force. However, the use of high SP dosage might also cause the bleeding problem which can be seen with K-CRT 2a-2b mixtures that were designed with 2.3% SP dosage. Therefore, in terms of workability, the SP dosage at 2% from cementitous content is suitable for K-CRT mixtures (K-CRT 2a-2a), where it only 21.4% higher than its K-N mixtures. The figures also indicated that the slump value and slump flow of K-CRT decrease as the percentage of SF increases. The K-CRT mixtures with 12% of SF (K-CRT 2a-2a2) had resulted in great reduction of workability aspect. The finer particle size of SF caused the increased content of SF has led to the increase in water amount needed for the mixtures to obtain a high level of workability. Other than that, the K-CRT 2a-2a had shown the highest increase of slump flow from its K-N mixtures, about 21.4% higher. In addition, it did not show any segregation and bleeding problems. Several past studies [26-28] also claimed that the use of SF as a partial replacement of cement may reduce the risk of material segregation and bleeding.

3.2. Compressive Strength
The studies found that the use of GS and GC as a replacement of natural coarse aggregates has significantly decreased the compressive strength, up to 22% lower than control specimens. The strength reduction is because of the smooth surface texture of GS and GC, which using both as coarse aggregates has weakened its bonding with the mortar [6,9]. Even so, this study also proved that the use of optimum mix design of K-CRT mixtures has pointedly increased the compressive strength and lowered the strength reduction with the control. Figure 4 indicated that regardless of the selection of w/b ratio, SP dosage, CA and SF content, all concrete mixtures had shown the same trend that is the compressive strength increased with the increase of curing days. The highest compressive strength of K-CRT specimens is indicated by the mix K-CRT 2a-2a at 43.1 MPa, 54.8 MPa, and 61.4 MPa for curing age of 7, 14, and 28 days. Meanwhile, the specimens K-CRT 3a showed the lowest compressive strength, 51.9 MPa at 28 days. Generally, the decreasing of w/b ratio has led to the increasing of compressive strength. The higher the content of the cement paste, the better the strength of K-CRT since the bonding between the mortar and the CRT glass products will be stronger [19, 29-32]. However, the results also indicate that among the K-CRT specimens, the decrease of w/b ratio from 0.31 to 0.29 did not show any major impact on compressive strength. It can be observed that the compressive strength of K-CRT 2a specimens were not much different from the specimen containing higher cementitious material, since it was only 0.8 MPa lower than K-CRT 3a specimens. Thus, the optimum w/b ratio for K-CRT specimens is 0.31 because it showed the comparable strength and able to save about 9.4% cementitious content. Besides that, K-CRT 2a-2 specimens containing 43% GS and GC as CA indicated higher compressive strength than the specimens containing highest content of CA, 48%. It indicates that the decrease of GS and GC content has reduced the point of weakness and failure of the K-CRT. The failure of K-CRT was generally because of the weak bonding between the glass particles and mortar. It is mainly due to the smooth surface texture of the glass and spherical shape of GS material. This argument is similar to the findings from the previous studies [33-35], which they claimed that the smooth and flat surfaces of glass particles are the reasons for the content need to be reduced for limit the strength reduction. However, this observation is contrary to the K-N specimens, in which the reduction of NCA content has decreased the compressive strength. The different trend of the influence of percentage content of CA to the compressive strength of K-CRT and K-N has able to lower the gap of strength differences, at only 6.7% to 11.2% lower. Hence, the suitable percentage content of GS and GC as CA is at 43% of the K-CRT volume.
In addition, the studies also found that the increase of SP dosage to 2.3% has weaken the bonding of cement particles and aggregates, as the compressive strength for K-CRT 2a-2b specimens decreased about 15%. It is because of the excessive dosage of SP may also increase the content of entrapped air, which then reduces the strength of concrete [25,36,37]. Meanwhile, the K-CRT specimens prepared with 2% SP (K-CRT 2a-2a) had the lowest percentage reduction at only 6% to 9%. Thus, the use of 2% SP in preparing the K-CRT mixtures has allowed the cement particles to spread widely and this reduces the amount of non-hydrated particles. SF is a reactive pozzolana material that reacts with calcium hydroxide to produce a greater volume of calcium silicate hydrate gel (C-S-H), leading to higher strength of cement paste [15,38,39]. Because of that, SF was used as partial replacement of cement in K-CRT mixtures, which intended to enhance the bond between the materials. By comparing the K-CRT mix of 2a-2a, 2a-2a1, and 2a-2a2, it can be observed in Figure 4 that at the early curing ages (7 and 14 days), the increased percentage content of SF has enhanced the compactness and bonding between the CRT glass particles and mortar, which it acts as a void filler in the K-CRT mixtures [22,28,38-40]. However, on the 28th day of curing, the increased compressive strength of K-CRT specimens was limited to 10% content of SF. It is due to the specimens with 12% SF (K-CRT 2a-2a2) had shown significant reduction in compressive strength. But, K-CRT mix with 8% SF (K-CRT 2a-2a1) shows higher percentage reduction at 11% lower than the control, while the K-CRT specimens containing 10% SF (K-CRT 2a-2a) had shown the lowest percentage reduction, 9%. The increase in compressive strength has shown that at 10% content of SF, K-CRT specimens would have a better pore structure [21,41,42]. Therefore, the suitable percentage replacement of SF for the K-CRT specimens was 10%.

3.3. Empirical Equations
The aspects of workability and compressive strength of K-CRT specimens can also be correlated by empirical equations with high coefficient of determination (R²). It was developed using regression analysis. As mentioned above, the aspect of workability and compressive strength of concrete containing GS and GC were influenced by the selection of w/b ratios, percentage content of CA, dosage of SP, and percentage of SF. Eq. 1 to Eq. 4 shows the relationship between workability and compressive strength with the w/b ratios. Where W is the workability, f′c is the 28-day compressive strength, and x is the w/b ratio. It indicates that the quadratic empirical equations that correlate the slump value to the w/b ratio. While, the compressive strength of K-CRT was linearly correlated to the w/b ratio. The empirical equations that correlates the workability and compressive strength with the total content of CA were shown in Eq. 5 to Eq. 8. Where, the x is the percentage content of CA. As can be seen, linear relationship that correlates the slump value with the total content of CA in K-CRT and K-N mixes. On the other
The compressive strength of K-CRT specimens is correlated with the total content of GS and GC using quadratic equations, whereas for K-N specimens, the compressive strength was linearly correlated to the content of NCA. Other than that, the empirical equations that correlate the workability and compressive strength with the dosage of SP were shown in Eq. 9 to Eq. 12. Where, the x is the percentage dosage of SP. It was found that the linear empirical equations that correlate the workability and K-CRT and K-N specimens to the SP dosage. From the aspect of compressive strength, polynomial empirical equations that correlates it to the SP dosage. Besides that, Eq. 13 to Eq. 16 shows the relationship between workability and compressive strength with the percentage content of SF, where x is indicated as the percentage of SF. These equations indicated that only the workability of K-CRT mixes correlated with the percentage content of SF using linear empirical equations. Meanwhile, for K-N mixes, polynomial empirical equations that correlates both workability and compressive strength aspects to the percentage content of SF. Same goes with the relationship of compressive strength for K-CRT mixes with the content of SF.

\[
W_{K\text{-CRT}} = -36667x^2 + 24600x - 4009.3 \\
W_{K\text{-N}} = -28333x^2 + 19050x - 3106.7 \\
f'c_{K\text{-CRT}} = -96.571x + 85.939 \\
f'c_{K\text{-N}} = -131.7x + 109.33 \\
W_{K\text{-CRT}} = -709.21x + 433.34 \\
W_{K\text{-N}} = 313.16x - 57.632 \\
f'c_{K\text{-CRT}} = 1463.3x^2 - 1377.2x + 380.61 \\
f'c_{K\text{-N}} = 44.842x + 46.822 \\
W_{K\text{-CRT}} = 20000x - 60 \\
W_{K\text{-N}} = 13947x - 0.2632 \\
f'c_{K\text{-CRT}} = -735667x^2 + 29150x - 227.38 \\
f'c_{K\text{-N}} = -423667x^2 + 16794x - 98.89 \\
W_{K\text{-CRT}} = -21875x^2 + 3312.5x + 227.5 \\
W_{K\text{-N}} = -625x + 344.17 \\
f'c_{K\text{-CRT}} = -7625x^2 + 1462.5x - 8.6 \\
f'c_{K\text{-N}} = -2625x^2 + 492.5x + 44.5
\]

4. Conclusions
In conclusion, this study shows that there was great potential for using the annealed and crushed CRT funnel glass waste as a 100% replacement of natural rock in producing high strength concrete. The features of GS and GC in which they have a smooth surface texture, larger size, spherical shapes, and less water absorption have resulted in concrete with higher slump values than conventional concrete. However, these features have caused a significant reduction in compressive strength. Not just that, the performance of CRT concrete was also affected by the selection of mix design. The optimum mix design of K-CRT mixtures of w/b ratio 0.31, 43% content of CA, 2% SP, and 10% SF had produced the highest compressive strength of K-CRT, at 61 MPa with 340 mm slump flow. In addition, the percentage reduction of the compressive strength for K-CRT specimens had decreased to only 9% lower than K-N specimens.

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