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REDUCING CARBON EMISSIONS THROUGH CIRCULAR USE OF WASTE GLASS IN CEMENTITIOUS MATERIALS

Summary: The use of finely ground waste cathode ray tube (CRT) glass as a partial replacement for cement directly links the principles of circular economy with the reduction of carbon dioxide emissions. Instead of ending up in landfills, glass is returned to the production cycle as a pozzolanic material, reducing the need for extracting natural resources and producing clinker—the most carbon intensive component of cement. Since manufacturing one ton of clinker emits roughly 800–900 kg of CO_2, replacing up to 35% of cement with glass powder can lower the overall carbon footprint of concrete. This study examined concrete in which up to 35% of the cement was replaced with glass powder finer than 63 microns, demonstrating how turning waste into a valuable material directly supports climate benefits and the core principles of the circular economy.

Keywords: waste CRT glass, circular economy, pozzolanic material, compressive strength

SMANJENJE EMISIJE UGLJEN-DIOKSIDA KROZ CIRKULARNU UPOTREBU OTPADNOG STAKLA U CEMENTNIM MATERIJALIMA

Rezime: Upotreba fino samlevenog otpadnog stakla katodnih cevi (CRT) kao delimične zamene za cement direktno povezuje principe cirkularne ekonomije sa smanjenjem emisije ugljen-dioksida. Umesto da završava na deponijama, staklo se vraća u proizvodni ciklus kao pucolanski materijal, čime se smanjuje potreba za eksploatacijom prirodnih resursa i proizvodnjom klinkera – komponente cementa sa najvećim ugljeničnim otiskom. S obzirom na to da proizvodnja jedne tone klinkera emituje približno 800–900 kg CO_2, zamena do 35% cementa staklenim prahom može značajno smanjiti ukupni ugljenični otisak betona. U ovom radu je ispitivan beton u kojem je do 35% cementa zamenjeno staklenim prahom granulacije ispod 63 mikrona, čime je pokazano da pretvaranje otpada u vredan materijal direktno doprinosi klimatskim benefitima i osnovnim principima cirkularne ekonomije.

Ključne reči: otpadno CRT staklo, cirkularna ekonomija, pucolanski materijal, čvrstoća pri pritisku

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1. INTRODUCTION

The concept of utilizing various types of waste materials for the production of new construction products has a long and well-established tradition in the field of civil engineering. In this context, a substantial number of experimental and theoretical studies have been conducted over the past decades, focusing on the valorization of industrial by-products—primarily fly ash, blast furnace slag, and silica fume—through their application as mineral admixtures in concrete and precast elements. The findings of these studies clearly demonstrate multiple benefits, including improvements in both mechanical and durability properties, as well as a reduction in environmental impact. Materials that were once considered a significant ecological burden due to their accumulation in landfills worldwide are now recognized as valuable resources and have found widespread application in modern construction practice.

In this regard, the concept of circular economy and sustainable resource management has further stimulated research aimed at identifying new pathways for the utilization of various waste materials. One material that has gained increasing attention is waste glass, including specific types such as cathode ray tube (CRT) glass. Its potential use in cement-based composites, either as a replacement for natural raw materials or as an additive to existing material systems, remains an active area of investigation. Previous studies indicate considerable potential of this material, but also highlight the need for further research to fully understand its influence on the performance and long-term behavior of cementitious composites.

Due to its specific chemical composition and the complexity of the recycling process, the reuse of CRT glass represents a significant technical and technological challenge. These characteristics limit its broader application and necessitate detailed investigation to identify suitable valorization strategies. The following section provides an overview of relevant previous research dealing with the use of different types of waste glass in the production of new materials and products. Particular emphasis is placed on its application in the construction industry, especially in the production of mortars and concrete, where this material has demonstrated considerable potential [1].

1.1. PRIMENA OTPADNOG STAKLA ZA IZRADU NOVIH PROIZVODA

Dondi et al. [2] investigated the feasibility of incorporating CRT glass into the production of bricks and roofing tiles, where the glass was ground to a particle size below 1 mm to ensure compatibility with existing manufacturing processes. A series of mixtures containing panel and funnel glass in proportions ranging from 2% to 5% was prepared, alongside reference industrial samples. After shaping, drying, and firing at temperatures between 900 and 1000 °C, it was observed that the presence of CRT glass reduced the plasticity of fresh mixtures and increased shrinkage during drying. Furthermore, an addition of approximately 2% resulted in satisfactory properties, whereas higher contents (around 5%) led to a deterioration of physical and mechanical characteristics. Based on the obtained results, the optimal CRT glass content was determined to lie between 2% and 4%.

Andreola et al. [3] examined the applicability of CRT glass in the production of ceramic glazes, focusing on its role as a substitute for non-plastic components, particularly glassy materials. Special attention was given to the presence of oxides such as Ba, Sr, Zr, and Pb, which contribute to the functional properties of the glazes. Three types of CRT glass (panel, funnel, and their mixture) were investigated, and based on chemical and technological analyses, glazes incorporating panel glass exhibited the most favorable characteristics. Subsequent studies therefore focused exclusively on panel CRT glass, where it constituted a major portion of the glassy phase. The maximum allowable content of CRT glass was determined based on stability assessments and defect formation. The results indicated that the inclusion of CRT glass does not significantly affect the chemical resistance compared to conventional glazes, while it improves abrasion resistance. Additionally, a life cycle assessment (LCA) demonstrated that the use of CRT glass can reduce the environmental impact by approximately 36% compared to traditional glazes [3].

1.2. WASTE GLASS AS A PARTIAL REPLACEMENT FOR CEMENT IN CONCRETE

Kim et al. [4] investigated the potential use of waste glass sludge (WGS), a by-product of flat glass manufacturing, as a partial replacement for cement in order to enhance the durability of concrete. Five concrete mixtures with varying WGS contents were prepared, and their performance was evaluated through compressive strength testing, freeze–thaw resistance (with and without de-icing salts), chloride ion penetration, and surface scaling tests. The results indicated that incorporating WGS improved the mechanical performance, particularly when combined with fly ash, and significantly enhanced durability properties. Compared to the control mixture containing 20% fly ash, WGS-modified concretes exhibited better resistance to freeze–thaw cycles, reduced chloride ingress, and improved resistance to surface scaling.

Nassar et al. [5] explored the use of milled waste glass as a supplementary cementitious material in recycled aggregate concrete, aiming to improve its typically inferior mechanical and durability properties. The study focused on the incorporation of finely ground glass as a partial cement replacement, demonstrating that, at micro-scale particle sizes, the material exhibits pozzolanic activity through reactions with cement hydration products, leading to the formation of additional calcium silicate hydrate (C–S–H). These reactions contributed to a densification of the cement matrix and improvements in the interfacial transition zone between recycled aggregates and the cement paste. As a result, notable enhancements in both strength and durability were observed, along with a mitigation of alkali–silica reaction. The findings highlight the potential of milled waste glass to enable high-value utilization of recycled materials while simultaneously diverting significant quantities of glass waste from landfills.

Zidol et al. [6] investigated the potential of glass powder (GP) as an alternative supplementary cementitious material by comparing its performance with conventional additions such as Class F fly ash (FFA) and ground granulated blast furnace slag (GGBS). Concrete mixtures were prepared with 0%, 20%, and 30% GP, alongside reference mixes incorporating 30% FFA or GGBS, covering a wide range of water-to-binder ratios (0.35–0.65). The study evaluated compressive strength as well as durability-related properties, including chloride ion permeability and diffusion. The results indicated that GP exhibits mechanical performance comparable to fly ash and demonstrates superior efficiency in reducing permeability. In particular, GP significantly decreased chloride ingress regardless of the w/b ratio, leading to enhanced durability of concrete, thereby confirming its strong potential as a sustainable supplementary cementitious material.

Based on the above, it can be concluded that the use of waste glass offers a range of potential benefits, which can generally be classified into three main categories: environmental, economic, and engineering. From an environmental perspective, the use of waste glass—such as a partial replacement for cement in mortars and concretes—contributes to reducing the amount of waste disposed of in landfills, while also mitigating the negative impacts associated with Portland cement production, including carbon dioxide emissions and the consumption of natural resources. From an economic standpoint, assessing the feasibility of its application requires a comprehensive techno-economic analysis, encompassing key factors such as waste collection and disposal costs, transportation, processing and recycling procedures, as well as the production costs of new materials and products [7]. At the same time, from an engineering perspective, the incorporation of waste glass into cementitious composites may alter both fresh and hardened properties, highlighting the importance of detailed investigation and optimization of its proportion in the mixture.

2. MATERIALS USED IN EXPERIMENT AND MIX DESIGN

The experimental program was based on the use of conventional binder, recycled glass powder, and natural aggregates of varying particle sizes. Ordinary Portland cement (CEM I 52.5R), supplied by CRH Novi Popovac, served as the primary cementitious material, meeting the requirements of EN 196-1, EN 196-3, EN 196-6, and EN 197-1 standards.

Recycled cathode ray tube (CRT) glass was obtained from the "Jugo–Impex E.E.R." d.o.o. recycling facility located in Niš. Following collection, the material was processed to produce a fine powder suitable for use in cement-based systems. Natural river aggregate was employed in three distinct size classes: 0–4 mm, 4–8 mm, and 8–16 mm. The initially supplied CRT glass consisted of coarse fragments, which required further size reduction. Grinding was performed using a laboratory ball mill until complete passage through a 0.063 mm sieve was achieved. No residual material remained on the sieve after processing. The produced glass powder was characterized by a density of 2.84 g/cm³ and a Blaine specific surface area of 245 m²/kg. The grading properties of the aggregate fractions were determined using the dry sieving technique in accordance with EN 933-1. The resulting particle size distribution curves for all fractions are illustrated in Figure 1.

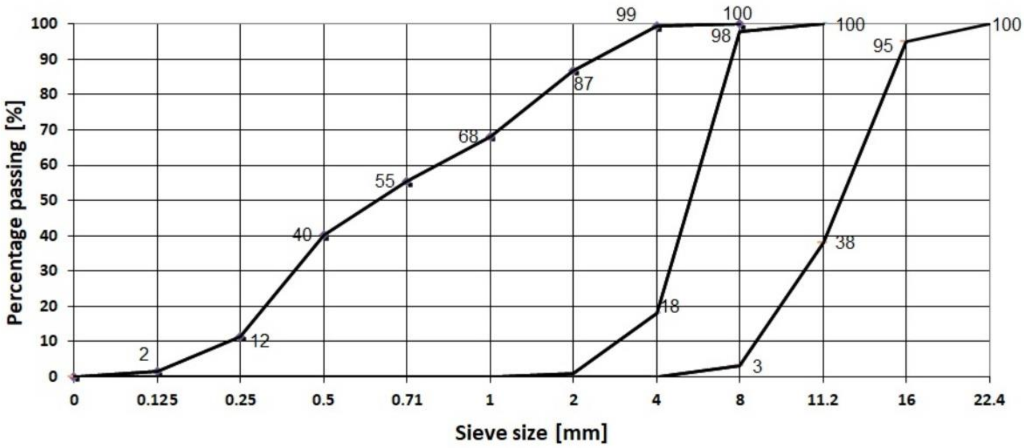

Figure 1: Particle size distribution of fractions 0/4 mm, 4/8 mm, 8/16 mm of river aggregate

An experimental campaign comprising four distinct concrete mixtures was conducted to evaluate the influence of partial cement replacement with finely ground CRT glass on hardened concrete properties. The reference mixture was designed with a binder content of 400 kg/m³ of cement and a total aggregate content of 1800 kg/m³, consisting of three river aggregate fractions. The proportions of aggregate fractions were fixed at 43% (0–4 mm), 23% (4–8 mm), and 34% (8–16 mm). A constant water-to-binder ratio (w/b) of 0.438 was maintained for all mixtures. To achieve adequate workability at a reduced water content, a polycarboxylate-based superplasticizer was incorporated.

The substitution of cement with waste glass powder was performed at levels of 10%, 20%, and 35% by mass of cement. The upper replacement limit (35%) was selected in accordance with typical maximum mineral admixture contents in CEM II-type cements. Mixture designations were assigned based on the replacement level, where the notation "WG" refers to waste glass. All mixtures were proportioned to achieve a target workability corresponding to slump class S3 (100–130 mm). The consistency of fresh concrete was determined using the slump test in accordance with EN 12350-2. The detailed mix proportions for all concrete formulations are provided in Table 1.

Table 1: Composition of experimental concrete mixtures

Concrete	Aggregate			Cement	CRT	Water		Additive
	0/4 mm	4/8 mm	8/16 mm	CEM I 52,5 R	< 0.063 mm	city wat. supply	w/b	Super-plasticizer
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	-	kg/m^3
E	774	414	612	400	-	175.3	0.438	2.40
WG10	774	414	612	360	40	175.3	0.438	2.40
WG20	774	414	612	320	80	175.3	0.438	2.40
WG35	774	414	612	260	140	175.3	0.438	2.40

3. EXPERIMENTAL RESULTS AND DISCUSSION

Compressive strength was determined on standard concrete cubes with dimensions of 150 mm, tested at curing ages of 2, 7, 28, and 90 days in accordance with EN 12390-3. For each testing age, the reported value corresponds to the mean result obtained from three specimens.

As expected, all concrete mixtures exhibited a continuous increase in compressive strength with prolonged curing time, Figure 2. At early ages (2 and 7 days), the reference mixture consistently achieved the highest strength values. During this initial stage of hydration, a clear trend can be identified: increasing the proportion of cement replacement with CRT glass leads to a reduction in compressive strength, with more pronounced declines observed at higher replacement levels.

For example, at 7 days, mixtures WG20 and WG35 showed reductions of 24.4% and 37.6%, respectively, compared to the reference concrete. A similar tendency was observed at 28 days, where strength values for WG20 and WG35 remained lower by 15.7% and 37.0%, respectively, relative to the control mixture.

However, the results obtained after 90 days indicate a notable shift in behaviour, requiring a reassessment of the earlier observations. Specifically, mixtures WG10 and WG20 demonstrated a substantial recovery in strength, significantly narrowing the difference relative to the reference concrete to only 5.2% and 3.5%, respectively. Figure 3 illustrates the variation in compressive strength development of concrete mixtures at curing ages of 2, 7, 28, and 90 days as a function of the percentage of CRT glass powder used as a cement replacement.

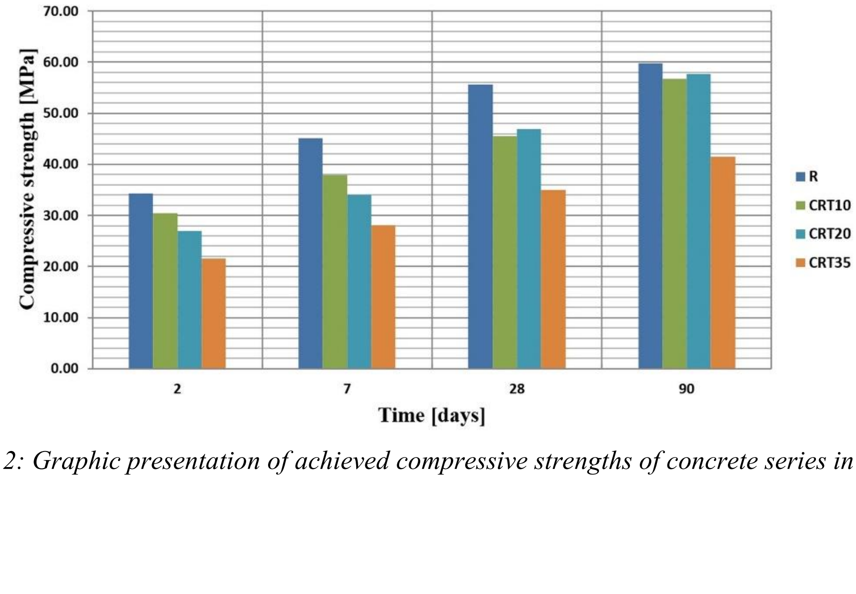

Figure 2: Graphic presentation of achieved compressive strengths of concrete series in time

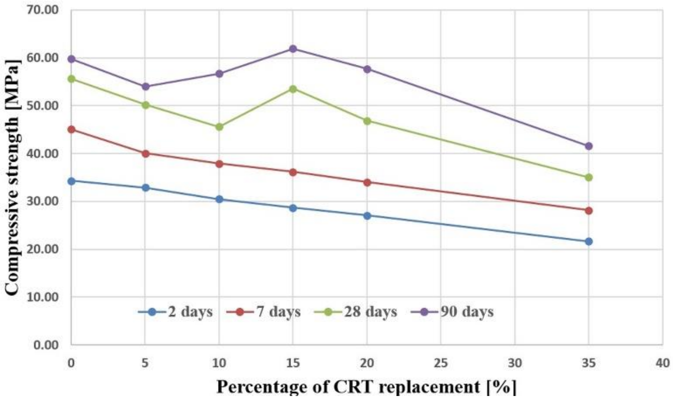

Figure 3: Variation of compressive strength of concrete at the ages of 2, 7, 28 and 90 days in the function of percentage of replacement of CRT glass powder

The surface hardness of concrete was evaluated using a non-destructive testing method based on the Schmidt rebound hammer. This method relies on measuring the rebound of a spring-driven mass impacting the concrete surface, where the rebound index is correlated with the compressive strength of concrete.

Prior to testing, the concrete surface was cleaned and prepared to ensure reliable measurements. The rebound hammer was applied perpendicular to the test surface, and multiple readings were taken at each test location to obtain representative values. The recorded rebound numbers were then used to estimate the surface compressive strength in accordance with the relevant standards SRPS EN 12504-2. The purpose of this method is to estimate the internal compressive strength of concrete by measuring its surface hardness, which inherently introduces a certain level of error. These inaccuracies arise from the dispersion of results caused by variations in surface hardness among the tested specimens [118]. In order to establish a more accurate correlation between the rebound number (Schmidt hammer index) and the actual compressive strength of concrete, the testing was performed on cubic concrete specimens with a side length of 15 cm, immediately prior to compressive strength determination.

The measurements were carried out using a Schmidt hammer device "N-34 Proceq SA", Switzerland. Before testing, each specimen was subjected to a constant load of 50 kN using a hydraulic press. The rebound index (Ri) was measured on two opposite faces of the specimen, perpendicular to the casting direction, at an angle of 0°, at a total of eighteen test points. The procedure of rebound number testing using a Schmidt hammer on a single concrete specimen is illustrated in Figure 4.

Figure 4: Schmidt hammer rebound number testing (left); Appearance of the Schmidt hammer

Figure 5 presents the average rebound values obtained for the concrete series at different ages. As expected, an increase in concrete age results in higher rebound values for all mixtures. At early ages (2 and 7 days), it can be observed that increasing the glass content in the mixture leads to a decrease in rebound values for the same curing period. For mixtures WG10 and WG20, the results at 28 days indicate relatively uniform rebound values, although still slightly lower compared to the reference concrete. At 90 days, up to 20% cement replacement with glass results in rebound values comparable to those of the control mixture. At this age, mixture WG35 exhibited the lowest compressive strength among all series and, consequently, the lowest rebound value of 43.

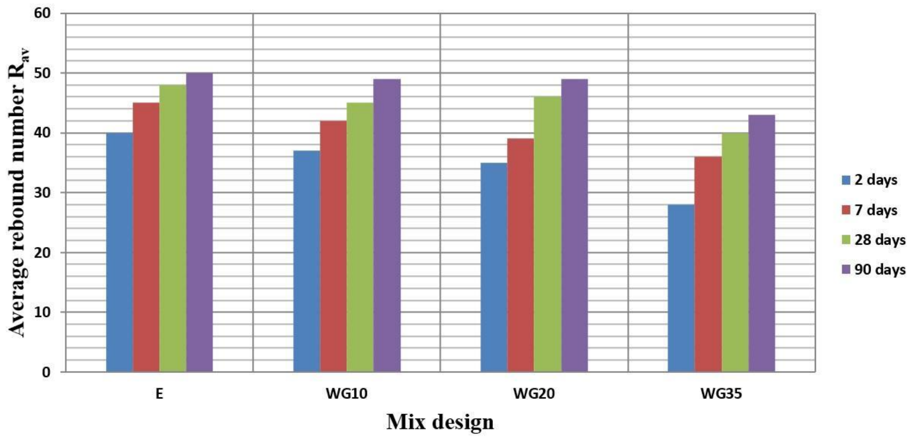

Figure 5: Schmidt hammer rebound at different concrete ages

Given that the surface hardness of concrete is directly related to its compressive strength, the measured rebound values follow the strength development over time. Based on the average rebound values and the experimentally obtained compressive strengths, a functional relationship between the Schmidt hammer rebound index and the compressive strength of concrete was established (Figure 6). Statistical analysis of the results yielded a second-degree polynomial function with a correlation coefficient close to unity. A review of the available literature revealed no studies addressing rebound measurements on concrete incorporating finely ground waste glass, and therefore, the obtained results could not be compared with findings reported by other researchers.

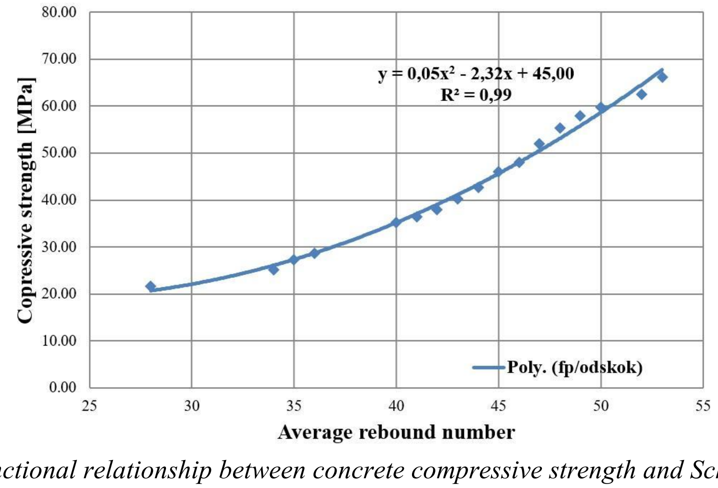

Figure 6: Functional relationship between concrete compressive strength and Schmidt rebound number

4. CONCLUSIONS

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

- Early-age results (2 and 7 days) show that the reference concrete achieved the highest compressive strength. Although mixtures with CRT glass exhibited reduced strength at 28 days, significant recovery was observed at 90 days for WG10 and WG20, with differences reduced to 5.2% and 3.5%, respectively. This indicates that moderate glass replacement (up to 20%) can yield comparable long-term performance despite initial strength reductions.
- At 28 days, mixtures WG10 and WG20 exhibited relatively uniform rebound values, slightly lower than the reference concrete. However, at 90 days, up to 20% cement replacement resulted in comparable rebound values to the control mixture, while WG35 showed the lowest rebound (43), consistent with its reduced strength. The results were well described by a second-degree polynomial relationship with a correlation coefficient close to unity, indicating a strong dependence between rebound index and compressive strength.
- The combined findings indicate that the partial replacement of cement with finely ground CRT glass, particularly up to 20%, can ensure satisfactory long-term mechanical performance, supported by both compressive strength and rebound measurements. Moreover, the utilization of waste glass contributes to the reduction of cement consumption and promotes the reuse of industrial waste, aligning with the principles of circular economy and sustainable development. Therefore, the application of CRT glass as a supplementary cementitious material represents a promising and environmentally responsible approach in modern concrete production.

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