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Review Article

Cathode Ray Tube Glass as an Aggregate: A Step Towards Greener Concrete

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ABSTRACT

The use of Cathode Ray Tube (CRT) glass as an aggregate in concrete is a promising approach for sustainable construction. The CRT technology, once innovative, is now obsolete, leading to the accumulation of millions of CR tubes globally, posing disposal challenges due to their toxic composition. The CRT glass, consisting mainly of silica along with various oxides and heavy metals, holds potential for recycling and reuse applications. Recycling methods for CRT glass, including closed-loop and open-loop recycling, offer avenues to mitigate waste and conserve resources. Integrating CRT glass into concrete improves mechanical properties and durability. Although replacing natural sand with CRT glass may slightly reduce compressive strength, innovative mix designs offset this effect. Concrete with CRT glass exhibits resistance to environmental factors, making it suitable for diverse construction applications. Addressing environmental concerns related to CRT glass disposal requires efficient recycling technologies and stringent regulations. Overall, integrating CRT glass into concrete presents a sustainable solution to mitigate environmental impacts while enhancing concrete performance.

Keywords: CRT glass; Concrete; Recycling methods; Environmental impact; Sustainable development.

1. INTRODUCTION

Cathode ray tube (CRT) - the display component of an electronic device has almost lost its importance in the present high-tech era. It is rarely being used and has become a thing of past now. The piling up of millions and millions of CRTs around the globe has made its disposal a matter of concern for its toxic chemical nature. It is composed of three main parts: 65% front panel, 30% funnel glass, and 5% neck glass (Ciftci and Cicek, 2017) (Fig.1). Frontal Panel Glass, the outermost glass layer on which the image is formed has the lowest lead oxide content (2–3%) (Ciftci and Cicek, 2017), phosphorus (14–22%), small quantities of cadmium and zinc but appreciable amount of barium oxide (Tsydenova and Bengtsson, 2011). Panel glass is manufactured only of barium–strontium glass with least quantity of lead (Pant and Singh, 2013). Funnel glass inclusive of thin metal sheet layer behind the front panel (shadow mask) contains 22–30% lead, depending on the CRT type, the manufacturer and varies between 1.5–3.0 kg by weight (Zeng *et al*. 2017). It directs the rays coming from the electron gun to the front panel. The glass in the funnel is of very high quality (contaminant and defect-free) made from chemically or thermally tempered glass to reduce the weight of CRT. This peculiar glass production technique known as *melt* expends mostly on the energy used to melt the raw materials. Frit solder ties together lead glass and panel glass, and contains about 80% lead and has a low melting point (Nnorom *et al.* 2011). Lead in CRTs is found in the funnel and neck components, and concentrated in the neck glass (Pant and Singh, 2013). The role of lead is absorbing UV and X-ray radiation produced by the CRT (Pant *et al.* 2012).

The chemical composition of CRT glass varies from manufacturer to manufacturer and to some extent also according to the type of CRT as depicted in Table 1. No big differences in the chemical composition between the monochromatic and color CRTs is recorded. Silica (SiO_2) forms the highest percentage across all the components in both CRTs. In both types, the panel glass contains little lead. In addition to smaller amounts of other oxides and heavy metals, panel and funnel glass include barium oxide, whereas neck glass of both monochrome and color CRT and funnel glass in color CRT contains lead oxide (Shi *et al*. 2011). Given the overall composition of the CRT, the main concern is the presence of lead as it has toxic and adverse health and environmental effects if not handled properly (Garlapati, 2016).

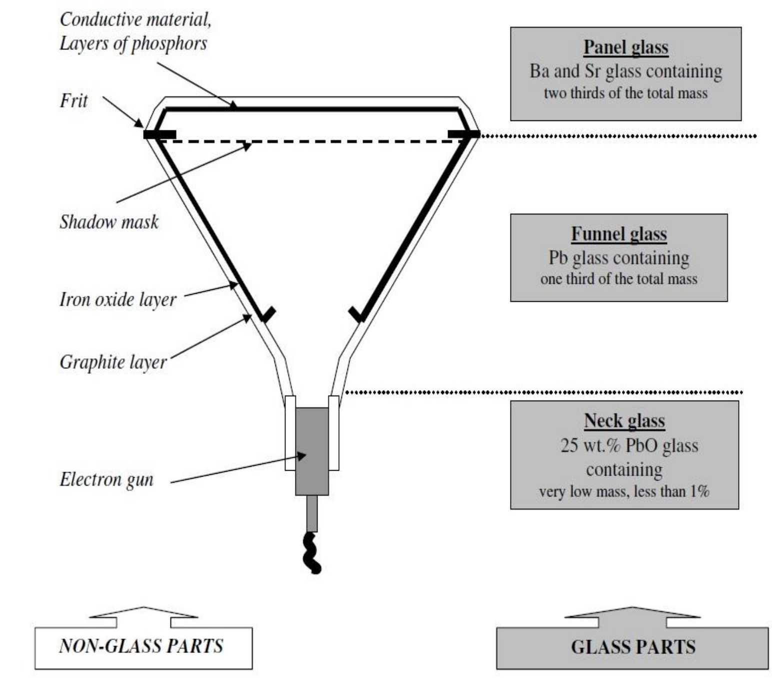

Fig. 1: Illustration of a CRT (Méar *et al.* 2006)

Table 1. Chemical content (%) of monochrome and color CRT glasses (Andreola *et al.* 2005)

Oxide	Black & White CRT Glasses		Color CRT Glasses	
	Panel Glass	Funnel Glass	Panel Glass	Funnel Glass
SiO_2	66.05	65.49	61.23	56.72
Al_2O_3	4.36	4.38	2.56	3.42
Na_2O	7.63	7.05	8.27	6.99
K_2O	6.65	5.72	5.56	5.37
CaO	0.00	0.00	1.13	3.12
MgO	0.01	0.00	0.76	2.02
BaO	11.38	11.20	10.03	4.03
SrO	0.99	0.94	8.84	1.99
Fe_2O_3	0.44	0.44	0.10	0.11
CoO	0.01	0.01	0.02	0.00
TiO_2	0.13	0.03	0.35	0.19
ZrO_2	0.07	0.01	0.91	0.24
ZnO	0.00	0.00	0.18	0.22
PbO	0.03	0.00	0.02	15.58
NiO	0.04	0.03	0.03	0.02
P_2O_5	0.00	0.00	0.00	0.00
Others	1.96	3.56	-	-
Total	100	100	100	100

2. ENVIRONMENTAL CONCERNS RELATED TO CATHODE RAY TUBE GLASS DISPOSAL

The disposal of CRT glass presents significant environmental challenges primarily due to its high lead content. The CRT monitors can contain between 0.5 kg and 2.9 kg of lead, mainly found in the leaded glass of their funnel portion, comprising 22% to 25% lead by weight (Xu *et al*. 2012; Karagiannidis *et al*. 2005). Lead is known for its toxic effects on the nervous system, kidneys, and reproductive organs (Wei *et al*. 2020), with children being particularly vulnerable to developmental and cognitive impairments (Lee and Hsi, 2002). Improper disposal, such as landfilling, might result in leaching of lead into the soil and groundwater, posing risks to both the environment and human health. Wildlife can also suffer adverse effects from lead contamination, disrupting ecosystems. Moreover, CRTs are classified as hazardous waste due to their lead content, subject to strict regulations under frameworks like the Resource Conservation and Recovery Act in the United States (Herat, 2016). The global trade of CRTs further compounds environmental issues, exacerbated by inadequate recycling policies and implementation processes, particularly in certain regions (Xu *et al*. 2013). To address these environmental and legal concerns, a comprehensive strategic action plan is required. This would envisage the development of efficient recycling technologies, implementation of stringent disposal regulations, and foster international collaboration to mitigate the environmental impact of CRT glass disposal.

3. RECYCLING OF CRT GLASS

Recycling of CRT glass is challenging due to the toxic substances present in it. Safe extraction and handling of CRT requires specialized techniques. Limited recycling infrastructure further complicates the recycling process, leading to stockpiling or landfilling of CRT glass in some regions (Grdić *et al.* 2022). Cathode ray tube glass recycling methods can be categorized into two types: closed-loop recycling, where old CRT glass is transformed into new CRT glass, and open-loop recycling, where CRT glass is used as a raw material to make various products (Iniaghe and Adie, 2015; Mostaghel and Samuelsson, 2010). These methods complement each other by creating synergies that promote sustainable resource management and waste reduction strategies (Fig.2).

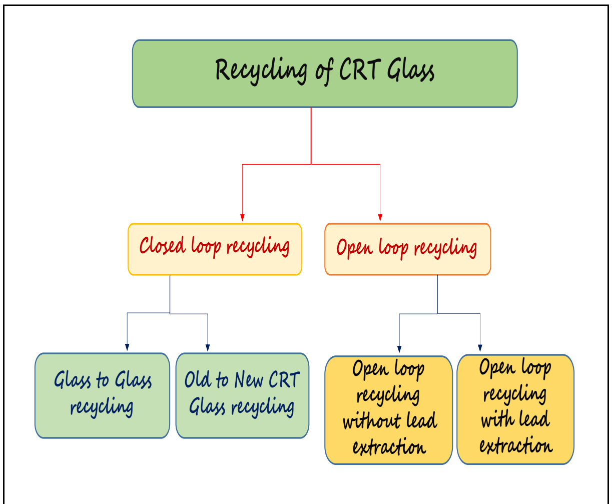

Fig 2: Flow chart showing different methods of CRT Glass recycling

3.1 Closed-loop Recycling

Closed-loop recycling of CRT glass involves a process where the glass is recycled within the same production cycle, minimizing waste and preserving resources (Herat, 2008). This method typically includes two primary approaches: Glass-to-Glass Recycling and Old CRT Glass to New CRT Glass.

3.1.1 Glass-to-Glass Recycling

Old CRT glass is recycled into new CRT glass, ensuring a closed loop where the material is reused for the same purpose (Qi *et al.* 2019).

3.1.2 Old CRT Glass to New CRT Glass

This method involves directly converting old CRT glass into new CRT glass, maintaining the integrity of the material and reducing the need for virgin resources (Ciftci and Cicek, 2017).

The closed-loop recycling process offers several benefits compared to producing CRT with new raw materials, which include material and energy conservation and reduced contamination (Ciftci and Cicek, 2017). Closed-loop recycling, once considered as sustainable disposal process, has however, now become outdated because of technology advancements (emerging open-loop methods) (Singh *et al.* 2016), decreased consumer demand for recycled degraded materials and environmental concerns.

3.2 Open-loop Recycling

Open-loop recycling entails utilizing waste CRT glass for the production of various materials or products, rather than reintroducing it into the original production process (Xu *et al.* 2012). Two distinct approaches based on the treatment of lead content in CRT glass are employed. First approach utilises specialized techniques for safe and effective extraction and handling of lead during the recycling process (Qi *et al.* 2019), while the second approach does not utilise any specific treatment for lead separation from leaded glass of CRT (Jin *et al.* 2020).

3.2.1 Open-loop Recycling without Considering Lead

In specific sectors, waste CRT glasses are subjected to dismantling, cleaning, and other pretreatment procedures before being directly repurposed as secondary materials (Pindar and Dhawan, 2021). These materials do not necessitate special consideration for lead, barium, and other heavy metals (Liu *et al.* 2020). They fulfil diverse roles, such as serving as building materials, glass-based materials, radiation protection materials, cost-effective adsorbent materials, secondary raw materials for the metallurgical industry, and constituents for fluorescent lamps (Al *et al*. 2022).

3.2.2 Open-loop Recycling Considering Lead

In various industries, there is a high demand for waste CRT glasses, but lead poses a significant challenge due to its presence by increasing environmental and health risks (Marcus *et al.* 2019). To mitigate this threat, lead must be immobilized or extracted during recycling process (Pindar and Dhawan, 2021). Technologies like pyrometallurgy, hydrometallurgy, and mechanical activation have been innovated for lead extraction from lead-containing waste CRT glasses (Gulliani *et al*. 2023) to minimize environmental impact and ensure safety in open-loop recycling practices. Pyrometallurgy involves high-temperature processes for lead recovery (Tian and Wu, 2016), while hydrometallurgy utilizes chemical processes with solvents (Zhang *et al*. 2013). Mechanical activation involves mechanical processes to enhance lead extraction efficiency (Lu *et al.* 2013). These technologies contribute to sustainable waste management by recovering lead and mitigating environmental hazards.

4. USE OF CRT GLASS IN CONCRETE

Substantial rise in the global consumption of concrete over the years, resulting in increased extraction of raw materials such as aggregates, water, and cement (Miller *et al.* 2018) led to concerns about its environmental impact, including issues related to energy consumption, carbon emissions, and land use (Eštoková *et al*. 2022). As concrete remains one of the most widely used construction materials globally, addressing its environmental implications is crucial for sustainable development and the conservation of natural resources. Reducing the amount of virgin aggregate in construction application is possible through the use of recycled or waste materials (Bawab *et al.* 2021). Sustainable and economical alternatives include: crushed rock sand, industrial byproducts and recycled aggregates (Kirthika *et al*. 2020).

4.1 Effect of Use of CRT Glass on Mechanical Properties of Concrete

Silica, forming a significant portion of CRT glass, improves its structural strength and compatibility with concrete (Pauzi *et al*. 2019). Concrete's durability and mechanical qualities have been shown to improve with treatments given to CRT glass sands, which strengthens the material's resilience (Grdić *et al.* 2022). The density of CRT glass is 2916 kg/m³, which is larger than that of fine aggregates (2574 kg/m³) (Qaidi *et al.* 2022). Precast concrete with ground panel CRT glass exhibits strength similar to regular concrete, guaranteeing long-lasting constructions (Wang *et al.* 2019). The practicality of CRT glass waste is increased by the fact that it may be used in a variety of concrete applications, such as in place of sand or coarse aggregates (Bawab *et al.* 2021).

Table 2. Compressive strength of different concrete mixes with varying replacement of natural sand with CRT glass

Authors	W/C	Replacement Level of fine aggregate with CRT Glass	Compressive Strength at 28 days (MPa)
Ling and Poon, (2012)	0.42	25	40
		50	37.5
		75	37
		100	36
Romero *et al*. (2013)	**	10	28.5
		20	32.3
		30	30.8
Tian *et al*. (2016)	0.40	20	55
		40	54
		60	49
		80	47
		100	45
Liu *et al*. (2018)	0.6	30	34.20
		60	33.55
		100	30.49

W/C= Water-Cement ratio | ** Not reported

A meticulous review of literature (Table 2) reveals that as the quantity of CRT glass replacing natural fine aggregate increases, the compressive strength of the mixes decreases. However, this decrease is more pronounced at higher replacement levels, while at lower replacement levels, particularly up to 25% by weight of fine aggregate, the decrease is relatively small. In one study, heavyweight concrete barite was used as coarse aggregate and treated CRT glass waste as fine aggregate replacement (25-100%) with a water-cement ratio of 0.42. Replacing fine aggregate with CRT glass waste decreased compressive strength. The control mix had 42.1 MPa strength, one quarter replacement 40 MPa and full replacement 35.1 MPa after 28 days (Ling and Poon, 2012). In another study conducted by Zhao *et al.* (2013) 15% of ordinary Portland cement was replaced with fly ash, and CRT funnel glass sand (Transparent Conductive Films) substituted river sand fine aggregate at levels 0%, 25%, 50%, 75% in high-density concrete. The TCF glass sand improved initial slump and wet density but reduced mechanical properties like compressive strength and tensile splitting strength. The fact that increased replacement of fine aggregate with crushed CRT glass waste decreases the compressive strength of concrete is substantiated by the findings of Romero *et al*. (2013), who found that substituting fine aggregate with crushed CRT glass waste in concrete enhanced compressive strength initially (10-20% replacement) due to limestone's presence as coarse aggregate. However, beyond 20% replacement, compressive strength declined. The feasibility of using CRT funnel glass as a fine aggregate in concrete paving blocks was demonstrated by Ling and Poon (2014). The use of 100% CRT funnel glass resulted in increased resistance to drying shrinkage and water absorption, reduced alkali silica reaction expansion, and better compressive strength. However, it is recommended not to use more than 25% CRT glass in concrete blocks to reduce lead leaching. Walczak *et al*. (2015) examined the potential of CRT funnel glass waste and fluidized fly ash as substitutes for river sand in concrete. They tested three mix variations: one without CRT and fly ash, one fully replaced with CRT, and a final mix with 80% CRT and 20% fluidized fly ash. The final mix displayed higher compressive strength compared to other materials, attributed to the enhanced pozzolanic activity of fluidized fly ash and the greater reactivity of CRT funnel glass waste relative to river sand.

A study conducted on substituting sand with finely ground CRT glass in concrete at replacement levels of 0%, 10%, 15%, 20%, and 25% by weight revealed reduced workability with increased glass content, yet a notable 44.8% increase in compressive strength with 20% replacement after 90 days (Iniaghe and Adie, 2017). This suggests potential for CRT glass as a fine aggregate substitute, with lead leaching within safe limits, supporting its integration up to 25% without environmental risks. Another study conducted by Jamil *et al.* (2018) also suggests potential for complete natural aggregate replacement with CRT waste glass integration in concrete. They used CRT waste glass as coarse aggregate in concrete, fully replacing limestone aggregate in steel fibre reinforced concrete. Steel fibre, up to 1.5%, was added. Results revealed CRT glass maintains concrete's design strength, with steel fibre enhancing compressive and splitting tensile strength.

Waste CRT glass, when incorporated in concrete as fine aggregate improves its resistance to freezing-thawing cycles, sulphate attack, and chloride ion penetration with higher waste glass ratios. However, reduced compressive and flexural strength are observed due to decreased adhesion between cement paste and waste glass (Kim *et al*. 2018). Cathode ray tube glass is also considered ideal for a variety of prefabricated concrete elements. In a study, fresh and hardened self-compacting concrete (SCC) using CRT glass as a powdered mineral additive demonstrated acceptable physical-mechanical properties. Durability was tested by placing curbs during street renovation in Niš (Grdić *et al*. 2018). As high as 40% sand substitution by CRT funnel glass as compared to 20%, 60%, 80%, and 100%, was found optimal admixture with fine barite aggregate and 5–10 mm coarse barite aggregates in preparation of the radiation shielding barite concrete (Liu *et al*. 2019). As an alternate approach to recycle CRT glass by substituting it for natural fine aggregates in plaster mortars, the lead content in the mortars was found to be below the threshold for detection, indicating that the mortars had high chemical stability (Marcus *et al.* 2019). In SCC containing metakaolin as partial replacement to cement at weight ratios of 5,10, and 15% and CRTG as partial replacement to natural sand at weight ratios of 0,10,20,30,40, and 50%, mixes with up to 50% CRTG substitution had improved durability (Ouldkhaoua *et al*. 2020). Substituting up to 15% of cement with CRT glass enhances concrete compressive strength without compromising durability besides maintaining comparable freeze-thaw resistance, de-icing salt resistance, abrasion resistance, and sulphate attack resistance as standard concrete. These observations were derivable from a study conducted by Grdić *et al.* (2021), when they examined replacing a portion of cement with finely ground CRT glass (<63 μm) in concrete, with replacement percentages ranging from 5% to 35%. The addition of crushed CRT glass without lead extraction as a replacement to sand as fine aggregate in various ratios in ultra-high-performance concrete (UHPC) increases the flowability and decreases the compressive and flexural strength of UHPC. The deteriorated strengths of UHPC containing 100% CRT glass can still satisfy the strength requirement in real engineering practice (Liu *et al.* 2020). Cathode ray tube waste can be used as a complete replacement for natural aggregate in Polymer Concrete (PC) with its quality dependant on the matrix crosslinking and RGA particle size. Performance of PC containing fine recycled glass aggregate can be further improved by adding 4 percent by weight of silane coupling agent (Malchiodi *et al.* 2022). Cathode ray tube glass milled to a particle size of 91 μm works very well as a filler with no negative effect either on workability or compressive strength of hybrid reinforced polymer concrete, produced by using ground CRT glass, sand and cut-glass fibres (Smoleń *et al.* 2022). When 10% of the sand in a reinforced concrete beam is substituted with CRT glass, its compressive strength, flexural strength, elastic modulus and load carrying capacity is higher than that of the control beam and the beams with 20% and 30% substitution of CRT glass (Bawab *et al.* 2021a). Concrete specimens with 15% to 20% cement replacement with finely ground CRT glass by mass as compared to 5%, 10%, and 35% show satisfactory compressive strength and resistance to sulphate attack after soaking these specimens in a 5% solution of Na_2SO_4 for 36 months (Grdić *et al*. 2023).

5. CONCLUSION

The disposal of cathode ray tube glass creates considerable environmental challenges due to its toxic lead concentration, necessitating proper recycling processes and disposal regulations. Both closed-loop and open-loop recycling methods have viable answers, each with their own environmental concerns. While closed-loop recycling was previously deemed sustainable, it has become outdated with the emergence of open-loop methods and decreased demand for recycled materials. Open-loop recycling, despite facing challenges in lead extraction and environmental risks, shows promise with technologies like pyrometallurgy and hydrometallurgy. Moreover, the incorporation of CRT glass into concrete provides a viable solution, though the effect on the concrete's mechanical properties must be considered. While replacing natural sand with CRT glass may slightly reduce compressive strength, innovative mix designs offset this effect. Concrete with CRT glass is resilient to environmental factors like freezing-thawing cycles and sulphate attack, making it versatile in construction applications. However, continuous technological improvements seek to maximize the recycling advantages of CRT glass while minimizing the impact on the environment.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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