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Utilization of recycled glass derived from cathode ray tube glass as fine aggregate in cement mortar

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ABSTRACT

Rapid advances in the electronic industry led to an excessive amount of early disposal of older electronic devices such as computer monitors and old televisions (TV) before the end of their useful life. The management of cathode ray tubes (CRT), which have been a key component in computer monitors and TV sets, has become a major environmental problem worldwide. Therefore, there is a pressing need to develop sustainable alternative methods to manage hazardous CRT glass waste. This study assesses the feasibility of utilizing CRT glass as a substitute for natural aggregates in cement mortar. The CRT glass investigated was an acid-washed funnel glass of dismantled CRT from computer monitors and old TV sets. The mechanical properties of mortar mixes containing 0%, 25%, 50%, 75% and 100% of CRT glass were investigated. The potential of the alkali-silica reaction (ASR) and leachability of lead were also evaluated. The results confirmed that the properties of the mortar mixes prepared with CRT glass was similar to that of the control mortar using sand as fine aggregate, and displayed innocuous behaviour in the ASR expansion test. Incorporating CRT glass in cement mortar successfully prevented the leaching of lead. We conclude that it is feasible to utilize CRT glass in cement mortar production.

1. Introduction

1.1. Background

The management of discarded cathode ray tubes (CRT) which are a key component in computer monitors and televisions (TV) has become a major environmental concern in many countries around the world. The glass derived from the rear part (funnel) of a CRT is classified as hazardous waste due to its high-lead content [1]. If the funnel CRT glass waste is not properly handled or simply disposed of in landfills, the hazardous materials (lead) from the broken funnel glass will lead to serious pollution of the environment and endangerment of public health.

In Hong Kong, there are about 6 million computers currently being used and about 20% of these are replaced annually. It is estimated that more than 490,000 old TV sets and CRT monitors are discarded from households every year due the widespread use of flat screen plasma/LCD/LED TV and monitors in Hong Kong. Therefore, since 2003, a pilot CRT recovery programme has been launched by the Environmental Protection Department (EPD) to reduce the quantity of discarded CRT monitors and TV sets that are to be disposed in landfills. This programme is fully funded by the industry and EPD, and has been well received by the public. Nearly 150,000 waste computers and computer accessories have been recovered at the collection services. Some of these computers were repaired and donated to the needy. However, the supply of the discarded CRT monitors and TV sets exceeds the demand of the second-hand market; hence the majority of these harmful wastes still need to be placed in landfills [2].

1.2. CRT recycling and current recycling approach used in Hong Kong

Studies have been carried out by various researchers to solve the discarded CRT waste problem, particularly with regard to the methods to reuse/recycle leaded funnel glass as it contains a large amount of lead [3–7]. Generally, there are three possible options for leaded CRT glass recycling. The first option is to re-utilize the discarded lead-laden funnel glass for new CRT manufacturing. However, this method seems to be impractical because of the much lower demand for new CRT manufacturing after the introduction of flat-screen technologies. The second option of recycling is reuse the lead CRT glass waste using the lead smelting method as it can be treated as a fluxing agent for bricks, glass tiles, form glass and ceramic manufacturing [8–10]. This method is considered not profitable due to the high cost involved in the separating, sorting and processing of the glass to meet the standards required by manufacturers [9,11].

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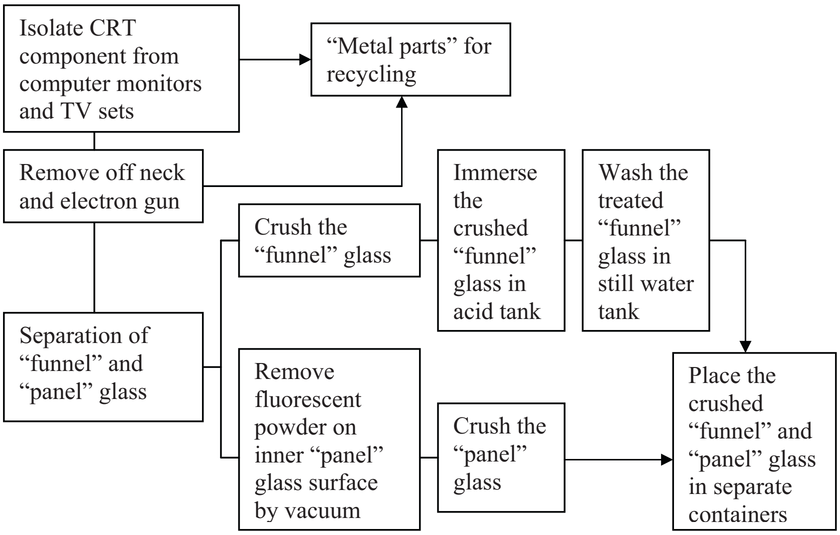

Fig. 1. Work flow of CRT recycling process.

Table 1
TCLP results of acid treated and untreated crushed CRT funnel and panel glasses.

Type of CRT glass	Sample ID	Pb (mg/L)	Ba (mg/L)
Crushed CRT funnel glass	CRT-FG1	376.1	7.8
	CRT-FG 2	371.1	18.2
	CRT-FG 3	373.2	17.5
Crushed CRT panel glass	CRT-PG 1	0.2	3.6
	CRT-PG 2	0.2	3.7
	CRT-PG 3	0.2	3.7
Treated crushed CRT funnel glass	T- CRT-PG 1	2.2	0.47
	T- CRT-PG 2	2.2	0.45
	T- CRT-PG 3	2.2	0.47

Table 2
Chemical compositions and physical properties of cement and fly ash.

Chemical compositions (%)	Cement	Fly ash
Calcium oxide (CaO)	63.15	<3
Silicon dioxide (SiO_2)	19.61	56.79
Aluminium oxide (Al_2O_3)	7.33	28.21
Ferric oxide (Fe_2O_3)	3.32	5.31
Magnesium oxide (MgO)	2.54	5.21
Sodium oxide (Na_2O)	0.13	0.45
Potassium (K_2O)	0.39	1.34
Sulfur trioxide (SO_3)	2.13	0.68
Loss on ignition	2.97	3.90
Physical properties		
Specific gravity	3.16	2.31
Blaine fineness (cm^2/g)	3519	3960

The third option has been developed recently in Hong Kong and it involves a process of crushing, acid washing and water rinsing. The work flow of the CRT recycling process used is illustrated in Fig. 1. The external electronic, plastic casing and metallic parts are first removed from the computer monitors and TV sets. The "funnel" and "panel" of the CRT glass is then separated by laser cutting or by a hot wire separation method. Since the lead contents of "funnel" and "panel" are different, these two kinds of glass are processed with two different production lines and recycling methods. The recycling process of CRT panel glass mainly involves the removal of fluorescent powder on the inner surface by vacuum, and then using a mechanical crusher to break it down into smaller particle size in a safe manner. Then the crushed panel glass can be used directly as glass aggregate in construction products due to its low lead content (see Table 1).

As for the funnel glass, since it contains a significant amount of lead (average PbO content of 22–25%), a specifically designed process of treatment was needed before it could be reused. The crushed CRT funnel glass was surface-treated by immersing it in a bath of 5% nitric acid (HNO_3) solution for 3 h to extract lead from the surface of the crushed glass. The lead oxide (PbO) was dissolved in the nitric acid solution to form soluble lead nitrate ($Pb(NO_3)_2$), according to the following reaction: $PbO + 2HNO_3 \rightarrow Pb(NO_3)_2 + H_2O$. A similar chemical reaction might also happen for other metal oxides found in the crushed CRT glass. After that, the acid-treated crushed glass was removed from the nitric acid bath and was thoroughly rinsed by using tap water to remove the remaining acid. The wastewater containing high concentrations of the dissolved heavy-metal (Pb) which was regarded as a hazardous waste was sent to a local chemical waste treatment plant for further treatment and disposal. As per Table 1, the treated crushed funnel glass had been tested by TCLP and it satisfied the 5 mg/L TCLP limit for lead and 100 mg/L for Barium specified by the local Environmental Agency and was regarded as a non-hazardous waste [12].

1.3. Significance of the research

There is an urgent need to develop alternative management methods for CRT funnel glass. This study investigates the potential use of acid-treated CRT funnel glass as a substitute for natural aggregates in cement mortar. The fresh and hardened properties of mortar mixes containing 0%, 25%, 50%, 75% and up to 100% crushed CRT glass are investigated. The potential of the alkali-silica reaction and leachability of lead from the cement mortar are also evaluated.

2. Experimental programme

2.1. Materials

2.1.1. Cementitious materials

ASTM Type I ordinary Portland cement and fly ash complying with ASTM class F ash was used as the cementitious material in this study. The chemical compositions and physical properties of the cement and fly ash are presented in Table 2.

2.1.2. Fine aggregate

Natural river sand having a particle size of less than 5 mm and a fineness modulus of 2.09 was used as the natural fine aggregate.

Table 3
Particle size distributions and physical properties of sand and CRT glass.

Sieve size (mm)	River sand (% passing)	CRT glass (% passing)
5	100	100
2.36	95.8	99.1
1.18	86.9	58.0
0.6	67.4	19.6
0.3	33.5	4.9
0.15	3.5	0.8
Fineness modulus	2.2	3.2
Relative density (g/cm^3)	2.09	2.99
Water absorption (%)	0.87	~0

2.1.3. Cathode ray tube glass

The cathode ray tube glass used in this study was crushed funnel glass sourced from a CRT glass Waste Recycling Centre located locally. The recycling centre used an acid treatment process designed to remove Pb oxide, which was the most concerned hazardous chemical in the management of CRT glass from the crushed funnel glass. It was carried out by using a diluted acid. Through visual inspection, the texture of the CRT glass was the same before and after the acid treatment. Lough [13] also observed that the surface texture of treated CRT glass particles was smoother after it was rinsed with an acid solution and tap water. Before the crushed glass was used for mixing, it was allowed to pass through a 5 mm test sieve. The particle size distribution and physical properties of river sand and crushed CRT glass are presented in Table 3.

2.2. Mix proportions

A cement mortar with a mix proportion of 0.75:0.25:2.5:0.45 (cement:flyash:sand:water) was prepared as the control mix. In this study, all mix design parameters were kept constant except for that of the fine aggregate. That is, the cementitious material content, water/cement (w/c) ratio, and aggregate volume were kept constant. The crushed CRT glass was used as a replacement for an equal part of river sand by volume. Four replacement levels were used at 25%, 50%, 75% and 100%. Since the CRT glass was denser than sand, the overall weight per unit volume of the mortar prepared with the glass was increased. The mix proportions of all the mortar mixes are shown in Table 4.

2.3. Mortar specimen preparation

All the mortar mixes were mixed for 5 min using a standard laboratory rotating drum type mixer. The fresh mortar samples were placed into the steel moulds of appropriate sizes in two layers of approximately equal depth. After each layer was filled, vibration was applied by a mechanical vibrating table. Following casting, the mortar specimens were covered with a thin plastic sheet in the laboratory at 23 ± 3 °C for 24 h. After one day, the mortar specimens were demoulded and then water cured except for samples designed for the drying shrinkage experiment which was transferred to a drying chamber at a temperature of 23 °C and relative humidity of 50% until further testing.

Table 4
Mix proportions of mortar mixes (kg/m^3).

Notation	Cement	Fly ash	Sand	CRT glass	Water	w/c
CRT-0	456	152	1519	0	273	0.45
CRT-25	456	152	1139	433	273	0.45
CRT-50	456	152	759	867	273	0.45
CRT-75	456	152	380	1300	273	0.45
CRT-100	456	152	0	1734	273	0.45

2.4. Test methods

2.4.1. Flow properties

The flow table test was used to determine the workability of the fresh mortar mix as described by ASTM C 1437. A higher flow table (spread) value of the mixture indicates a higher workability.

2.4.2. Hardened density

The hardened density of the mortar specimens was determined by using a water displacement method according to ASTM C 642. The results of the average of three specimens are reported.

2.4.3. Water absorption

Water absorption of the mortar specimens was determined according to ASTM C 642. The results are the average values of three specimens.

2.4.4. Flexural strength

A three point flexural strength test in conformity with ASTM C 348 was performed at 1, 3, 7, 28 and 90 days after casting. Prism specimen size of 40 mm × 40 mm × 160 mm was tested under a central line load while simply supported over a span of 120 mm. In this test, a universal test machine with a load capacity of 50 kN and a displacement rate of 0.20 mm/min was used. The results are the average values of three specimens.

2.4.5. Equivalent compressive strength

The equivalent compressive strength test was carried out according to ASTM C 349. The compressive strength was determined using a conventional compression machine with a load capacity of 3000 kN on the broken pieces (portions of the prisms broken in the flexure strength test). The reported test results are the average of six measurements.

2.4.6. Drying shrinkage

A modified British standard (BS ISO-Part 8, 1920) method was used for the drying shrinkage test. After demoulding, the initial length of three 25 mm × 25 mm × 285 mm mortar bar specimens was measured. After the reading, the specimens were conveyed to a drying chamber with a temperature of 23 °C and a relative humidity of 50% until further measurements on the 1st, 4th, 7th, 28th, 56th and 90th day, and the final length measurement was recorded on the 112th day. The length of each specimen was measured within 15 min after removal from the drying chamber.

2.4.7. Expansion due to the alkali-silica reaction

Three 25 mm × 25 mm × 285 mm mortar bar specimens were used for the ASR test in accordance with ASTM C1260- (the accelerated mortar bar method). A zero reading was taken after storing the prisms in distilled water at 80 °C for 24 h. The mortar bars were then transferred and immersed in 1 N NaOH solution at 80 °C until the testing time. The expansion of the mortar bars was measured within 15 ± 5 s after they were removed from the 80 °C water or alkali storage condition by using a length comparator. The measurements were conducted on the 1st, 4th, 7th, 14th, 21st and 28th day.

2.4.8. Toxic characteristic leaching procedure (TCLP)

In order to identify the leaching of lead from the different samples, the TCLP test was conducted according to the US Environmental Protection Agency method [12]. The broken samples were taken after the mechanical testing on the 28th day and were crushed to pass through a 10 mm sieve before the test. The extraction fluid with a pH value of 2.88 was prepared by diluting 5.7 mL of glacial acetic acid in 2 L of distilled water. Then the extraction was done by putting 20 g of sample in 400 mL of the prepared extraction

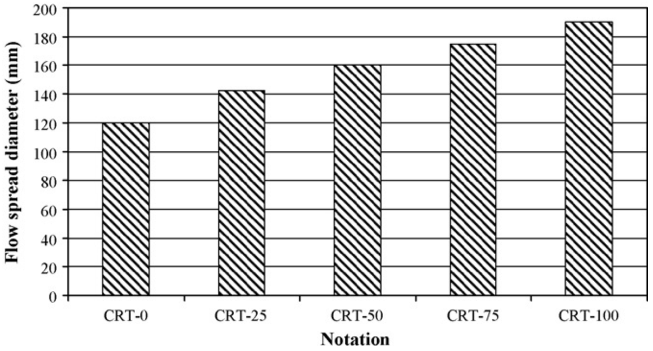

Fig. 2. Effect of CRT glass replacement on the flow spread diameter of fresh mortar mixes.

fluid and the mixture was tumbled for 18 h in a rotary mixer. The lead and Barium concentrations were determined using an atomic absorption spectrophotometer.

3. Results and discussion

3.1. Flow properties

The results of the flow table values (workability) of all the fresh mortar mixes are shown in Fig. 2. By keeping a constant w/c ratio of 0.45, it was possible to compare the flow table values due to the very different rheological properties of mortar mixtures prepared with different glass content. As expected, inclusion of the CRT glass in the mortars significantly increased the flow values because of its impermeability and smooth surface [14]. The flow table values of the fresh mortar mixtures increased from 120 mm to 190 mm with increasing CRT glass replacement levels from 0% to 100%.

3.2. Hardened density

Fig. 3 shows the effect of CRT glass replacement on the hardened density of the mortar mixes. The hardened density increased with increasing CRT glass content. The maximum density of 2472 kg/m^3 corresponded to 100% CRT glass, whereas the minimum density of 2208 kg/m^3 corresponded to 0% CRT glass. Using these two mixes as examples, the average density of mortar specimens was increased by about 3% for every 25% CRT glass replacement. The increase in density of the mortar specimens was attributed to the CRT glass having a higher specific gravity than that of sand due to the presence of lead in the glass.

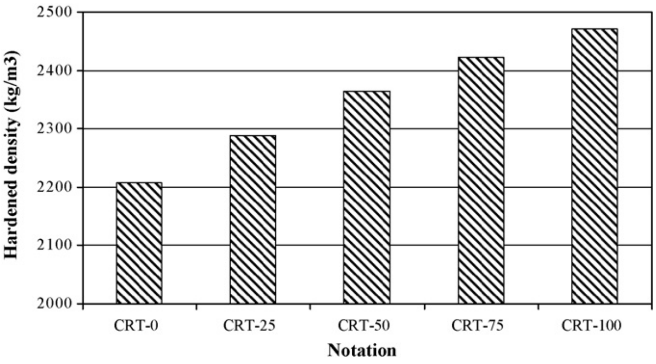

Fig. 3. Effect of CRT glass replacement on the hardened density of mortar.

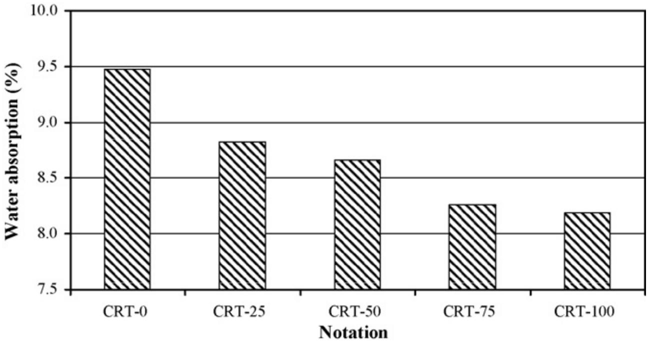

Fig. 4. Effect of CRT glass replacement on the water absorption of mortar.

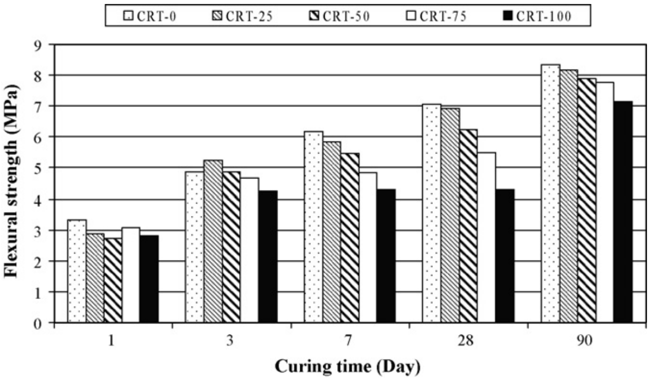

Fig. 5. Effect of CRT glass replacement on the flexural strength of mortar.

3.3. Water absorption

The results of water absorption of the mortar mixes are shown in Fig. 4. The water absorption was reduced by the inclusion of CRT glass as sand replacement in the mortar. This was due to the fact that glass by its nature is an impermeable material and therefore has a relatively thinner water layer covering its surface than that of sand in the wet state. Once hardened, the control mortar mix that had no CRT glass might contain more air voids, thereby permitting a larger amount of water to be absorbed when compared to the mortar specimens incorporating CRT glass, which is similar to the results reported in a previous study [15].

3.4. Flexural and equivalent compressive strengths

The 1, 3, 7, 28 and 90-day flexural and equivalent compressive strengths of the mortar mixes are shown in Figs. 5 and 6,

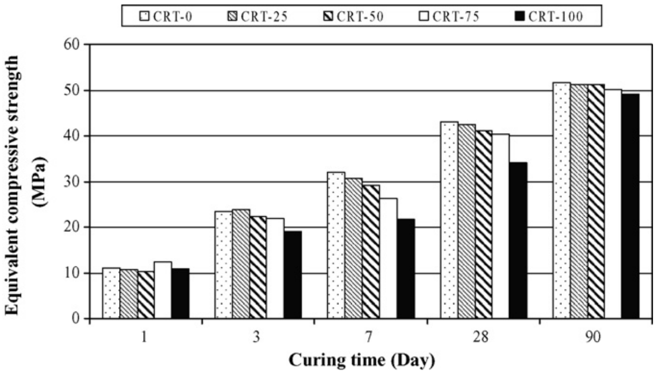

Fig. 6. Effect of CRT glass replacement on the equivalent compressive strength of mortar.

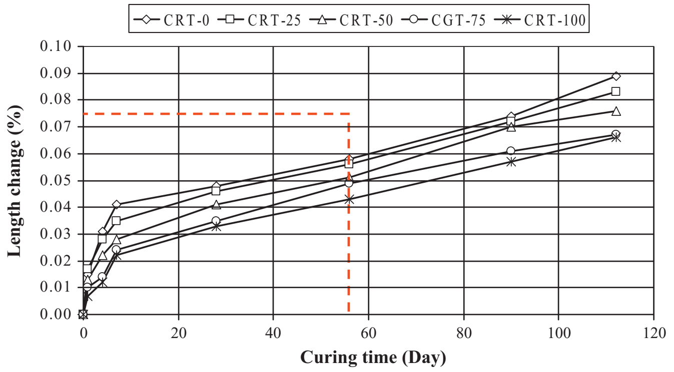

Fig. 7. Effect of CRT glass replacement on the dying shrinkage.

respectively. The results show a gradual reduction in strength with increasing CRT glass content. The mortar containing 100% CRT glass showed the lowest strength at all ages as compared to other mortar mixes. The decrease in strength was mainly attributed to the weaker bonding between the smooth surface of the CRT glass and the cement paste [16–18].

The effect of CRT glass content on the reduction of strength was more pronounced at 7 and 28 days. However, the relative reduction of strength due to the CRT glass was decreased when the curing age reached 90 days. At 90 days, CRT-100 achieved flexural and compressive strength values of 7.2 MPa and 49.1 MPa, respectively. This might be attributed to the pozzolanic reaction of the fine CRT glass particles in the hydrated cement paste contributing to the longer-term strength [19].

3.5. Drying shrinkage

Fig. 7 shows the length change (drying shrinkage) with time for all the mortar mixes. All the mortar mixes yielded approximately comparable length change values at the early age of 4 days. After 7 days, a clear distinction was observed between the mortar mixes prepared with different content of CRT glass. The 56-day drying shrinkage for all the mortar mixes was within the limit of 0.075 stipulated by the Australia standard. It was noticed that the mortar mixes with CRT glass had lower drying shrinkage than the control mortar mix. This beneficial effect was more pronounced with increasing replacement levels of CRT glass. The possible reason for this may be the lower absorption capacity of CRT glass than that of sand [20].

The results of length change as a function of moisture loss for all the mortar mixes are plotted in Fig. 8. The length change increased when the moisture loss in mortar increased. For a given shrinkage value, the higher the CRT glass content incorporated in the mortar mix, the greater the moisture loss observed. This may be due to the moisture not being fully utilized during the hydration of Portland cement. This observation is consistent with the results shown in Figs. 5 and 6.

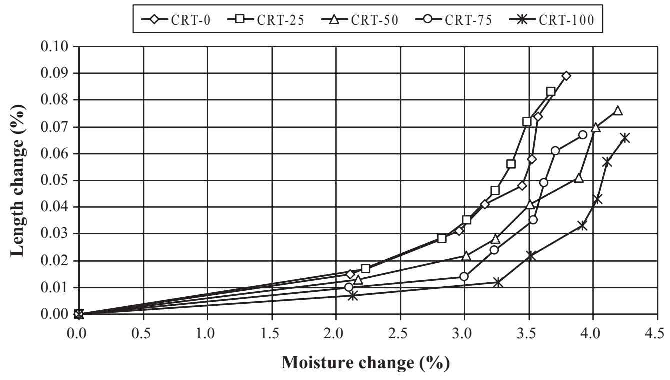

Fig. 8. Length change as a function of moisture loss in mortar under curing condition of 23 °C and 50% RH.

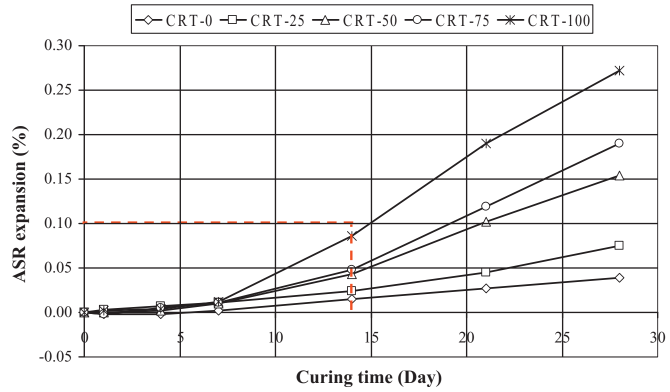

Fig. 9. Effect of CRT glass replacement on the ASR expansion.

3.6. Expansion due to the alkali-silica reaction

This test determined the ASR expansion of mortar bars, as an indication of potential reaction between amorphous silica in CRT glass aggregate and hydroxyl ions in cement. In this study, the accelerated mortar bar ASTM C1260 test method was adopted due to it required relatively smaller test specimens and could give a rapid and reliable result for slow and late expansive glass aggregates [21].

Fig. 9 shows the effect of CRT glass content on the ASR expansion of the mortar mixes. It was noted that the increase in CRT glass content led to an increase in ASR expansion. However, the expansions of all the mortar mixes were below 0.1% at 14 days, which could be rated as innocuous behaviour according to ASTM C1260. The expansion could be controlled within the permitted limit due to the use of fly ash in the mixes. This was due to the reduction in alkali hydroxide concentration in the pore solution through the pozzolanic reaction of fly ash. A similar observation has been reported by Byars et al. [22] and Schwarz et al. [23].

But longer term testing such as by using ASTM C227 (using a high alkali cement with curing conditions at 38 °C instead of immersion in 80 °C 1 N NaOH solution) may be necessary to ascertain the innocuous nature of the CRT glass in the mortar bars.

3.7. Lead leaching

The leaching behaviour of lead in cement mortar was measured by the toxicity characteristic leaching procedure (TCLP). The TCLP test results affirmed that the leaching of lead of all the tested (crushed mortar) samples was below the detection limit of 0.06 ppm. This value was lower than the TCLP results of the washed CRT funnel glass (Table 1) before it was incorporated in the cement mortar. Therefore, it can be concluded that the alkaline environment of the cement mortar was able to prevent heavy metal leaching [24,25]. The release of alkalis sourced principally from cement hydration had been proven to yield a pH value of 11–12 for retaining the heavy metals effectively, as indicated by previous studies [26,27].

In addition, the reduction could also be achieved by the combined mechanisms of physical (immobilizing) [28] and chemical reaction (complexing) [29] of the metal ion with the presence of fly ash. The former mechanism occurred because the use of fly ash improved the microstructure of the cement mortar, which in turn, induced additional physical impedance to the movement of ions within the cement matrix [30]. The latter mechanism occurred probably because of the formation of pozzolanic reaction products or lead silicate, which could limit the lead leaching process [31].

4. Conclusion

Based on the experimental results, the following conclusions can be drawn:

- Incorporating CRT glass increased the workability (flow table value) but reduced the water absorption and drying shrinkage values. These were mainly attributed to the lower water absorption capability of CRT glass than that of sand.
- The hardened density increased with increasing CRT glass content because of its higher specific gravity compared to that of sand.
- Inclusion of CRT glass in the mortar caused a reduction in both flexural and compressive strengths. The reduction was due to the loss of bonding strength between the smooth surface of CRT glass and cement paste.
- The increase in CRT glass content in mortar led to an increase in ASR expansion. But, all the mortar mixes showed innocuous behaviour with the use of 25% fly ash as an ASR mitigation agent.
- Incorporation of CRT glass in cement mortar successfully prevented the leaching of lead based on the TCLP test.

The overall test results of this study have demonstrated that it may be feasible to utilize CRT glass as fine aggregates in the production of cement mortar. However, further studies are needed to ascertain the complete safeness regarding the use of CRT glass in cement mortar before it can be introduced to the construction industry.

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