

A Review on Compressive Strength of Concrete Containing Waste Cathode Ray Tube Glass as Aggregates

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ABSTRACT: The issue of the cathode ray tube (CRT) technology facing its end-of-time and increasing quantities across the globe has acquired the responsiveness of many researchers. The use of waste CRT glass as a construction material has fascinated them due to its significant advantage in recycling the hazardous and non-biodegradable waste CRT glass. However, lack of knowledge about the effects and features of CRT glass as a construction material could be a hindrance to the excessive utilization of waste CRT glass. Therefore, in order to establish the idea of using CRT waste glass as a more common construction material, this paper reviews several recycling techniques of CRT glass and further detail on the workability, density, and compressive strength properties of concrete and mortar using CRT glass (treated or untreated) as fine aggregates. The review showed that, generally, the use of CRT glass as a complete or partial replacement of natural sand shows a slight increase in density, workability, and concrete strength compared to conventional concrete. However, there are no clear trends that can be concluded as this review also showed that various factors influenced its performance, such as percentage replacement, particle size, lead (Pb) content, and types of admixtures.

KEYWORDS: Cathode ray tube; waste glass; lead; concrete, strength

1. Introduction

Over the last few years, the amount of electronic waste (e-waste), especially CRT, has been on the rise and it has become an emerging concern in many developing countries. Through a global perspective review, the increasing amount of e-waste in the coming years is due to the rapid advances in information technology and the increase in market demand for electronic equipment [1–4]. Generally, CRT technology can be found in old television sets, computer monitors, video cameras, video game machines, automated teller machines, radar displays, and oscilloscopes. But, advances in electronic technology have led to the continuous replacement of CRTs by new technologies, such as Plasma Display Panels (PDPs) and Liquid Crystal Displays (LCDs) [5,6]. The replacement of CRT technology has caused an increase in CRT waste. In China in 2012, an estimated 74 million old TV sets and 190 million computer monitors were obsolete due to CRT technology, and the figures are expected to rise in the coming years [1]. The increment of CRT waste can also be seen in Thailand, as in 2004, 750 thousand tons of discarded CRTs were recorded, whilst in 2010, the amount increased to about 1.05 million [7]. Other than that, Rocchetti et al. [8] estimated that in Europe, about 50 thousand to 150 thousand tons of CRT waste are collected and then treated every year and that number

is expected to increase in the year ahead. Previous studies have shown that the amount of CRT waste has increased year by year and is expected to increase in the future. Yoshida et al. [2] claim that the highest generation of waste CRT technology is from the years 2015 to 2020. Meanwhile, Zhao et al. [9] expect a drastic increase in the amount of CRT disposed of in the year 2050, as it is expected to be 6 times higher than in 2013. The increasing amount of CRT's waste has become a world concern as the mismanagement of this waste can create a serious impact on the environment. It is because CRT glass consists of heavy metals, especially the high concentration of lead (Pb) metals [1,7,10]. According to Singh et al. [1], CRT is made of 85% glass that can be divided into three parts that are 65% of the glass is namely as panel glass, 30% as funnel glass and the remaining 5% is neck glass.

The neck part of the CRT contains the highest concentration of lead oxide (PbO), which is a maximum of 39% and a minimum level of 34%. Meanwhile, the funnel CRT glass contained PbO in amounts ranging from around 25% to 16%. The Pb metals contained in the funnel glass are used to protect the audience from the radioactivity of the electron gun, as the Pb metals help to eliminate X-ray radiation [11,12]. Thus, as the panel part of the CRT does not contain any electron guns, it explains the lower percentage of PbO at only 4%. Meng et al. [13] estimated that around 1.2 kg of Pb metal is distributed in one unit of the CRT monitor. On the other hand, it is found that inside the panel CRT glass, it contains a high concentration of barium oxide (BaO) and strontium oxide (SrO), about 7% to 11% and 9% to 17%, respectively. It is due to the panel glass, which must be colourless. Lead-silicate glass is a brown colored glass, while barium-strontium silicate glass is transparent under the exposure of X-ray radiation. The issue of the high content of hazardous metals, especially Pb, and the increasing amount of waste CRT glass has attracted attention from various parties.

Past studies considered the CRT glass as hazardous waste because it contains heavy metals (Pb, Ba, Sr, etc.) and the concentration of toxic elements in the leachate exceeds the allowable limit. Hence, it should not be disposed of in landfill sites without proper treatment as it has the potential to cause damage in the aspects of acidification, abiotic depletion, and global warming. Besides, it can also harm the human body. For that reason, the recycling of CRT waste glass is necessary since it helps preserve natural resources, reduces the use of landfill space, prevents environmental pollution and harm to the human body [5,6,14]. However, most of the CRT waste glass could not be recycled into new glass because of the different chemical compositions, impurities, mixed colors, and high costs that very much affect the quality of the new product [15]. Hence, one of the objectives of this paper is to identify the alternative recycling techniques recommended by past studies for effectively managing waste CRT glass. Literature shows that one of the most effective ways is to crush the waste CRT glass and use it as fine aggregate in mortar or concrete production, as it can prevent the immobilization of heavy metals (Pb, Sr, Ba, etc.) in the surroundings. Further, the foremost objective is to review the effects of using CRT glass as a complete or partial replacement of natural sand on the properties of mortar and concrete in the aspects of workability, density, and compressive strength.

2. Recycling techniques

The hazardous waste CRT glass should not be directly sent to the disposal areas before being given proper treatment. According to Yoshida et al. [2], in the Philippines, only one facility was provided for processing the CRT waste. Meanwhile, in Indonesia and Vietnam, the CRT

waste was wrongly disposed of together with the municipal solid waste. Compared to the recycling methods in Japan, the CRT unit is detached from any other components manually, so the exposed CRT is able to ventilate to remove the vacuum. After that, it is sold to the glass factory [2]. As shown in Table 1, various past studies have been conducted to determine the techniques for recycling waste CRT glass. There are eight different recycling techniques, most of which aim to remove the lead (Pb) elements from the CRT glass. The presence of lead (Pb) metals in the inner glass of CRTs impedes recycling of this waste. The Pb metals that have been extracted from the CRT glass either through lead smelting, mechanical activation, chloride volatilization process, or etc., can be used as the raw material for crystal products and fluorescent tubes, which offer an improvement in the properties of the product and save a lot of Pb resources. Meanwhile, the CRT glass that is freed from Pb metals can be used to make high-grade products such as glass foams, beads, containers, and glass windows [16,17].

A review of past studies also claimed that CRT glass, both treated (lead-free) and untreated, has the potential to be used as fine aggregate in the production of mortar and concrete [10,18–22]. The presence of lead (Pb) in untreated CRT glass is very effective in acting as a shielding material for X-rays and gamma rays. Ling et al. [11] have crushed the CRT funnel glass (treated and untreated) to a size less than 2.36 mm for use as fine aggregate in mortar, with the aim of shielding the surroundings from X-ray radiation. The results show the ability of hardened mortar with CRT glass aggregate as radiation-shielding since it can withstand the high-level of X-ray energy [23]. similar to the research conducted by Ismail et al. [24] that used Pb metals in concrete production as shielding materials for X-rays and gamma rays. Besides, several studies have proven that CRT waste glass that was crushed to a specific size is an effective replacement material for natural sand in either mortar or concrete production [18-28].

Table 1. Recycling techniques of waste CRT glass.

Recycling technique	Description	References
Smelting process	Extracting Pb elements	[16,29,30]
Crushing to certain size below 5 mm	Replacing natural sand in production of mortar and concrete	[7,11,22,27,31]
Self-propagating process	Produce a lead-free product by removing the Pb element	[32]
Mechanical activation	Extracting Pb element	[16,17,33]
Washed with nitric acid	Pb removal and then use as fine aggregate in concrete and mortar production	[9,21,23,31,34]
Thermal reduction with metallic iron	Extracting Pb element	[16,35]
Chloride volatilization process & acid-leaching process	Extracting Pb element	[36,37]
Alkaline leaching (S and NaS)	Extraction the Si and Pb elements	[38]

3. Properties of concrete and mortar with CRT glass

Recycling of CRT waste glass in mortar and concrete as fine aggregates has been examined by many scholars and has been determined as an effective way of preventing the immobilization of heavy metals in the environment. Therefore, the following paragraphs review the effects of using CRT glass as fine aggregates on the performance of mortar and concrete, in terms of workability, density, and compressive strength compared to the specimens with natural aggregates.

3.1. Usability

The workability aspect is indicated by the state of the concrete or mortar mixture, whether it is easy or hard to mix, handle, and compact. It can be assessed by measuring the slump or flow values of fresh concrete [39]. The results of past studies reveal that the workability of the mixture containing CRT glass as fine aggregates is influenced by various factors which are the level of replacement, particle sizes, shapes, and types of admixtures, as tabulated in Table 2.

Table 2. The effect of using CRT glass as fine aggregates on the workability aspect

Year	Types	Size	Content (%)	Increase of workability	Finding	Reference
2011	Panel and treated funnel	0.15 to 2.36 mm	25, 50, 75, 100	Yes	Flow values increase as increasing glass content	[19]
2012	Panel	0.15 to 0.50 mm	20, 40	No	Slump flow decreased as increasing glass content	[10]
2012	Treated and untreated funnel	0.15 to 4.75 mm	50, 100	Yes	Mixture with CRT glass has flow value higher than with beverage glass	[21]
2013	Panel and funnel	0.08 to 5 mm	10, 20, 30	No	Slump value decreased as increasing content of glass	[24]
2013	Treated funnel	600 μ m, 1.18, 2.36, 5.00 mm	100	Yes	Fluidity reduced as decreasing of glass particle size	[40]
2013	Treated funnel	0.15 to 2.36 mm	25, 50, 75	Yes	Reduced segregation and bleeding, mixture more consistent and homogenous	[9]
2013	Funnel	0.15 to 0.75 mm	20, 40	No	Addition of limestone powder can increase workability	[7]
2013	Panel	Less than 500 μ m	5,10, 20	No	Addition of SP can increase workability	[28]
2013	Funnel	0.15 to 4.75 mm	25, 50, 75	Yes	Sample using FA as mineral admixture has higher slump than GGBFS	[27]
2017	Treated and untreated funnel	0.15 to 4.75 mm	25, 50, 75	Yes	Lead (Pb) content decrease the slump flow	[41]
2019	Funnel	0.15 to 4.75 mm	5, 15, 25	No	Angularity, sharp and unrounded edges of CRT glass after crushing process generates high friction	[31]
2020	Treated funnel	1.18 mm	25, 50, 75, 100	No	Slump value decreased with increasing replacement rate	[42]

Several past studies claimed that the increasing replacement level of CRT glass as a fine aggregate led to an increase in slump values of concrete or mortar. Ling and Poon [19] claimed that the increasing replacement level of CRT glass would increase the flow values. By maintaining a constant water-cement (w/c) ratio of 0.45, the flow values increased (120 mm to 190 mm) with the increasing replacement level of CRT glass (0% to 100%). A year later, Ling and Poon [21] again indicated that the increase in glass content would increase the flow values. A similar observation was recorded in the next year by Zhao et al. [9,27]. Results [27] show that the loss rate of slump flow for 25% replacement was higher than 75% replacement, at 33.33%, and 7.95% replacement, respectively. While the authors [9] noticed the concrete specimens containing 25%, 50%, and 70% CRT glass sand obtained a much higher slump value

of 85 mm, 120 mm, and 135 mm, respectively, than control specimens of 40 mm. They [9,21] [19,27] suggest that the improvement in workability of the mixture with the increasing content of CRT glass is because the glass has a smooth surface and lower water absorption compared to sand. However, Sua-iam and Makul [10] observed a decreasing slump value with an increasing replacement level of CRT glass. Similar findings were obtained in the research done by Romero et al. [20], Maschio et al. [28], and Sua-iam and Makul [7]. According to them, the reduction may be caused by the angular or irregular particle shape of crushed CRT glass. It creates a stronger bonding between the aggregates and cement particles, which leads to a lower fluidity of the mixture and increases the water demand for obtaining a workable mixture. It can be seen from the results obtained by Sua-iam and Makul [7,10], where the slump flow values decrease with the increasing replacement of natural sand with CRT glass at 20% and 40% levels. It is shown that the slump flow of the SCC control specimen was 350 mm, while the flow values of SCC specimens containing 20% and 40% CRT glass were 340 mm and 330 mm, respectively. Besides that, Maschio et al. [28] reported that even in the case of lower replacement levels, at only 10% and 20%, the workability of the CRT glass mortar mixture is much lower than the control specimens.

Since 1998, it has been recognized that the reduction of aggregate size can significantly increase the water demand for obtaining good workability [39]. It had been confirmed by the research made by Sua-iam and Makul [7,10] and Maschio et al. [28]. They claimed that using CRT glass with a particle size between 0.15 to 0.75 mm and a size less than 500 μ m, replacing the river sand at a size less than 5 mm shows a reduction in slump value. Besides that, Ling and Poon [40] examined the effect of different glass particle sizes on the fluidity of mortar mixtures. The fluidity of the mortar mixtures gradually increases with the size of the glass particles. Therefore, mortar specimens containing 100% CRT glass with a size of less than 600 μ m have the lowest fluidity compared to other sizes of 1.18 mm, 2.36 mm, and 5 mm. The authors [40] state that the finer particle size has a larger surface area compared to coarser glass, causing more water to be required to envelop the solid particles. According to the research conducted by Ling and Poon [21], Zhao et al. [27], and Zhao and Poon [41], they observed that the higher fineness modulus of CRT glass aggregates yields a mixture with good workability. In addition, they crushed and sieved the CRT glass to a size range between 0.15 to 4.75 mm, and their size distribution is approximately the same as river sand. Then it showed that the mixture with CRT glass as a fine aggregate has a higher slump value compared to the mixture with natural aggregates. It may be due to the glass properties that it has a smooth surface and very low water absorption. Furthermore, it is to be noted from the study conducted by Zhao et al. [9] that the inclusion of CRT glass with a size between 0.15 mm and 2.36 mm reduces the impacts of segregation and bleeding of the concrete specimens. These have resulted in the improvement of the consistency and homogeneity of the concrete specimens.

The type of mineral admixtures used can also affect the workability of the mixture. According to Sua-iam and Makul [7], adding limestone powder can significantly improve workability by increasing the flowability and viscosity of SCC mixtures. This is because of the properties of limestone powder that has a finer particle size and spherical shape, resulting in improved particle packing. Meanwhile, Zhao et al. [27] observed that the addition of fly ash (FA) in mortar specimens containing CRT glass has shown a greater slump flow diameter than the specimens with ground granulated blast furnace slag (GGBFS) as the mineral admixture. It could be attributed to the spherical shape of FA, causing a reduction in friction between the

aggregate and cement paste interface [39]. Besides that, the use of superplasticizer (SP) as the water reducer agent also showed an increase in workability. As recommended by Maschio et al. [28], the addition of SP is advantageous to the rheological behavior and residual porosity of mortar specimens. Other than that, a recent study by Zhao and Poon [41] indicated that the use of untreated CRT funnel glass, which contains lead (Pb) metals, can retard the hydration process as the mortar samples containing untreated crushed CRT funnel glass have lower slump loss rates than those with treated (lead-free) CRT glass. It was observed at the same replacement level of 50% and 75%, as the loss rates of slump flow for the mortar specimens with the untreated funnel and the treated funnel were 7.95%, 18.31%, and 10.98%, 22.08%, respectively.

3.2. Density

Past studies stated that the use of CRT glass as fine aggregates had increased the density of hardened mortar and concrete. It is because the CRT glass has a higher density than natural aggregates, specifically river sand. Regardless of the Pb content of the CRT glass, Ling and Poon [40,43,44], Romero et al. [20], Zhao et al. [9], and Zhao and Poon [41] found that the density of CRT glass is between 2.98 and 3.10 g/cm³, while river sand is between 2.49 and 2.62 g/cm³. Thus, the increasing content of CRT glass as fine aggregate causes a higher density of hardened mortar or concrete. Romero et al. [20] claimed that the density increased directly with the increase in percentage replacement. Zhao et al. [9] reported the increased density of hardened concrete at levels of 25% (2941 kg/m³), 50% (2967 kg/m³), and 75% was 2992 kg/m³, which showed an increase of 0.93%, 1.82%, and 2.68%, respectively. Besides that, a complete replacement (100%) of sand with CRT glass has shown an increase in density of about 11% compared to control samples, as recorded by Ling and Poon [40].

Heavyweight concrete is desirable in other types of applications, such as radiation shielding [11,43,45,46]. However, this has become a discouraging factor in some applications as it causes an additional dead weight in building construction [6]. There are some studies that have been conducted that show that the density of hardened concrete and mortar containing CRT glass can be reduced by decreasing the glass particle size. Ling and Poon [40] pointed out that the milling of treated funnel glass, which undergoes an acid-treatment process into a finer size, can reduce its density as the higher amounts of Pb elements can be eliminated. Therefore, it is clearly shown that the high density of CRT glass can also be related to the content of Pb metals, mainly in the funnel part of CRT glass. Ling et al. [11] did a study on the significant effect of Pb elements in the CRT funnel glass on the mortar density. It was observed that the density increased with the presence of Pb in the mortar. The density of mortar specimens containing 100% untreated funnel glass and another specimen containing 100% treated funnel glass (lead-free), both as fine aggregates, shows an increased density of about 14.6% and 11.2%, respectively. It shows that the removal of lead (treated funnel) lowers the density of the mortar. A year later, Ling and Poon [40] reported a similar observation, claiming that the higher the presence of lead metals in CRT glass, the higher the mortar density goes with the concrete specimens containing panels of CRT glass. As a result of the lower amount of lead (panel CRT glass) compared to funnel CRT glass, the density of hardened concrete panel glass was less than funnel glass, which was about 2790 kg/m³ and 3000 kg/m³, respectively [26]. According to previous research, the relative density of untreated funnel CRT glass (containing Pb) ranges between 3.00 and 3.10 g/cm³, whereas treated funnel CRT glass is 2.99 g/cm³ [26,40,41,45].

3.3. Compressive strength

The compressive strength of hardened mortar and concrete is the essential mechanical aspect compared to others. Past studies claimed that replacing the natural sand with CRT glass had increased the compressive strength compared to control specimens [20,27,41,47,48]. On the other hand, there are also some studies reporting differing results [22,40-44,49]. Besides depending on the mix design, several researchers indicated there are several parameters such as replacement level, particle size, lead content, etc. that can affect the compressive strength of hardened mortar and concrete. Table 3 shows a summary of past studies on the effect of using CRT glass as a fine aggregate on the aspect of compressive strength of concrete and mortar.

Table 3. The effect of using CRT glass as fine aggregates on the aspect of compressive strength

Year	Types	Size	Content (%)	Increase of compressive strength	Finding	Reference
2012	Treated and untreated funnel	0.15 to 2.36 mm	25, 50, 75, 100	No	Presence of lead (Pb) in the glass does not give any significant impact on strength	[11]
2012	Treated and untreated funnel	0.15 to 4.75 mm	25, 50, 75, 100	No	Presence of lead (Pb) in the glass does not give any significant impact on strength	[44]
2013	Treated funnel	1.18 mm and 600 μ m	100	No	Strength of CRT glass mortars was comparable to beverage glass mortars	[40]
2013	Panel and funnel	0.08 mm to 5.00 mm	10, 20, 30	Yes	Strength increases as increase of the replacement level	[20]
2013	Funnel	0.15 to 4.75 mm	25, 50, 75	Yes	Addition of GGBFS gives higher strength than FA	[27]
2013	Funnel	0.15 to 0.75 mm	20, 40	No	Addition of limestone powder increased strength	[7]
2013	Panel	Less than 500 μ m	5,10, 20	Yes	Rapid increase of strength with addition of 1% SP	[28]
2014	Treated and untreated funnel	0.15 to 4.75 mm	50, 100	No	Presence of lead (Pb) in the glass does not give any significant impact on strength	[43]
2014	Treated funnel	0.15 to 4.75 mm	50, 100	No	Strength reduces with increase of replacement level	[22]
2015	Panel	80 μ m	80, 100	Yes	Increase strength by using smaller glass particle size and addition of fly ash	[47]
2017	Funnel	0.15 to 4.75 mm	100	No	Addition of incinerated sewerage sludge ash (ISSA) have decreased the strength compared to GGBFS and FA	[49]
2017	Treated and untreated funnel	0.15 to 4.75 mm	25, 50, 75	Yes	Strength increases as increase of replacement level and presence of Pb	[41]
2019	Funnel	0.15 to 4.75 mm	5, 15, 25	No	Strength decreases due to weaker interfacial transition zone	[31]
2020	Funnel	0.15 to 4.75 mm	5, 10, 15, 20	Yes	Strength increases with increase of replacement level	[48]
2020	Treated funnel	1.18 mm	25, 50, 75, 100	No	Addition of silica fume increased strength	[42]
2021	Funnel	0.15 to 4.75 mm	50, 100	No	Strength decreases with increase of replacement level	[46]

3.3.1. *Effect of replacement level of CRT glass*

The compressive strength of either concrete or mortar is affected by the amount of CRT glass replacing the natural sand. In 2012, the research done by Ling et al. [11] and Ling and Poon [44] showed that the compressive strength reduced with the increasing replacement level of CRT glass as fine aggregates, at 25%, 50%, 75%, and 100% by volume of sand. They [11,31,44,46] suggested that the decrease in mortar strength is because of the increase in weak points. The physical features of CRT glass that have a smooth and plane surface have created a weak point within the glass as aggregate and cement paste. The same findings were also reported by other researchers [50–53] using different types of glass (window, beverage, container glass, etc.). A year later, Zhao et al. [9] also reported similar findings as the reduction rates of 25%, 50%, and 75% of funnel glass as a fine aggregate were 11.38%, 18.19%, and 22.65%, respectively.

The SEM observation made by Ling and Poon [22] in 2014 supported the cause of strength reduction due to the glass smooth surface. The microstructure of the crushed specimen containing CRT glass reveals that the bonding between the glass aggregates and cement paste is weak compared to specimens using natural sand, which has a rougher surface than glass [42]. Besides, Ling and Poon [22] reported a decrease in the compressive strength with the increasing replacement level of CRT glass, as the replacement levels of 50% and 100% have lower strengths than normal concrete, 68.3 MPa, 55.6 MPa, and 68.6 MPa, respectively. The reduction of compressive strength can be overcome by using an optimum ratio of aggregate to cement and adopting a correct method of casting [43].

However, there are also some studies that indicate that the replacement of natural sand with CRT glass has increased the compressive strength of hardened mortar and concrete, as well as the replacement level is directly proportional to the compressive strength [20,27]. Romero et al. [20] assured that the fine aggregate replacement by crushed CRT glass has met and exceeded the compressive strength of control specimens, by 5.5%, 19.5%, and 13.2% at the level of 10%, 20%, and 30% replacement, respectively. The highest compressive strength is obtained at 20% replacement. Meanwhile, for the higher percentage replacement of 25%, 50% and 75%, Zhao et al. [27] reported the enhancement of compressive strength for each of the replacement levels. In addition, a recent study that had been conducted by Zhao and Poon [41] also claimed the same findings.

3.3.2. *Effect of particle size on the particle size of CRT glass*

The compressive strength of mortar and concrete using CRT glass as aggregate is greatly influenced by the glass particle size. Maschio et al. [28] replaced 10% of the river sand size less than 4.75 mm with CRT glass milled to less than 500 m in 2013. The compressive strength of hardened mortar improved from 45 MPa after 3 days of curing to 60 MPa after 7 days, 83 MPa after 28 days, 100 MPa after 90 days, and 105 MPa after 180 days compared to control specimens of 50 MPa, 66 MPa, 87 MPa, 97 MPa, and 100 MPa, respectively. Therefore, they [28] claim that the use of smaller sizes of CRT glass in replacing the natural aggregates can increase the compressive strength. In the next 2 years, a similar finding was also recorded by Walczak et al. [47]. They [47] examined the compressive strength of mortar containing CRT glass cullet that was crushed to a size around 80 μm with a Blaine fineness of 2000 cm^2/g . The results indicated an increase in compressive strength of 16% compared to control samples. The

improvement in compressive strength might be because of the pozzolanic activity that may develop from the use of CRT glass that was ground or crushed to a few tenths of a micrometres or powder and also might be due to the high concentration of silica in the CRT glass [7,22,28,47].

According to the SEM observation done by Maschio et al. [28], there is the presence of silicate hydrated crystal clusters on the mortar samples which contain CRT glass with a size less than 75 μm . Thus, it indicates that the use of specific sizes of CRT glass that are less than 75 μm possesses a pozzolanic reaction, as the silicate hydrated crystal clusters are developed only around the finer glass particles. The pores that exist in the cement and glass aggregate matrix may be occupied by the silicate hydrated crystals during the curing period, which then interlocks the surrounding material, resulting in densely packed structures and a higher compressive strength [28]. In addition, they [28] also observed that at the interface of glass particles and the cementitious matrix is explicit with no pores. The findings were also consistent with the previous studies that used different types of waste glass as fine aggregates, such as fluorescent lamps, containers, beads, and bottles of glass [54–56]. Shao et al. [54] and Raju and Kumar [57] pointed out that by crushing the glass to a size smaller than 38 μm and 45 μm , respectively, is an excellent filler with high pozzolanic reactivity which has the potential to replace a portion of the cement content.

However, there are also studies reporting that using a larger size of CRT glass as a fine aggregate can increase the compressive strength. They [40] recommend that the use of a larger particle size of CRT glass will provide a wider continuous particle size distribution in the mortar, resulting in better particle packing that improves the compressive strength. Ling and Poon [40] studied the effects of several particle sizes of CRT glass on the aspect of compressive strength. They [40] observed the increase of glass size from 600 μm to 1.18 mm, 2.36 mm, and 5 mm, showing a higher increment of compressive strength around 2.5%, 10.8% and 30.8%, respectively.

3.3.3. Effect of admixture and lead content

As widely reported previously, the addition of mineral admixtures in concrete and mortar mixtures may increase the compressive strength. In 2013, Zhao et al. [27] aimed to increase the compressive strength of hardened mortar using CRT funnel glass as a fine aggregate by replacing 25% of the OPC with FA and GGBFS. The results show that the compressive strength of mortar specimens with the addition of GGBFS is higher by 23% than mortar specimens with FA at the curing period of 28 days. But, Taha and Nounu [58] claim that the addition of 10% metakaolin (MK) is more useful in increasing the compressive strength of glass concrete compared to the specimens that used 60% GGBFS and 20% glass powder. However, in 2015, Walczak et al. [47] claimed that the mortar specimens with a 100% replacement of natural sand with 20% FA and the remaining 80% replaced by crushed CRT glass, had shown a higher compressive strength than control specimens. The improvement of compressive strength ensued as a result of the pozzolanic activity, filler role and speeding up of the cement hydration process. Other than that, a recent study by Li et al. [49] reported that the use of incinerated sewerage sludge ash (ISSA) in mortar mixtures containing CRT glass has decreased the compressive strength with the increasing content of ISSA. The contrasted findings may be due to the properties of ISSA that cannot counterbalance the low pozzolanic activity, thus leading to lower compressive strength compared to samples using FA and GGBFS as admixtures.

Sua-iam and Makul [7] investigate the influence of adding 5%, 10%, and 15% of limestone powder to the compressive strength of self-compacting concrete (SCC) mixtures with CRT glass (20% and 40%) as fine aggregate. The optimum SCC mixtures were recorded on the specimens with 5% limestone powder and 20% CRT glass, which showed the highest compressive strength among others, especially control specimens. The addition of fine limestone improves particle packing by broadening the grain-size distribution. Through the SEM observation on the fracture surface of the SCC specimens, Sua-iam and Makul [7] observed that crushed CRT glass was surrounded by limestone powder gel. They suggest that the limestone powder gel prevents the edges of glass from colliding with each other, which then causes the improvement of compressive strength. Meanwhile, Maschio et al. [28] reported that the adding of water reducers at levels of 1% and 2% of cement content to the mortar mixtures containing CRT glass has shown enhancement of compressive strength at every curing age of 3, 7, 28, 90, and 180 days. The use of water reducing agents allows for a lower w/c ratio, which improves the compressive strength of hardened mortar and concrete [28,39-43,59].

3.3.4. *Effect of treated or untreated CRT glass*

Some studies reported that there was no significant effect of the lead (Pb) content of the CRT glass on the aspect of compressive strength. The results from the studies conducted by Ling et al. [11] and Ling and Poon [43,44] reported that there was not much difference in compressive strength between mixtures containing untreated and treated CRT funnel glass, depending on whether the funnel glass was acid washed or unwashed. However, a recent study conducted by Zhao and Poon [41] claimed that the presence and increasing content of lead (Pb) in mortar results in higher compressive strength than lead-free mortar. Based on their [41] results, the mortar mixtures containing untreated CRT funnel glass (unwashed) at replacement levels of 25%, 50%, and 75% show a higher increase in compressive strength of 8.17%, 9.53%, and 10.08%, in comparison to the treated CRT funnel glass that has been washed with nitric acid.

4. Conclusions

Extensive past research has identified several recycling techniques for managing the increasing amount of waste CRT glass, and based on the review of past studies, the present study discovers that the difference in chemical composition, physical, and mechanical features of CRT glass as fine aggregates are affecting the properties of concrete or mortar. Several conclusions from the review of past studies are listed below:

- i. The physical properties of glass that have a smooth surface, are impermeable and have lower water absorption than river sand have increased the workability of the mixture.
- ii. However, some researchers also reported a reduction in workability due to the decreasing particle size, irregular particle shape, and presence of Pb metals in the CRT glass.
- iii. CRT glass has a higher relative density than river sand, which is in the range between 2.99 to 3.10 g/cm³ and 2.49 to 2.62 g/cm³, respectively. Thus, most of the past studies reported the increase of mortar and concrete density. One of the contributors is the lead (Pb) content in the CRT glass.

- iv. The majority of the researchers claimed that the physical feature of glass with a smooth surface caused the connection between aggregate and cement to become weak, resulting in a reduction of compressive strength.
- v. Some researchers reported that crushing the glass to a few tenths of a micrometers or powder can increase the strength as it shows pozzolanic activity since the CRT glass contains a high concentration of silica (Si) elements. But some researchers said otherwise. The use of a larger glass particle size offers better particle packing.
- vi. It is worth mentioning here that there is more than one parameter that can contribute to a better performance of concrete and mortar using CRT glass as fine aggregates, which are the percentage replacement, particle size, Pb content, types of admixtures and method of casting.

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Conflicts of Interest

The authors declare no conflict of interest.

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