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Evaluation of durability of concrete substituted heavyweight waste glass as fine aggregate

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HIGHLIGHTS

- Cathode ray tube (CRT) waste glass was recycled as fine aggregate of concrete.
- Durability of concrete containing CRT glass was investigated.
- As the mixing ratio of waste glass increased, durability is better in the concrete.
- This study showed that CRT waste glass can be used as fine aggregate in concrete.

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ABSTRACT

Concrete is the most widely used construction material, and huge amounts of natural resources are required to manufacture it. With relatively recent rapid industrial development as well as the improvement of people's living standards, the volume of domestic and industrial waste is increasing, and much of this waste is not recycled. Cathode ray tube (CRT) waste glass is an industrial waste material that has been studied by many researchers for use as fine concrete aggregate. As one example of its potential application, nuclear power plants and radioactive waste disposal sites are often located in areas vulnerable to attack by chloride and sulfate, and this may compromise the durability of the concrete structure designed to shield radiation. More durable concrete would therefore be desirable. We studied the durability of concrete mixed with waste glass through the following approach. Waste CRT glass containing heavy metals was recycled as fine aggregate for concrete; the durability of the concrete was investigated by performing freeze-thaw resistance, sulfate attack, and chloride ion penetration measurement. The test results showed that as the mixing ratio of waste glass increased, the freezing and thawing resistance, sulfate attack resistance, and chloride ion penetration resistance were all better in the concrete containing waste glass than in normal concrete. However, the compressive and the flexural strength of the concrete both decreased due to lower adhesion between cement paste and waste glass. In conclusion, it was confirmed that concrete substituted with heavyweight waste glass could be used in radiation shielding structures.

1. Introduction

Concrete is one of the most widely used construction materials, and it is a fundamental material in nearly all structures. Alternative aggregates are, however, very much needed because aggregate shortages abound due to the exhaustion of natural aggregates and strict environmental restrictions placed on the construction industry. In addition, with rapid industrial development as well as the improvement living standard, the amount of domestic and industrial waste is increasing. Treatment of such types of waste has become a serious issue, and a globally unified effort is needed to implement technologies for effective waste recycling and resource recirculation.

Against this context, several types of industrial waste are currently being used in the manufacturing of eco-friendly materials, which can replace existing construction materials. Among the various types of industrial waste, glass is considered to be the most suitable substitute as an aggregate due to its physical characteristics and chemical composition [1–3]. Furthermore, previous study has shown that recycled glass may be suitable for use in a wide range of applications, including concrete, bricks, and in highway engineering projects [4–7].

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In particular, since 2012, when analog TV broadcasting ended, and systems converted to digital TV broadcasting in South Korea, a large volume of cathode ray tube (CRT) TVs and monitors were discarded and replaced with LCD panels. The amount of electronic waste, including waste CRT glass from CRT TVs and monitors, increased from 910,000 ea. in 2012 to 970,000 ea., and is currently projected to increase to about 10 million ea. in 2020 [8,9]. Just as notable is that most of the old CRT TVs and monitors are not recycled despite the fact that parts, including the CRTs, can be. CRT glass products are classified into panels and funnels, wherein the panels may be reused as glass after washing, but the funnels, containing a large number of heavy metals such as iron and lead, are difficult to treat using conventional recycling technology. Heavyweight waste glass has therefore frequently been illegally dumped or buried in landfills, leading to serious environmental pollution [10]. As a result, it is important to find effective recycling methods for heavyweight waste glass that contains heavy metals. One possible option that has been studied includes applying waste glass as an alternative concrete aggregate [2,10–21], however, studies specifically on the durability of concrete are lacking.

Many of the existing studies involve mortar [11,14,21]. Most studies also used treated waste glass in the form of crushed glass in which heavy metals were removed [15–19]. Such waste glass treatment process is very complicated. In South Korea, a study was conducted to investigate the applicability of heavyweight waste glass crushed solely by a jaw crusher [10,21]. In this paper, heavyweight waste glass was simply crushed by jaw crushers, and not all of the heavy metal in the waste glass was removed, making it a very simple process.

Heavyweight aggregates can be used in heavyweight concrete, and most of the concrete used in radiation shielding in nuclear power plants and radioactive waste disposal involves heavyweight concrete. Nuclear power plants are mainly located on the coast and are susceptible to attack by chlorides, while radioactive waste disposal plants are often located deep underground and are vulnerable to sulfate attack, so these factors need to be considered. In addition to heavyweight aggregate, many researchers have studied the properties and radiation shielding performance of concrete mixed with lead mine waste, waste marble, recycled aggregate, electric arc furnace slag, ferrochromium slag, barite, and minerals [22–30]. Our research confirms that heavyweight waste glass can be used as a fine aggregate of concrete by previous study [21] and improve radiation shielding performance.

In summary, the development of alternative resources is required due to the depletion of natural resources, and efforts to use industrial wastes as alternative resources are continuing. Much research has been conducted on waste glass, which is an industrial waste, as concrete aggregate, and we conducted this study to apply heavyweight waste glass as an ingredient of radiation shielding concrete. In previous studies, lead mine waste, barite, and so on have been used as aggregate in a radiation shielding concrete, and studies on heavyweight waste glass are insufficient.

Thus, this study was conducted to investigate the durability of concrete prepared using heavyweight waste glass containing

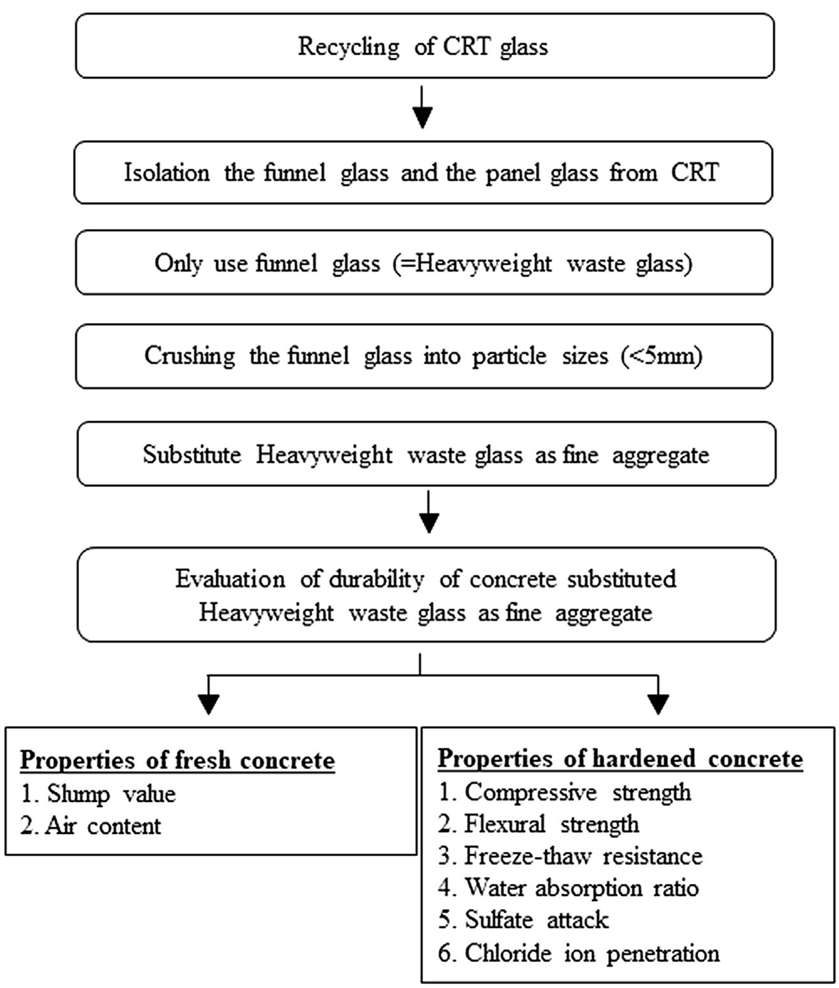

Fig. 1. Research Framework.

heavy metals. Freezing and thawing resistance, permeability resistance, sulfate attack, and chloride ion penetration were compared to quantitatively investigate the effect of heavy waste glass on concrete durability. We also examined whether heavyweight waste glass could be used for concrete shielding structures. An overview of the research framework is illustrated in Fig. 1.

2. Experimental procedures

2.1. Materials

2.1.1. Cement

In this study, Ordinary Portland Cement (OPC) (ASTM C 150 (2007) Type I) [31] was used in all of the mixtures. The physical and chemical compositions of the cement are shown in Table 1.

2.1.2. Aggregate

Crushed gravel was used as a coarse aggregate with a maximum size of 20 mm. The density and absorption ratio of the coarse aggregate was 2.68 g/cm^3 and 0.97%, respectively. River sand was used as a fine aggregate with a maximum size of 5 mm. The density and absorption ratio of the fine aggregate was 2.60 g/cm^3 and 1.01%, respectively. The material properties of the aggregate are shown in Table 2.

2.1.3. Heavyweight waste glass

The heavyweight waste glass used in this study as an alternative fine aggregate was collected from waste CRT funnels. The composition of the CRT glass produced by domestic individual manufacturers is shown in Fig. 2. There was a slight difference between the manufacturers, but there was no significant difference in the ingredients. The collected waste glass was crushed using a jaw crusher. Only crushed waste glass which passed through a 5 mm sieve was used as fine aggregate. The density of the waste glass was 3.0 g/cm^3. The crushed heavyweight waste glass is shown in Fig. 3. The particle size distributions of all fine aggregates used this study are presented in Fig. 4.

2.1.4. Admixture

The admixtures used in this study were an air-entraining agent (A.E.) and a water-reducing agent (W.R.A.) produced by domestic company J. The water-reducing agent was polycarbonate-based.

2.1.5. Experimental variables

The water-to-binder ratio (W/B) was 35%, 45%, and 55%, and the heavyweight waste glass was used as a substitute for fine aggregate at 0%, 50%, and 100%. Test variables and mix proportions of concrete are listed in Tables 3 and 4.

2.2. Test methods

2.2.1. Preparation of specimens

Concrete specimens were prepared in specified sizes according to the durability test items. The specimens for the test of the freezing and thawing resistance and flexural strength were prepared as rectangular columns with a size of 100 × 100 × 400 (mm), while those for the sulfate attack test, the chloride ion penetration test, compressive strength, and water absorption ratio were prepared as cylinders with a size of Ø100 × 200 (mm).

2.2.2. Properties of fresh concrete

To investigate the fresh properties of the concrete, slump value and air content were measured. The slump and air content tests were executed in accordance with ASTM C 143 (2010) [32] and ASTM C 231 (2003) [33], respectively.

Table 2
Material properties of aggregate.

Type	Density (g/cm^3)	Absorption (%)	F.M.
Fine	2.60	1.01	2.48
Coarse	2.68	0.97	7.01
Waste glass	3.00	0.00	3.34

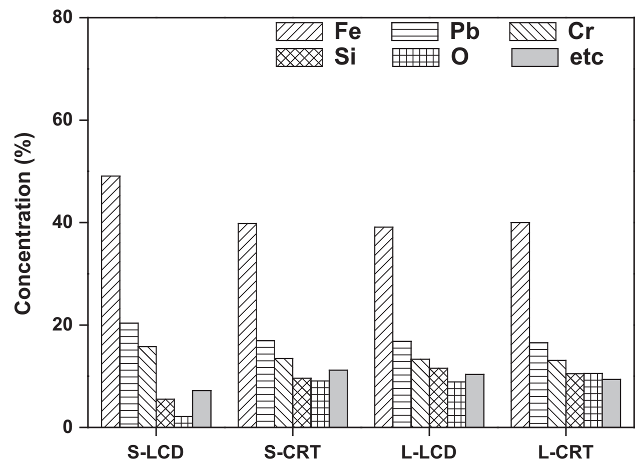

Fig. 2. Composition of waste glass.

Fig. 3. Heavyweight waste glass.

2.2.3. Properties of hardened concrete

Compressive and flexural strength tests were carried out at the curing ages of 7, 28, and 91 days. The compressive strength tests were executed in accordance with ASTM C 39 (2014) [34]. The flexural strength value was measured in accordance with ASTM C 78 (2002) [35].

Table 1
Physical and chemical composition of cement.

Chemical composition (%)						
SiO_2	Al_2O_3	Fe_2O_3	Cao	MgO	SO_3	LOI
21.36	5.03	3.31	63.18	2.89	2.30	1.40
Physical properties						
Specific gravity	Blaine (cm^2/g)	Initial setting time (min)	Final setting time (h)	Compressive strength (MPa)		
				3 Days	7 Days	28 days
3.15	3750	255	6:30	34	43	53

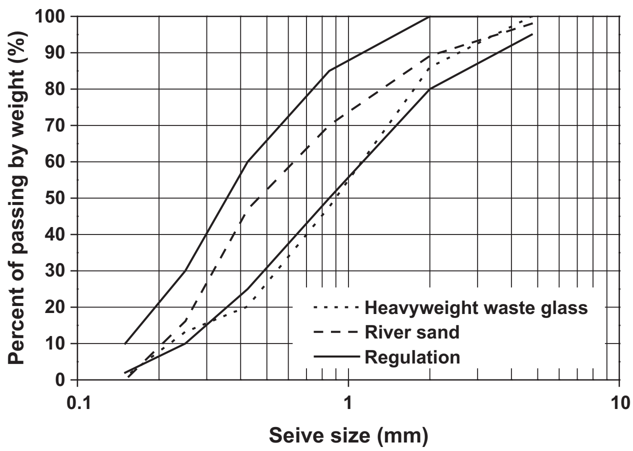

Fig. 4. Grading curve of fine aggregate.

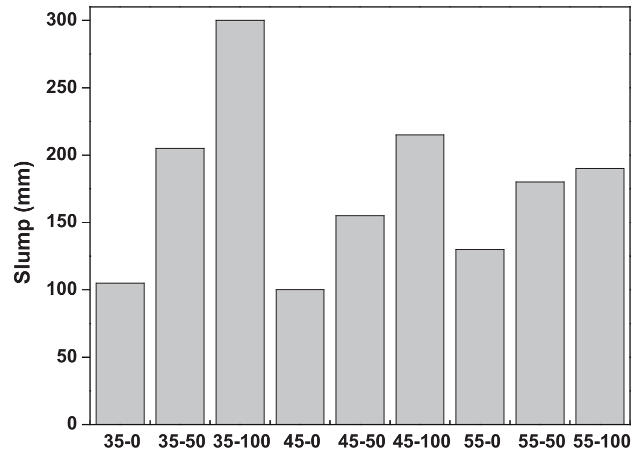

Fig. 5. Results of slump test.

Table 3
Experimental variables.

Conditions	Variables
W/B (%)	35, 45, 55
Heavyweight waste glass substitution ratio (%)	0, 50, 100
Specimen size (mm)	Ø100 × 200 (Compressive strength)
	Ø100 × 200 (Water absorption ratio)
	Ø100 × 200 (Sulfate attack)
	Ø100 × 50 (Chloride ion penetration)
	100 × 100 × 400 (Flexural strength)
	100 × 100 × 400 (Freeze-thaw resistance)
Curing condition	Water curing (20 ± 3 °C)
Curing days	7, 28, 91

Table 5
Increment ratio of slump value.

Type	Slump (mm)	Increment slump (mm)	Increment ratio (%)
35–0	105	–	–
35–50	205	100	95.2
35–100	300	195	185.7
45–0	100	–	–
45–50	155	55	55.0
45–100	215	115	115.0
55–0	130	–	–
55–50	180	50	38.5
55–100	190	60	46.2

To investigate the water absorption ratio of the concrete mixed the waste glass, the absorption ratio of the concrete was measured according to ASTM C 642 (2013) [36].

To evaluate the durability soundness, as it depended on the freezing and thawing of the concrete, the specified specimens were a curing age of 14 days. Then, a freezing and thawing test was performed in accordance with ASTM C 666 (Method B) (2015) [37]. The weight and the relative dynamic modulus of elasticity were measured every 30 cycles.

To investigate the resistance of the concrete to sulfate attack, a test was performed in accordance with JSTM C 7401 (1999) [38]. After 28 days of water-curing following demolding, specimens were dipped in a 10% sodium sulfate solution at the curing ages of 28, 56, and 91 days. Then, the compressive strength and the weight change ratio were measured. For evaluation, the results were compared with those for specimens water-cured for the same periods.

Referring to the electrical accelerated migration test suggested by Tang and Nilsson (ASTM C 1202 (2012)) [39], a chloride ion penetration test was performed by applying a voltage of 30 V for eight hours with a 0.3 M NaOH solution as a positive electrode (+) and a 3% NaCl solution as a negative electrode (−). The specimens were prepared by cutting a cylindrical specimen Ø100 × 200 (mm) to the size of

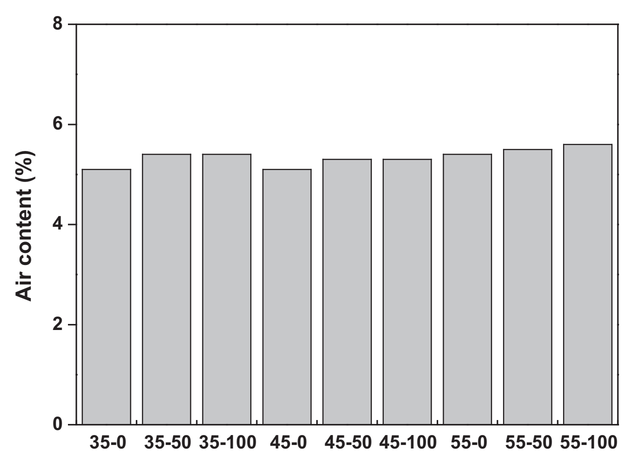

Fig. 6. Results of air content.

Table 4
Mix proportion of concrete.

Type	W/B (%)	S/a (%)	Content of H.G (%)	Unit weight (kg/m^3)					A.E (C × %)	W.R.A (C × %)
				W	C	S	G	H.G		
35–0	35	41	0	167	477	673	999	0	0.06	0.7
35–50			50			337		388		
35–100			100			0		777		
45–0	45	43	0	170	378	738	1008	0	0.05	0.5
45–50			50			369		426		
45–100			100			0		851		
55–0	55	45	0	173	315	792	998	0	0.01	0.4
55–50			50			396		457		
55–100			100			0		914		

H.G: Heavyweight waste glass, A.E: Air-entraining agent, W.R.A: Water reducing agent.

Ø100 × 50 (mm). The test was performed at the ages of 28 and 91 days in water-curing. The chloride penetration depth was measured by a colorimetric method. After splitting the specimen, a 0.1 N $AgNO_3$ solution was sprayed onto the specimen. Then, the penetration depth was measured and the diffusion coefficient was calculated. The penetration depth was calculated as an average of three specimens.

3. Results and discussion

3.1. Slump value and air content

Fig. 5 shows the results of the concrete slump value depending on the W/B ratio and the waste glass substitution ratio. The slump of the concrete increased as the waste glass substitution ratio increased, regardless of the W/B ratio, and the increment of the slump decreased as the W/B ratio increased. As shown in Table 5, in the case of 100% substitute of waste glass, the slump increment rate of W/B 35% was 185%, but increased the rate of W/B 55% was 46%. Substitution of waste glass could increase slump, especially at low W/B.

In contrast, previous studies conducted by substituting low-density waste glass for fine aggregates showed that slump decreased as the waste glass substitution ratio increased [2,4,13,40]. Such a tendency was considered to be related to the density of the waste glass. In the previous aforementioned studies, the density of the waste glass used was similar to or lower than that of sand. However, the density of the waste glass used in this study and in another previous study conducted by mixing CRT waste glass was as high as about 3.0 g/cm^3 [19]. Therefore, the high density of waste glass used as fine aggregate may have increased the slump, and the physical properties of the waste glass including smooth surface and low water absorption may also have affected the slump of the concrete [19].

In addition, in this study, an identical amount of admixture was added to both the concrete containing no waste glass and that containing waste glass. Therefore, the specified slump can be could by using a proper amount of admixture in preparing the high-density waste glass concrete.

Fig. 6 shows the air content depending on the waste glass substitution ratio and the W/B ratio. As the waste glass substitution ratio increased, air content increased, but only slightly. The range of the air content was from 5.1% to 5.6%, indicating that the air content was not significantly dependent on the W/B ratio or on the waste glass substitution ratio.

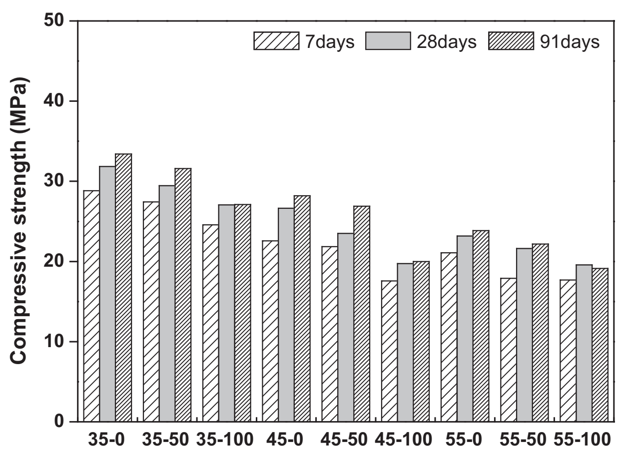

Fig. 7. Compressive strength.

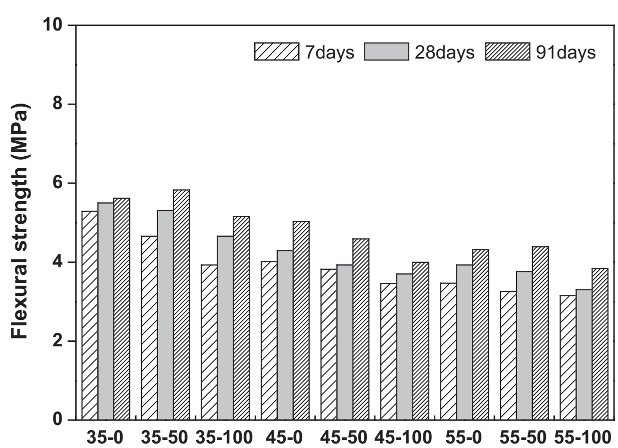

Fig. 8. Flexural strength.

3.2. Compressive strength and flexural strength

Fig. 7 show the results of the compressive strength test with the concrete containing waste glass. The results show that the compressive strength decreased as the waste glass substitution ratio increased. The smooth surface of the waste glass may hinder the adhesion to the cement paste, reducing the compressive strength. Previous studies involving waste glass in cement showed similar results [2,4,15,19,20,40].

Fig. 8 shows the flexural strength of the concrete. Under all conditions, the flexural strength decreased as the waste glass substitution ratio increased, as also shown by previous studies [2,4]. This is why the relatively smooth surface of the waste glass has a lower adhesion to cement paste than it does to sand. Tables 6 and 7 summarize the test results and reduction ratio of compressive and flexural strength. According to test results, when the 100% fine aggregate is substituted by waste glass, the average reduction ratio of compressive and flexural strength was 20% and 15%, respectively.

Table 6
Reduction ratio of compressive strength.

Type	7 days		28 days		91 days	
	Compressive Strength (MPa)	Reduction Ratio (%)	Compressive Strength (MPa)	Reduction Ratio (%)	Compressive Strength (MPa)	Reduction Ratio (%)
35–0	28.8	–	31.9	–	33.4	–
35–50	27.4	4.8	29.5	7.5	31.6	5.4
35–100	24.6	14.7	27.1	15.1	27.1	18.9
45–0	22.6	–	26.7	–	28.2	–
45–50	21.9	3.1	23.5	11.8	26.9	4.6
45–100	17.6	22.1	19.7	26.0	20.0	29.1
55–0	21.1	–	23.2	–	23.9	–
55–50	17.9	15.0	21.6	6.7	22.2	7.0
55–100	17.7	16.1	19.6	15.5	19.1	19.8

Table 7
Reduction ratio of flexural strength.

Type	7 days		28 days		91 days	
	Flexural Strength (MPa)	Reduction Ratio (%)	Flexural Strength (MPa)	Reduction Ratio (%)	Flexural Strength (MPa)	Reduction Ratio (%)
35–0	5.3	–	5.5	–	5.6	–
35–50	4.7	11.9	5.3	3.5	5.8	−3.7
35–100	3.9	25.7	4.7	15.3	5.2	8.2
45–0	4.0	–	4.3	–	5.0	–
45–50	3.8	4.7	3.9	8.4	4.6	8.7
45–100	3.5	13.7	3.7	13.8	4.0	20.5
55–0	3.5	–	3.9	–	4.3	–
55–50	3.3	6.1	3.8	4.3	4.4	−1.6
55–100	3.2	9.2	3.3	16.0	3.8	11.1

Fig. 9 shows the relationship between the root of compressive strength and the flexural strength of the concretes with heavyweight waste glass aggregates [30,41]. The relationship between the root of compressive strength and the flexural strength shows a linear correlation of 0.90 or more. Flexural strength was rated at about 74.5–98.7% of the root of compressive strength.

Fig. 10 shows compressive and flexural strength compared with design codes. In general, the flexural strength is in the range of 1/5 to 1/7 of the compressive strength. Therefore, in many countries, a prediction model of flexural strength using compressive strength is proposed. In this study, test results are compared with the predicted model results of KCI, CEB-FIP, ACI 363, and JSCE model codes [42–45]. As a result of the comparison, the test results were mainly placed between the ACI model and the KCI model. Although the heavyweight waste glass is used as fine aggregate, it is shown that the flexural strength of concrete can be anticipated from compressive strength by the modified model code.

3.3. Freezing and thawing resistance

Figs. 11 and 12 show the results of the freezing and thawing resistance tests of the concrete. The relative dynamic modulus of

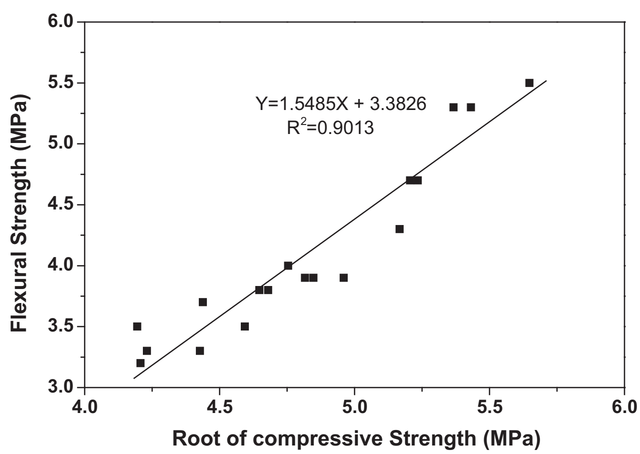

Fig. 9. The relationship between compressive strength and flexural strength.

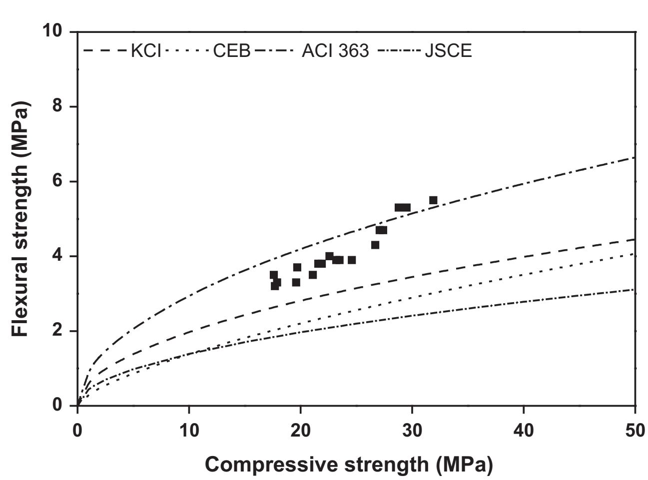

Fig. 10. The relationship between compressive & flexural strength and design codes.

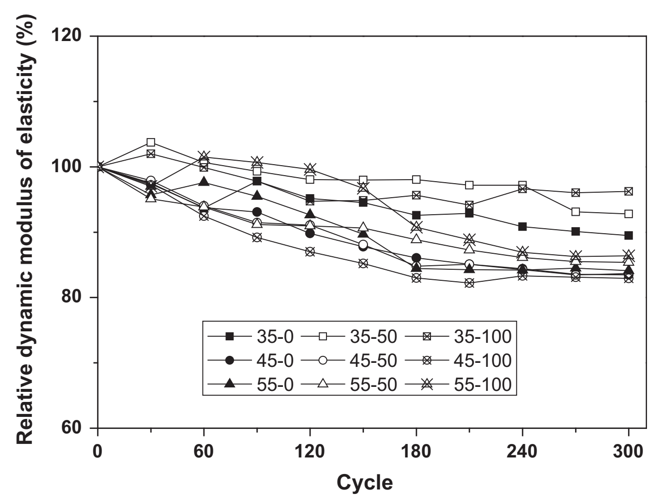

Fig. 11. Relative dynamic modulus of elasticity.

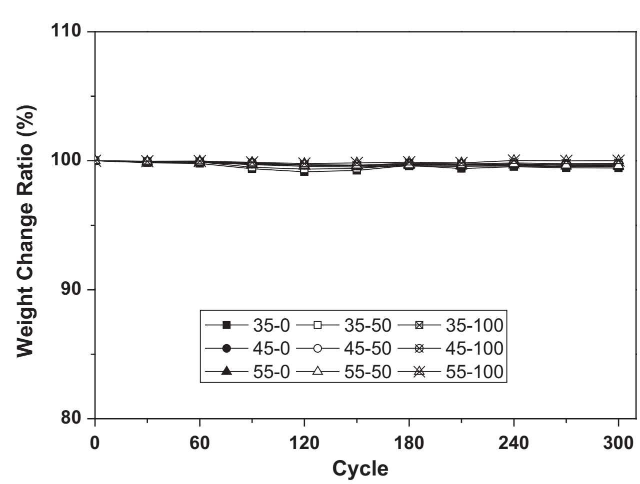

Fig. 12. Weight change ratio.

elasticity of the concrete in a freezing and thawing resistance test of 300 cycles is shown in Fig. 11. The test results show that the relative dynamic modulus of elasticity of the concrete was decreased by the freezing and thawing until 300 cycles under all mixing conditions, but the durability index remained good, ranging from 83 to 96. In other words, waste glass did not significantly affect the freezing and thawing resistance of the concrete. More specifically, the W/B ratio of 0.35 exhibited a durability index of over about 90% under mixed conditions. It can be seen that the effect of freezing and thawing on W/B ratio is larger than that of waste glass. Since waste glass is more impervious than sand and has fewer pores, it can be considered that it is less affected by freezing and thawing than sand. The changes of the weights of the concrete measured at every 30th are were shown in Fig. 12. Under all conditions, concrete had no significant weight change before or after the freezing and thawing and showed excellent durability.

3.4. Water absorption ratio

The water absorption ratio of the concrete was measured to investigate the effect of waste glass substitution on permeability resistance. As shown in Fig. 13, the waste absorption ratio increased as the W/B ratio increased, but decreased as the waste glass substitution ratio increased. Waste glass decreased the water absorption ratio, probably because the water absorption ratio of the waste glass is lower than that of sand [46]. In addition, since glass is impermeable, it might contain less moisture than sand. As shown in Table 8, as the W/B ratio and the substitution ratio increased, the water absorption reduction ratio gradually increased. That is, when the waste glass is used as an ingredient in concrete, permeability resistance is improved.

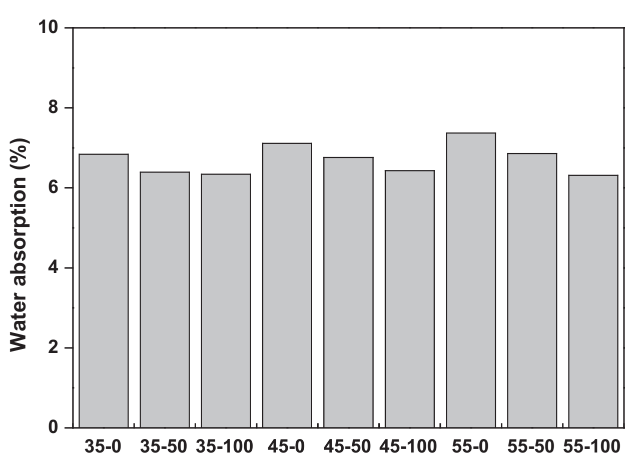

Fig. 13. Water absorption ratio.

Table 8
Water absorption and reduction ratio.

Type	Water absorption ratio (%)	Reduction Ratio (%)
35–0	6.84	–
35–50	6.39	6.6
35–100	6.34	7.3
45–0	7.11	–
45–50	6.76	4.9
45–100	6.43	9.6
55–0	7.37	–
55–50	6.86	6.9
55–100	6.31	14.4

3.5. Sulfate attack

To investigate the sulfate attack resistance of the concrete, the ratio of compressive strength and weight change were measured, with results shown in Figs. 14 and 15, respectively. The compressive strength ratio refers to the ratio of the compressive strength of the concrete dipped in a sulfate solution to that of the concrete

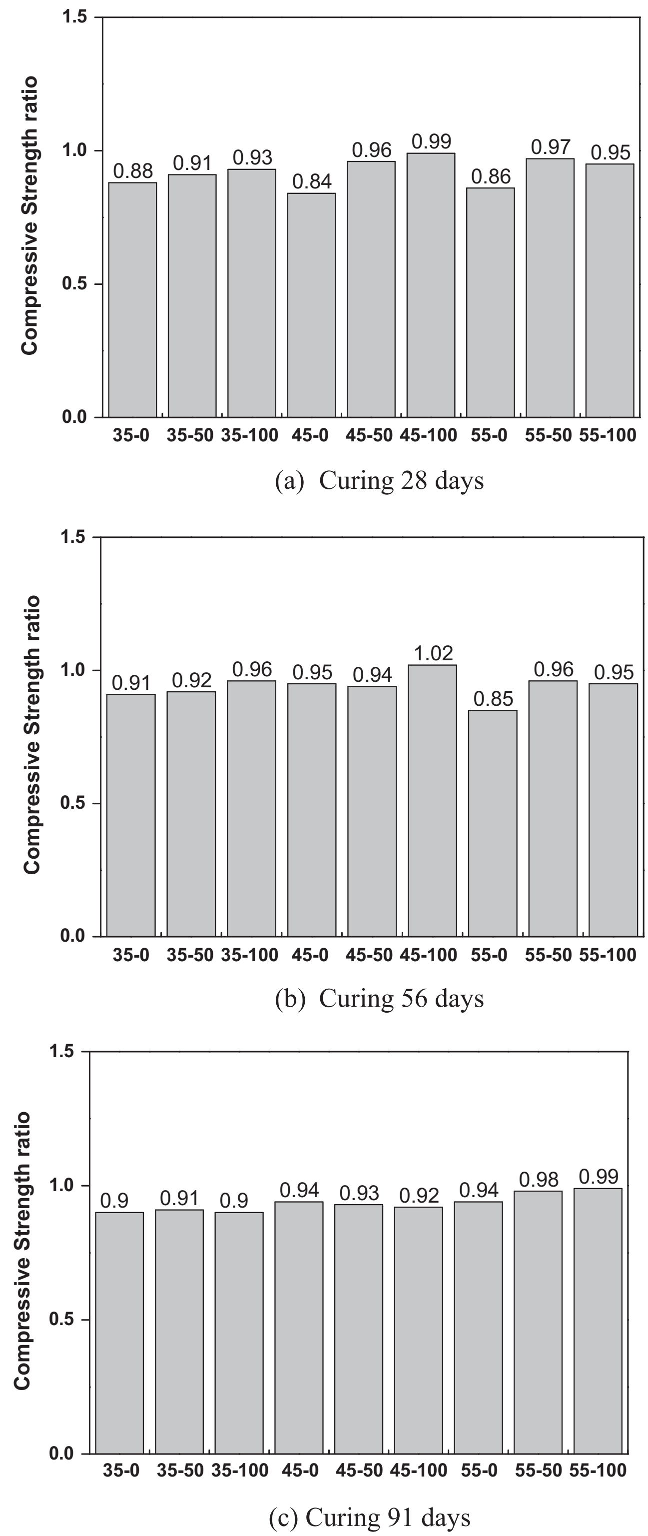

Fig. 14. Results of compressive strength ratio.

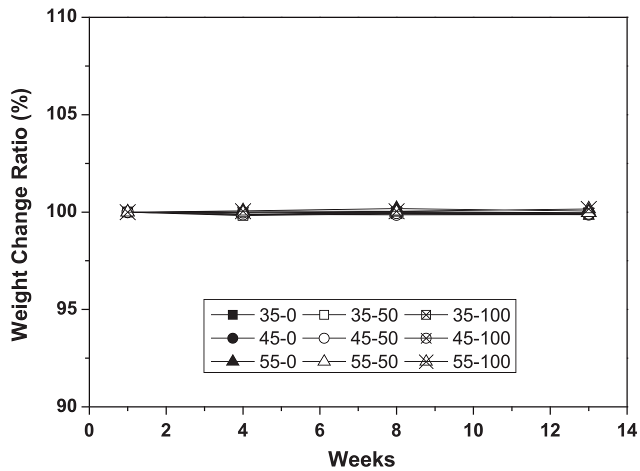

Fig. 15. Weight change ratio.

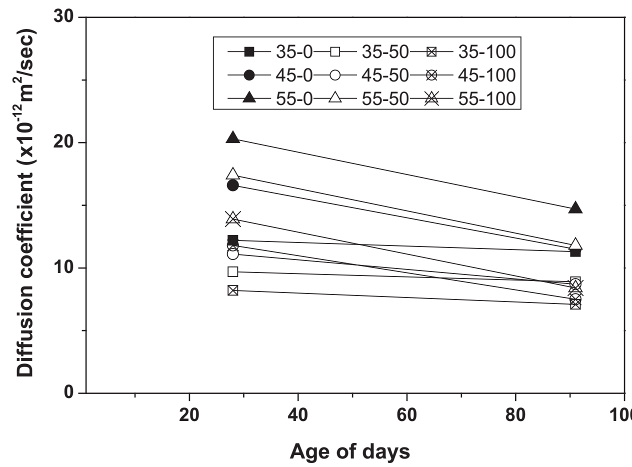

Fig. 17. Diffusion coefficient.

cured in water. A higher compressive strength ratio means a higher resistance to sulfate attack.

As shown in Fig. 14, comparison of the compressive strength showed that the decrease of the compressive strength was lower in the concrete containing waste glass than in the concrete containing no waste glass. This trend of compressive strength decrease was found in all of the mixing conditions; as the age increased, the difference gradually decreased. As waste glass is relatively denser than sand, the resistance to sulfate increased as the waste glass substitution increased. That is, the substitution of waste glass may have improved the resistance to sulfate attack.

Fig. 15 shows the weight change ratio, depending on the W/B ratio, and the waste glass substitution ratio, of the concrete dipped in a 10% sodium sulfate solution for curing ages of 28, 56, and 91 days. The weight change ratio of the concrete depending on the dipping period showed that the weight was not significantly changed by the sulfate attack in all of the mixing conditions. This indicates that concrete containing waste glass has a high resistance to sulfate, as was also shown by previous studies [2,40].

3.6. Chloride ion penetration

The chloride ion penetration resistance of the concrete, depending on the W/B ratio and the waste glass substitution ratio, is shown in Figs. 16 and 17, respectively. As Fig. 16 shows, the chloride ion penetration depth decreased as the waste glass substitution ratio increased in all of the mixing conditions. The chloride ion resistance was further improved by mixing the waste glass at a higher W/B ratio. As shown in Table 9, in the case of 50% substitution of waste glass, the penetration depth reduction was an average of 20%, and in the case of 100% substitution of waste glass, the penetration depth reduction was an average of 36% at a curing of 91 days. The use of waste glass as a substitute for sand can therefore improve chloride penetration resistance [2,13,40].

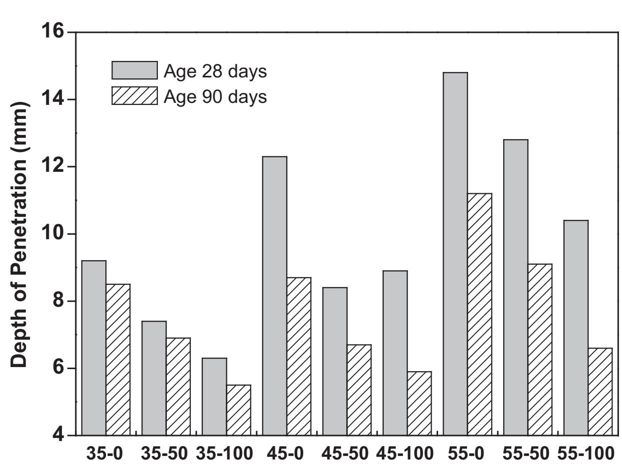

Fig. 16. Depth of penetration.

Table 9
Reduction ratio of chloride penetration depth.

Type	Curing 28 days		Curing 91 days	
	Depth of penetration (mm)	Reduction ratio (%)	Depth of penetration (mm)	Reduction ratio (%)
35–0	9.2	–	8.5	–
35–50	7.4	19.6	6.9	18.8
35–100	6.3	31.5	5.5	35.3
45–0	12.3	–	8.7	–
45–50	8.4	31.7	6.7	23.0
45–100	8.9	27.6	5.9	32.2
55–0	14.8	–	11.2	–
55–50	12.8	13.5	9.1	18.8
55–100	10.4	29.7	6.6	41.1

As shown in Fig. 17, the diffusion coefficient decreased as the waste glass substitution ratio increased at a constant W/B ratio. The results also showed that the diffusion coefficient greatly decreased as the waste glass substitution ratio increased, especially at a high W/B ratio, indicating that the chloride ion penetration resistance was effectively improved. This may have been because of the water impermeability of the waste glass, as well as it having a porosity lower than that of sand. The substitution of the waste glass improved the chloride ion penetration resistance by making the concrete microstructure denser.

4. Conclusions

In this study we evaluated the durability of concrete prepared by substituting heavyweight waste glass for fine aggregates. The following conclusions were obtained from this study.

1) Slump increased as the waste glass substitution ratio increased, but the increment decreased as the W/B ratio increased. Air content slightly increased as the waste glass

substitution ratio increased, but the increase was not significantly dependent on the W/B ratio or on the waste glass substitution ratio.
2) Compressive and flexural strength of the concrete decreased as the W/B ratio and the waste glass substitution ratio increased. The decrease of the strength may have been due to decreased adhesion between the waste glass surface and the cement hydrates.
3) The freezing and thawing resistance test showed that the weight of the concrete did not significantly change due to freezing and thawing. The ratio of the relative dynamic modulus of elasticity was higher than 80% in all of the mixing conditions, indicating that concrete containing heavyweight glass waste had good freeze–thaw resistance.
4) The permeability resistance of the concrete increased as the waste glass substitution ratio increased, because of the low water absorption ratio of the waste glass. Additionally, the heavyweight waste glass content may have improved the sulfate attack resistance of the concrete. Chloride ion penetration resistance is significantly improved when heavyweight waste glass is used as fine aggregate.

It is confirmed that concrete mixes with heavyweight waste glass show excellent durability, thus can be used in radiation shielding structures. The low compressive and flexural strength can be increased by using low W/B ratio and low air content. In subsequent studies, we will evaluate the possibility of concrete containing heavyweight waste glass through a direct shielding performance verification test.

Conflict of interest

None.

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