Chapter 7

Research on Strength, Alkali-Silica Reaction and Abrasion Resistance of Concrete with Cathode Ray Tube Glass Sand

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Additional information is available at the end of the chapter

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Abstract

In this study, the effects on the mechanical and durability properties of concrete with cathode ray tube glass sand (CRTS) obtained by recycling the screens of cathode ray tubes (CRTs) were investigated. CRTS was used by the ratios of 5, 10, 15, and 20% in the concrete. The unit weight, workability, water absorption, compressive strength, flexural strength, ultrasonic pulse velocity, static and dynamic elastic moduli, abrasion resistance, and alkali-silica reaction (ASR) expansion tests on the concrete were examined. The use of CRTS improved specific properties of concrete according to the fraction of glass aggregate used between 0 and 20%. Plain concrete (P) and CRTS of 5% in concrete gave better results in terms of mechanical properties. Use of CRTS above 5% in concrete declined the mechanical properties but on the 90th day, CRTS concrete reduced the difference. CRTS up to 20% in concrete especially improved abrasion resistance in comparison to P without CRTS; furthermore, this addition did not increase ASR expansion to a deleterious level.

Keywords: concrete, cathode ray tube glass sand, mechanical properties, ultrasonic pulse velocity, alkali-silica reaction, abrasion resistance

1. Introduction

For centuries, glass has been one of the main man-made materials that characterize societies. It is part of everyday life in both developed and developing countries. So much consumer glass is regularly produced in the World. However, its disposal creates serious problems because only small percentages of glass are reused or recycled. As a result, most glass products become solid waste and consume ever-scarce landfill capacity [1, 2].

To facilitate problems related to disposal, many countries are currently legislating sustainable waste management and conservation of resources, which includes recycling. In particular, glass has inherent value that can be utilized in numerous applications [3, 4]. Demand for recycled glass has gradually increased in some European countries and North America. Currently, 34% of container glass in Great Britain is recycled, but this rate is far below that in other countries such as Germany, Switzerland, the Netherlands, and Finland where the recycling rates are as high as 80%. In the USA, the rates are considerably less, and millions of tons of waste glass remain as landfill [5, 6].

Adding value to a waste product generates both economic and environmental benefits that are particularly effective if certain inherent properties of a specific waste material are utilized. Concrete is an important construction material that can eliminate certain components of the waste stream with promising results [7]. The most successful and widespread modification is the use of fly ash, slags, and silica fume to partially replace ordinary Portland cement. In addition, other waste stream components such as glass, foundry sands, and rubber are successfully used as concrete ingredients. Studies of glass as an aggregate for concrete have been primarily limited to soda lime glass, which is used for household containers and bottles. On the other hand, studies on the use of LCD glass have also been conducted [8]. The chemical makeup of different glass widely varies even with the glass color, which affects the properties of concrete. In addition, various types of recycled glass can be used in concrete [4].

The recycling of old TV sets and computer monitors with cathode ray tubes (CRTs) poses additional problems. CRTs consist of four structures with different components and properties (screen or panel, cone or funnel, neck and frit junction). Most CRT components contain heavy metals (e.g., Pb, Ba, and Sr) that pose serious environmental health concerns. Thus, CRTs have a notably low recycling rate, which necessitates their disposal in specially engineered landfills [9, 10]. Moreover, depositing glass materials in engineered landfills is expensive [7]. Waste CRTs require a special procedure before they are sent to landfills because of their high lead content. In Hong Kong, a simple method with four steps is used to remove lead on the surface of CRTs: (i) removing the leaded funnel glass from the CRT; (ii) crushing the CRT into small particles of sizes below 5 mm; (iii) cleaning the lead from the glass surface by immersion in a 5% nitric acid solution for 3 h; and (iv) removing the remaining acid by rinsing in tap water [11]. The front panel, which is a component of the CRT, is made of barium strontium glass and is free of lead [12]. CRT can be used instead of raw aggregate if it is known it has good performance on properties and durability in concrete. Using of to CRT replace fine aggregate is possible owing to its close association with natural aggregate as chemical and composition [13].

According to Topçu and Canbaz and Ismail and Al-Hashmi, waste glass concrete exhibits slightly smaller slump values than plain concrete [14, 15]. In a study on workability by Kou and Xing, glass powder minimally decreases the workability according to flow table results [16]. It is expected that glass positively affects the mechanical properties of concrete because of its excellent mechanical properties if it is used as an aggregate or in finely ground powder as a partial cement replacement [2]. Ismail and Al-Hashmi showed that the replacement of sand with glass at up to 20% in concrete can increase compressive and flexural strength [15]. Nevertheless, a glass aggregate content of more than 20% leads to notable decrease in the

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compressive and flexural strength, ultrasonic pulse velocity and dynamic elasticity modulus [1, 14]. One of the problems encountered when using glass as an aggregate in concrete is glass cracking and progression of these cracks [2, 5, 14]. A smooth glass surface facilitates the movement of the cracks, and this effect decreases the strength [11]. The flexural strength of a mortar specimen with glass aggregate can be 10% less than that of a specimen without glass aggregate. Expansion from 1 to 4 mm in the size of the glass aggregate increases flexural strength from 2.6 to 3.2 MPa. Mortars with 3 and 4 mm glass aggregates have stronger resistance to cracks and exhibit high energy [17]. Investigations are still lacking in the area of abrasion resistance of concrete containing glass aggregates. In studies by Ling and Poon, Turgut, and Turgut and Yahlizade, the replacement of sand with glass aggregates in the mortar increased the abrasion resistance [18–20]. Use of glass aggregate at up to 20% in concrete resulted in better performance in comparison to plain concrete from the standpoint of material properties [20, 21].

It is also well known that silica in glass can chemically react with alkali in the cement matrix, which is known as ASR. The resulting ASR gel swells in the presence of moisture and causes potentially serious cracking damage [2, 5, 22]. Topçu et al. reported that the ASR caused expansion and internal stresses in the concrete in direct proportion to the amount of glass in the concrete. It was necessary to add 2% Li_2CO_3 and 20% fly ash to the mix to constrain the expansion below the acceptable limit [22]. As reported by Özkan, clear glass performed better than brown glass in terms of strength and durability. That study also considered mortar with up to 50% blast furnace slag, which replaced Portland cement, and it was found that 25% slag led to the least amount of ASR expansion. Large amounts of fly ash and slag reduced the early strength but significantly increased the alkali resistance of concrete [1]. Polley et al. and Kou and Poon reported that the use of fly ash significantly decreased the influence of the ASR [21, 23]. Lane and Ozyildirim concluded that the strength and durability increased when small amounts of silica fume were used with large amounts of fly ash or slag. ASR tests according to ASTM C1293 indicated that as little as 15% of fly ash was sufficient to prevent detrimental expansion. In addition, a slag ratio of at least 35% was found to be advisable. This performance was also achieved with 25% slag and 2.5% silica fume due to the beneficial combination of silica fume and blast furnace slag [24]. Cota et al. showed that waste glass of 7.5 or 15% did not deteriorate mechanical properties or ASR durability when Portland cement replaced 15% of metakaolin [25]. Ismail and Al-Hashmi noted that it is not always necessary to use pozzolana to prevent ASR. In that study, high-quality pozzolanic waste glass sand (67.72% SiO_2 and 6.9% CaO) that was modified with 10, 15, and 20% sand was used. The concrete strength and ASR durability increased with increasing waste glass content [15]. According to Schwarz et al., fine glass dust can improve the durability of concrete [26]. The results of Shayan and Xu indicate that if the glass particle sizes are thinner than 0.30 mm, they will not cause deleterious expansion. Particle sizes above 0.60 mm cause significant deleterious expansion [2]. In their other study by Shayan and Xu, powder glass did not cause ASR because it had pozzolanic properties [27]. According to Meyer, it is possible to reduce ASR expansion depending on the cement and climatic conditions and the structure and thickness of the glass [28]. In addition, because ASR swelling occurs only in the presence of moisture, measures to prevent the ingress of moisture are expected to be effective in preventing ASR damage.

The present study investigated the effects of substituting various amounts of CRT glass for fine aggregates in concrete on the following physical, mechanical, and durability properties: unit weight, workability, water absorption, compressive and flexural strength, ultrasonic pulse velocity, static and dynamic elastic moduli, abrasion, and ASR expansion. The crushed sand replacement by cathode ray tube glass sand (CRTS) constituted 5, 10, 15, and 20% by weight of the total aggregate.

2. Materials and methods

2.1. Materials and mix design

The cement in this study was CEM I/42.5 R according to TS EN 197-1 [29]. Fly ash (FA) was used to increase the resistance against ASR and supply utilization by recycling this waste material. CRTS obtained by recycling computer screens was provided from Exitcom Corp. in Turkey. The chemical and physical properties of the cement, FA, and CRTS used in this study are provided in **Table 1**. A superplasticizer was also added to ensure concrete workability.

Four different types and sizes of aggregate were used: river sand (0–3 mm), crushed sand (0–4 mm), coarse aggregate 1 (5–12 mm), and coarse aggregate 2 (12–20 mm). The coarse aggregates consisted of crushed stone and their maximum size was 20 mm. **Figure 1** shows river sand, crushed sand, and CRTS. The gradation curves for CRTS and the other fine aggregates are shown in **Figure 2**.

Five different mix designs were investigated, as shown in **Table 2**. These mix designs contained CRTS in the amounts of 0, 5, 10, 15, and 20% by weight of total aggregate crushed sand replacements. After the workability of fresh concrete was determined for each mix, five cubes of size 150×150×150 mm, five beams of size 100×100×400 mm, five cylinders of 150 mm in diameter and 300 mm in length, five cubes of size 71×71×71 mm, and five prisms of size 25×25×285 mm were cast to determine the compressive strength, flexural strength and pulse velocity, elastic modulus, abrasion, and ASR, respectively.

2.2. Test methods

Workability. The slump of fresh concrete was measured using the standard slump test apparatus according to ASTM C143 [30].

Densities and water absorption. Dry, saturated densities and water absorption of hardened concrete were measured according to ASTM C642 [31].

Compressive strength. The compressive strength of the hardened concrete was determined according to ASTM 39 [32] at the ages of 3, 7, 28, and 90 days for the cube specimens of 150×150×150 mm in size. These cubes were removed from the molds after 1 day and cured in water at 21°C before testing.

Chemical properties				Physical and mechanical properties			
Constituent (%)	**Cement**	**Fly ash**	**CRTS**	**Properties**	**Cement**	**Fly ash**	**CRTS**
SiO_2	20.5	50.2	50.9	Specific gravity (g/cm^3)	3.12	2.04	2.70
Al_2O_3	4.65	12.7	2.62	Blaine (m^2/kg)	360	212	—
Fe_2O_3	3.40	9.00	0.12	Mass stability (mm)	2.00	—	—
CaO	62.7	12.53	1.54	Setting period start (min)	153	—	—
Free CaO	1.09	—	—	Setting period stop (min)	188	—	—
MgO	1.02	4.33	0.64	90 μ sieve (%)	0.20	—	—
SO_3	2.21	0.39	—	45 μ sieve (%)	12.8	—	—
Na_2O	0.18	2.75	3.60	2 day-strength (MPa)	30.2	—	—
K_2O	0.41	2.50	4.30	7-day strength (MPa)	51.1	—	—
PbO	—	—	0.29	28-day strength (MPa)	62.2	—	—
BaO	—	—	9.10				
Sb_2O_3	—	—	0.31				
ZrO_2	—	—	0.91				
SrO	—	—	5.97				
TiO	—	—	0.39				
CeO_2	—	—	0.25				
Cl^-	0.01	—	—				
Insoluble residue	0.60	—	—				
Ignition loss	2.15	0.54	—				

Table 1. Chemical composition and physical properties of cement, fly ash and CRTS.

Figure 1. Photographs of CRTS, crushed sand, and river sand used in the study.

Flexural strength. The flexural strength of the hardened concrete was determined at the ages of 3, 7, 28, and 90 days for the beams of 100×100×400 mm in size. These beams were removed from the molds after 1 day and cured in water at 21°C before testing. The flexural strength was

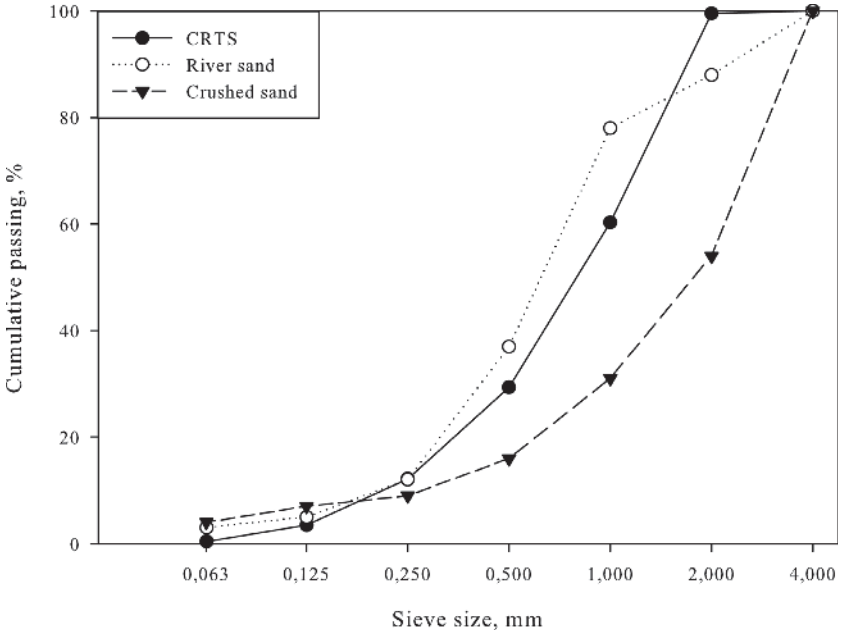

Figure 2. Particle size distributions of fine aggregates.

Components	CRTS content (%)				
	0	5	10	15	20
Cement (kg/m^3)	300	300	300	300	300
Fly Ash (kg/m^3)	60	60	60	60	60
Water (kg/m^3)	155	155	155	155	155
Natural sand (kg/m^3)	517	517	517	517	517
Crushed sand (kg/m^3)	360	270	180	90	0
CRTS (kg/m^3)	0	94	188	282	376
Coarse aggregate 1 (kg/m^3)	470	470	470	470	470
Coarse aggregate 2 (kg/m^3)	512	512	512	512	512
Admixture (%)	1.30	1.30	1.30	1.30	1.30
Water/(FA + C)	0.43	0.43	0.43	0.43	0.43
Slump (mm)	170	160	158	150	143
Unit weight (kg/m^3)	2379	2383	2387	2391	2395

Table 2. Concrete mix designs.

determined using three-point bending tests according to ASTM C78 [33] with an effective span of 300 mm.

Ultrasonic pulse velocity. The ultrasonic pulse velocity of the hardened concrete was determined by selecting a measurement distance of 400 mm at the ages of 3, 7, 28, and 90 days on the 100×100×400 mm beams. The measurements were performed according to ASTM C597 [34] before the flexural strength tests.

Static and dynamic elastic moduli. The static elastic modulus was determined on 150×300 mm cylinders at the age of 28 days in compression according to ASTM C469 [35]. The dynamic elastic modulus was determined using the 28-day data that were obtained from the ultrasonic pulse velocity of the beams according to ASTM C597, formula obtained from ASTM C597 was used to calculate the dynamic elastic modulus. The formula of dynamic elastic modulus was showed in Eq. (1).

$$V = \sqrt{\frac{E\,(1-\mu)}{\rho\,(1+\mu)(1-2\mu)}} \tag{1}$$

Alkali-silica reaction. ASR was determined on the mortar bars of 25×25×285 mm according to ASTM C1260 [36].

***Abrasion**.* The amount of horizontal surface abrasion was determined on the cubes of 71×71×71 mm using the Bohme testing method according to BS EN 13892–3 [37] after 28 days.

3. Experimental studies and discussion

3.1. Workability

The workability was negatively affected with increasing CRTS content, as shown in **Table 2**. The slump value slightly decreased when the CRTS content increased by 5%. However, the slump decreased by only 2.75 cm when the CRTS content increased to 20%. According to Ling and Poon, fine particle size glass increases water absorption [38]. Similar to these results, Topcu and Canbaz reported that increasing glass content reduced the workability but the reduction was insignificant [15]. Concrete with glass requires more water to achieve the same workability [5, 21]. Ismail and Al-Hashmi, Kou and Xing, and Shayan and Xu, also reported that glass added to concrete decreases the workability [2, 15, 16].

3.2. Unit weight and water absorption

Table 3 indicates that up to 15% CRTS content in concrete increases the density of hardened concrete in comparison to plain concrete. However, glass content above 15% decreases the density [23]. Changing the glass content from 15 to 20% produces the largest increase in water absorption, which suggests that glass content above 15% leads to higher porosity than specimens without CRTS. The study by Shayan and Xu also indicates that the density decreases

CRTS content (%)	0	5	10	15	20
Slump (cm)	17	16	15.75	15	14.25

Table 3. Effect of CRTS content on the workability.

CRTS content (%)	**Dry density (kg/m^3)**	**Saturated density (kg/m^3)**	**Water absorption (%)**
0	2213	2354	6.46
5	2219	2363	6.26
10	2289	2427	6.05
15	2274	2413	6.09
20	2198	2354	6.97

Table 4. Densities and water absorption of the specimens.

with glass addition above 15% as aggregate or glass powder [2]. The dry and saturated density of the concrete exhibits identical trends. **Table 4** shows that the water absorption decreases from 6.46 to 6.05 when the CRTS composition reaches 10%. Water absorption increased when CRTS content is higher than 10% in the concrete. This increase is remarkable when the fraction is 20%.

3.3. Compressive strength

The use of 15 and 20% CRTS decreased the compressive strength in concrete over the first 28 days in **Figure 3**. The study by Maschio et al. (2013) presents a similar relationship [39]. After 28 days, the rate of increase of strength was faster than that of P and specimens with 5 and 10% glass aggregate and approached these values for 15 and 20% CRTS in concrete [8]. This result demonstrates that the glass contents of 15 and 20% have a pozzolanic effect that becomes more obvious after 28 days [15]. The glass replacements of 5 and 10% do not significantly change either the early or the end strength values in comparison with P [6]. The specimen with 5% CRTS exhibited a notably constant value throughout the period of 90 days, which approached approximately 40 MPa after 90 days. An increase of compressive strength was observed for 10, 15, and 20% CRTS from 28 to 90 days, which can be attributed to the pozzolanic effect of CRTS [40]. Intervals of minimum and maximum compressive strengths for all specimens were 13–24, 22–30, 32–39, and 37–41 MPa for 3, 7, 28, and 90 days, respectively. After 90 days, the difference between the minimum and maximum values of the specimens was relatively small [8]. It is remarkable that the interval decreased from 9 to 4 in 90 days. However, the increase in glass content generally decreases the compressive strength [2]. Ling and Poon explained that the compressive strength might be negatively affected by the bonding between the glass particles and the cement paste [11].

SEM micrograph in **Figure 4** displays the interface between concrete and CRTS exposed to compression. This micrograph was obtained by enlarging the field under SEM 500 times. This SEM micrograph was similar to those reported by Ling and Poon: a smooth surface of CRTS can lead to a weaker interface that results in loss of bonding between CRTS and cement paste,

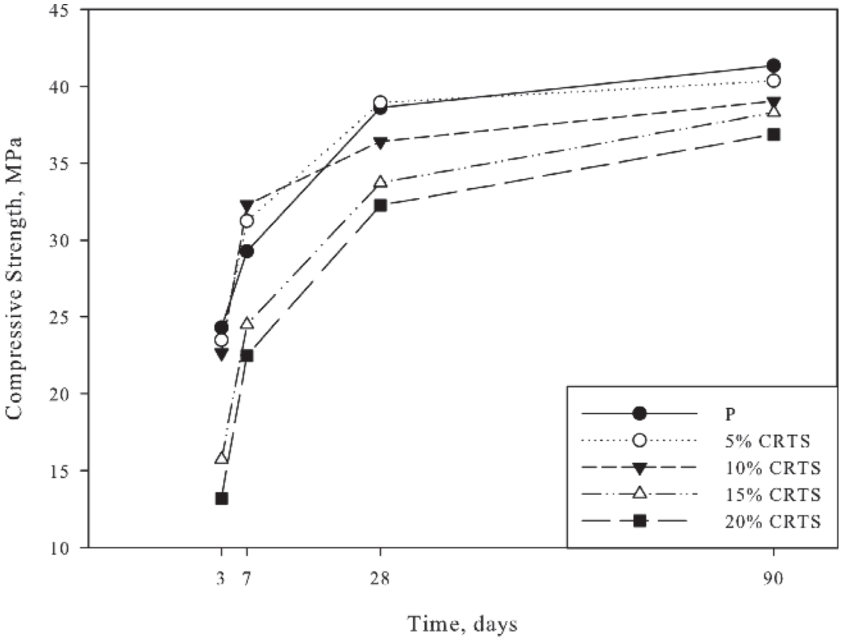

Figure 3. Improvement in compressive strength of the specimens over 90 days.

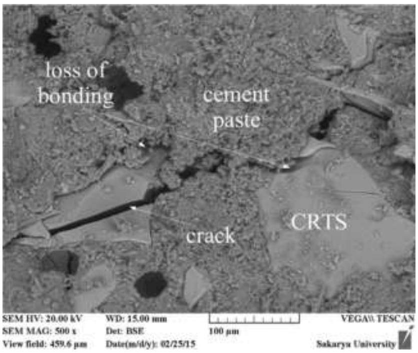

Figure 4. SEM micrographs showing the bond between CRTS and cement paste in concrete after compression loading.

and cracks originating from loading can spread faster [11, 41]. Therefore, the strength of the concrete with glass aggregate decreases [2, 5, 14, 17, 41].

3.4. Flexural strength

The flexural strength-time graph is shown in **Figure 5**. The specimen with 5% CRTS replacement is notably similar to the P sample throughout 90 days in terms of the compressive strength. The flexural strengths for the 5% CRTS and P samples on the 28th and 90th days

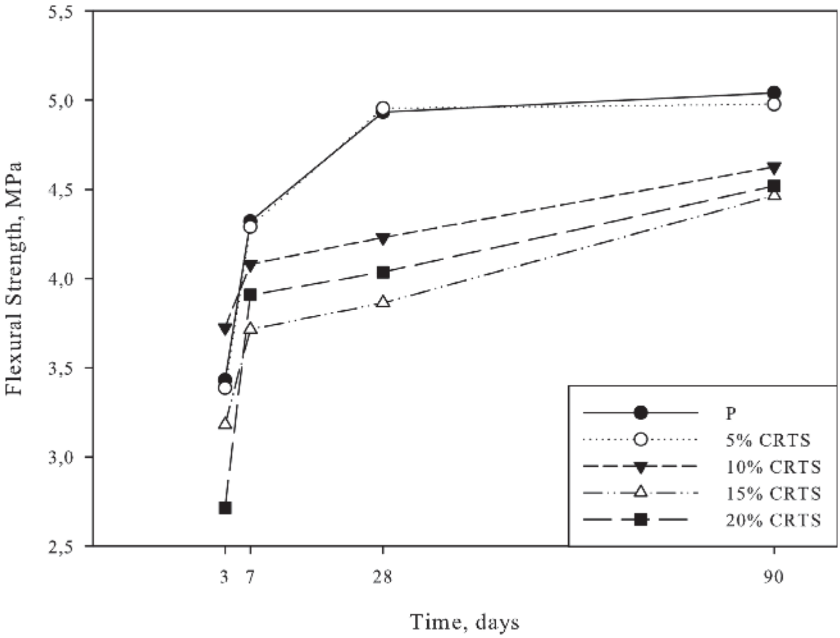

Figure 5. Improvement in flexural strength of the specimens over 90 days.

were almost the same. The specimens with 10, 15, and 20% CRTS have similar trends each other. The maximum difference in values of flexural strength on 90th day decreases to 0.7 MPa, whereas it is 1 MPa after 28 days. The flexural strengths of P and 5% CRTS concrete are approximately 5 MPa at 90 day, whereas the others approach approximately 4.5 MPa. The increase in glass content in the mix generally decreases the flexural strength [2, 8, 14].

3.5. Ultrasonic pulse velocity

The pulse velocity graph in **Figure 6** reveals that the specimen with 20% CRTS replacement exhibits relatively low values for the first 28 days in comparison with the others. The specimens with 5 and 10% CRTS replacement exhibit a relatively higher pulse velocity than P for the first 28 days. Their values are almost identical to that of P at the end of 90 days. All specimens have notably similar pulse velocity values at the end of 90 days, and there are also differences between 28 and 90 days, as shown in the graphs of compressive and flexural strengths in **Figures 3** and **5**. The ultrasound pulse velocity is approximately proportional to the compressive and flexural strengths [2].

3.6. Static and dynamic elasticity moduli

Static and dynamic elasticity modulus values are very similar in **Figure 7**. The dynamic elasticity modulus found using the ultrasonic pulse velocity is generally larger than the static

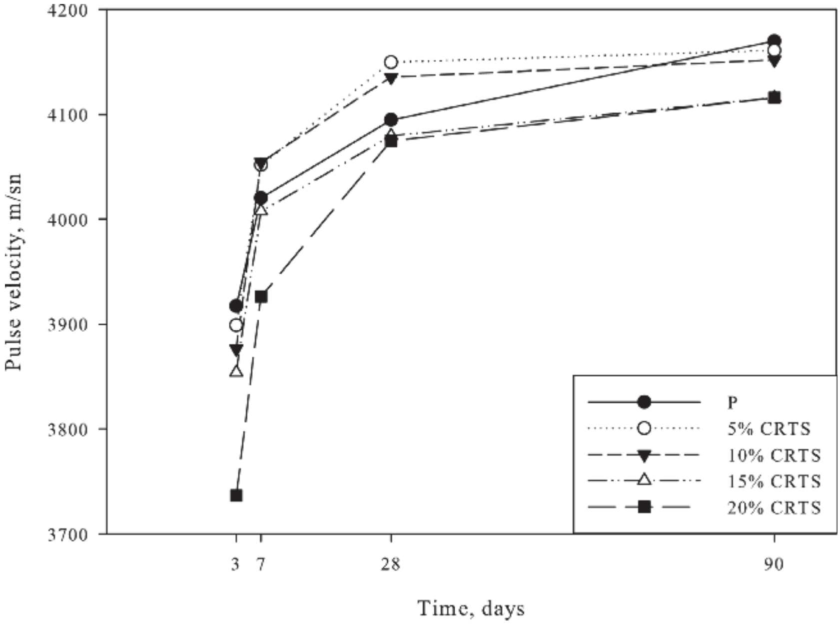

Figure 6. Improvement in ultrasonic pulse velocity of the specimens over 90 days.

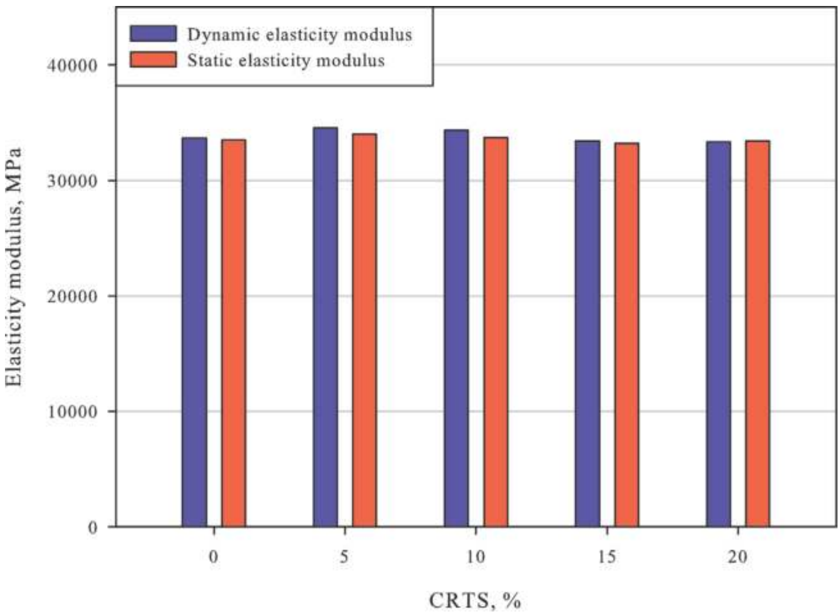

Figure 7. Static and dynamic elasticity moduli of the specimens at 28 days.

elasticity modulus. The specimen with 5% CRTS replacement in concrete has the highest value, and that with 10% glass replacement has a better value than the specimen without CRTS. The specimens with 15 and 20% replacement have notably similar values, which are slightly lower than that of the specimen without CRTS [2, 23]. The elasticity moduli of all specimens are related to the compressive strength, flexural strength, and ultrasonic pulse velocity at 28 days [42].

3.7. Alkali-silica reaction

The 21-day expansion of the mortar bars is shown in **Figures 8** and **9**. In **Figures 8** and **9**, the expansion can be observed to increase with increasing CRTS content and time. The bars with fly ash in **Figure 8** expand slightly less than the bars without fly ash (CRTS-F) in **Figure 9** because of the pozzolanic effect of fly ash [43]. After 21 days, all specimens with CRTS have similar values except for the specimens without CRTS. The highest expansion for the specimens with 20% CRTS is less than 0.03% in **Figures 8** and **9**, which is below the upper limit of 0.1% according to ASTM C1260. The study of Zhao et al. (2013b) also showed the expansion value of FA series mortar samples with glass sand are found to be below 0.1% [44]. The importance of using fine glass was reported by Ismail and Al-Hashmi, who used aggregate with a fineness modulus of 2.36, which decreased the ASR. In this study, the fineness modulus of the CRTS is 2.95, which indicates that the aggregate is sufficiently fine for ASR resistance.

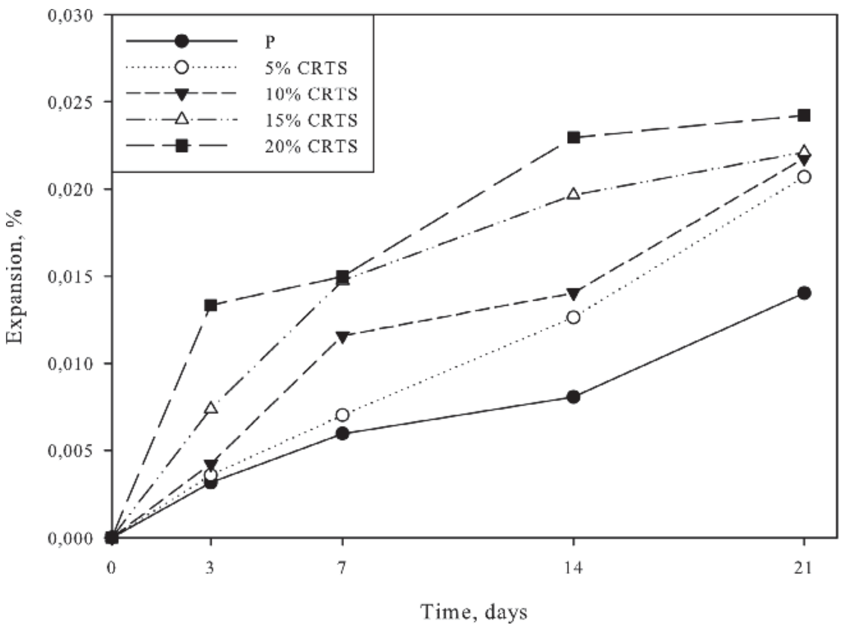

Figure 8. Improvement in ASR of the specimens over 21 days.

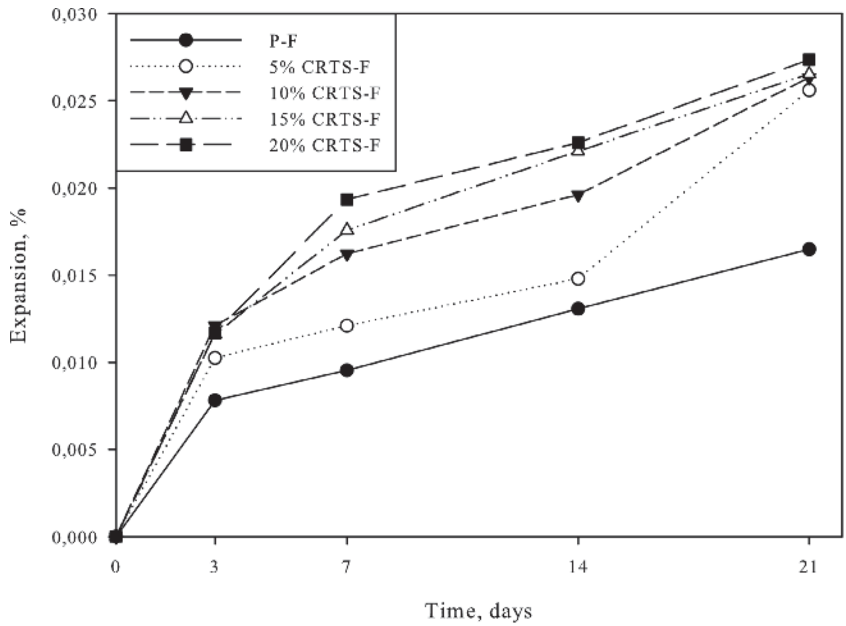

Figure 9. Improvement in ASR of the specimens without fly ash over 21 days.

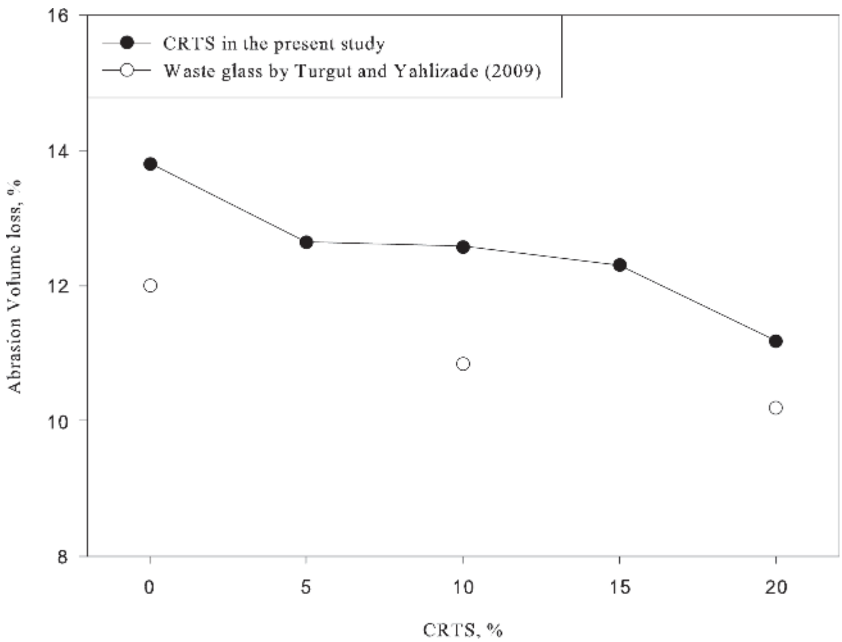

Figure 10. Change in abrasion loss (%) of the specimens after 28 days as a function of CRT comparing with the research by Turgut and Yahlizade.

3.8. Abrasion resistance

Figure 10 shows the results of abrasion volume loss (%) found using the Bohme abrasion test machine. It clearly appears that the abrasion volume loss (%) decreases with increasing [18–20, 45]. The research by Turgut and Yahlizade supports these results. They found that the use of glass replacement with fine aggregate up to 20% by weight decreased the abrasion volume loss (%). In this research, the decrease slows down between 5 and 15%; however, Turgut and Yahlizade did not investigate these proportions. The difference of abrasion volume loss of specimen with glass content of 20% compared to the specimen without CRTS is approximately 2.5% in this research; whereas it was 2% in the research by Turgut and Yahlizade. Their study was based on concrete paving blocks and window glass.

4. Conclusions

Based on the results of the experimental studies carried out in the research, the results obtained are presented below:

1. CRTS slightly affects the slump values; an increase in the glass content in concrete reduces the slump value.
2. CRTS content up to 10% increases the density and decreases water absorption. However, a CRTS content of 20% increases water absorption in the concrete. This shows that the CRTS up to 10% in concrete increases the filling by entering the gaps and introduces voids above 10%.
3. Increasing the CRTS content decreases the compressive and flexural strengths, except when the content is 5%. Although CRTS content of 15 and 20% reduces the strength, the strength of these specimen increases more than that of the other specimens after 28 days, which indicates a pozzolanic effect. This effect is less observed in specimens with 10% CRTS.
4. CRTS content of 15 and 20% leads to the lowest pulse velocity values in comparison with the other concrete. The specimens with CRTS content of 5 and 10% exhibit higher pulse velocity compared to the specimens without CRTS until 28 days have passed. All values are close to each other at 90 days.
5. Static and dynamic elasticity moduli exhibit similar trends to each other and also to the compressive strength at 28 days. The concrete specimens with CRTS content of 5 and 10% have larger moduli than P. The elasticity moduli decrease when the CRTS content reaches 15%. Specimens with 20% CRTS exhibit similar moduli to those with 15% CRTS.
6. An increase in CRTS content decreases the ASR resistance but not to a problematic level because the level is below the 0.1% ASTM C1260. The specimens with fly ash have lower values than those without fly ash. The use of fly ash in concrete with CRTS has a positive effect against ASR, as expected.

7. The abrasion volume loss (%) decreases with increasing CRTS content up to 20%. The decrease is approximately 2.5%.

In conclusion, the concrete with CRTS aggregate exhibits a performance similar to that of the concrete without CRTS. This result shows that the use of CRTS can contribute to the properties of concrete. The mixture of CRTS in concrete can be adjusted according to the application and desired specific properties. The performance of abrasion resistance of concrete with 20% CRTS is especially notable. Research is needed on concrete with more than 20% CRTS. Furthermore, the use of CRT funnels in concrete is also an important matter because of their lead content. Lead is harmful to the environment. In this respect, recycling of CRT funnels is important, and there is a need for research on this subject.

The study is notable in terms of the potential use of recycled CRTS because of the quantity of waste CRTS used. Concrete properties can be improved with CRTS, resulting in the reduction of piles of waste CRTs when they are used in concrete.

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