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Waste E-glass particles used in cementitious mixtures

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Abstract

The properties of concretes containing various waste E-glass particle contents were investigated in this study. Waste E-glass particles were obtained from electronic grade glass yarn scrap by grinding to small particle size. The size distribution of cylindrical glass particle was from 38 to 300 μm and about 40% of E-glass particle was less than 150 μm. The E-glass mainly consists of SiO_2, Al_2O_3, CaO and MgO, and is indicated as amorphous by X-ray diffraction (XRD) technique. Compressive strength and resistance of sulfate attack and chloride ion penetration were significantly improved by utilizing proper amount of waste E-glass in concrete. The compressive strength of specimen with 40 wt.% E-glass content was 17%, 27% and 43% higher than that of control specimen at age of 28, 91 and 365 days, respectively. E-glass can be used in concrete as cementitious material as well as inert filler, which depending upon the particle size, and the dividing size appears to be 75 μm. The workability decreased as the glass content increased due to reduction of fineness modulus, and the addition of high-range water reducers was needed to obtain a uniform mix. Little difference was observed in ASR testing results between control and E-glass specimens. Based on the properties of hardened concrete, optimum E-glass content was found to be 40–50 wt.%.

Keywords: Mixture proportioning; Alkali-aggregate reaction; Compressive strength; Durability; Waste management

1. Introduction

Waste glass as other industry by-products can be reused/recycled to prevent from environmental problems resulting from improper solid waste disposal. In Taiwan, most of waste glass from containers, windows, light bulbs, E-glass, etc. are to be stockpiled or sent to landfill [1]. Waste E-glass material is chopped from electronic grade glass yarns, which are mixed with epoxy resin to reinforce integrated circuit (IC) board. Hundred thousand tons of waste E-glass materials from electronic manufacturing plants need to be disposed per year. Traditional landfill or stockpile method is not an environment-friendly solution and the disposal process is also very difficult to meet EPA regulations recently. How to reuse the non-disposable waste E-glass becomes an important research topic.

Many efforts have been made to use industry by-products such as fly ash, silica fume, ground granulated blast furnace slag (ggbs), glass cullet, etc., in civil constructions for many years [1–6]. The potential applications of industry by-products in concrete are to be partial aggregate replacement or partial cementitious materials, depending on their chemical composition and grain size [7–12]. Previous studies have indicated the successful use of fly ash and silica fume as partial cement replacement materials in concrete mix, in which pozzolanic reaction may improve concrete strength as well as durability [13–15]. Glass cullet from glass containers has been used as aggregate in road constructions and building materials such as tiles and bricks [16]. Recent studies [11,12,17] have shown that reuse of very finely ground waste glass in concrete has economical and technical advantages. For solving the disposal of large amount of waste E-glass material, reuse in concrete industry may be the most feasible application. Waste E-glass can be used as coarse aggregate, fine aggregate, cementitious materials or ultra fine filler in concrete, depending on its chemical composition and particle size.

A possible disadvantage of using glass or glass fibers in concrete is deleterious effect caused by alkali-silica reaction (ASR). The chemical composition and particle size of glass were reported to influence the susceptibility of the chemical reaction [2,8]. Silica-rich glass particles may react with the

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Table 1
Chemical compositions of various recycled materials and Type I cement (by wt.%)

Chemical compositions	E-glass	Container glass	GGBS	Fly ash	Type I cement
SiO_2	54	73	34	57	21
Al_2O_3	15	1	14	24	6
Fe_2O_3	0	0	1	8	3
CaO	17	12	42	2	64
MgO	4.5	0.6	6.5	1.3	2.9
Na_2O+K_2O	0.8	13.5	–	0.9	0.6

alkali in the pore solution of concrete to induce internal stress and result in potential durability problems. E-glass particle has lower SiO_2 content comparing with regular glass. The use of fly ash and ggbs in the mixes can reduce the alkali concentration in concrete, which may inhibit the expansion of concrete [2,18]. In addition, ASR induced expansion could be reduced when fine glass was incorporated in concrete as supplementary cementitious material [11,12,17]. In general, three major characteristics were found in pozzolanic material: high silica content, X-ray amorphous, and large specific surface area. Fine grain size can provide large specific surface area, which may influence the effect of E-glass addition on concrete. And, it was also found if a low reactive pozzolan was mixed with a high reactive pozzolan, the combined pozzolanic activity could be promoted [11,13].

Shayan and Xu [12] have depicted that glass could be used as coarse aggregate, fine aggregate, or supplementary cementitious material in concrete. Coarse glass used as aggregates may induce ASR expansion in concrete, but fine glass powder could suppress ASR tendency, i.e. glass may satisfy the requirements of a pozzolan if its particle size is small enough to eliminate the alkali-silica reaction in concrete.

A series of laboratory tests were conducted to assess the properties of concretes containing various amounts of E-glass particles. The size effect of E-glass particle on workability, compressive strength, sulfate resistance, chloride-ion penetration, and potential alkali reactivity were also reported.

2. Methods

2.1. Materials

Waste E-glass particles were crushed and ground from the electronic grade glass fiber scrap, which was an industrial by-product of IC-plate manufacturing plants in Taiwan. The chemical compositions of E-glass are listed in Table 1 comparing with container glass, class F fly ash, ground granulated blast-furnace slag and Type I Portland cement. The SiO_2 and (Na_2O+K_2O) of E-glass are much less than regular container glass and the equivalent reactive component ($SiO_2+Al_2O_3+Fe_2O_3$) is about the same. Waste E-glass has higher CaO content than class F fly ash, and higher SiO_2 content than ggbs. The SiO_2 content of E-glass is 54%, not much different from fly ash. The specific gravities of E-glass and river sand are almost equal. The fineness modulus of river sand is 2.78. The size distribution of E-glass particles is from 38 to 300 μm and 40% of E-glass particles is less than150 μm as indicated in Tables 2 and 3. The E-glass particle is in cylindrical shape with a diameter of 12.4 μm and is amorphous by X-ray diffraction analysis as shown in Figs. 1 and 2. The modulus of elasticity of E-glass is about 72.5 GPa, which is higher than that of regular container glass.

Table 2
Physical properties of E-glass particle and fine aggregate

Properties	E-glass particle	Fine aggregate
Special gravity	2.56	2.65
Absorption (%)	<0.2	0.75
Color	white	dark
Shape	cylindrical	angular

Table 3
Sieve analysis of E-glass particles and fine aggregate

Sieve # (size)	E-glass particles		Fine aggregate	
	Retained on sieve (wt.%)	Cumulative retained on sieve (wt.%)	Retained on sieve (wt.%)	Cumulative retained on sieve (wt.%)
#4 (4.75 mm)	0.00	0.00	0.91	0.91
#8 (2.36 mm)	0.26	0.26	12.52	13.43
#16 (1.18 mm)	1.27	1.53	24.49	37.92
#30 (600 μm)	9.31	10.84	20.70	58.62
#50 (300 μm)	7.89	18.73	18.07	76.69
#100 (150 μm)	43.60	62.33	13.39	90.08
#200 (75 μm)	26.05	88.38	–	–
Bottom	11.62	100.00	9.92	100.00
Fineness modulus	0.94		2.78	

The E-glass contents are calculated as weight percent of fine aggregate in the control mix. The equivalent fineness modulus of mixed fine aggregate with various E-glass contents is between 1.86 and 2.78 as indicated in Table 4. The E-glass particles can be considered as partial fine aggregate substitute and/or supplementary cementitious material by taking the particle size effect into account. The divided particle size is assumed to be 75–150 μm.

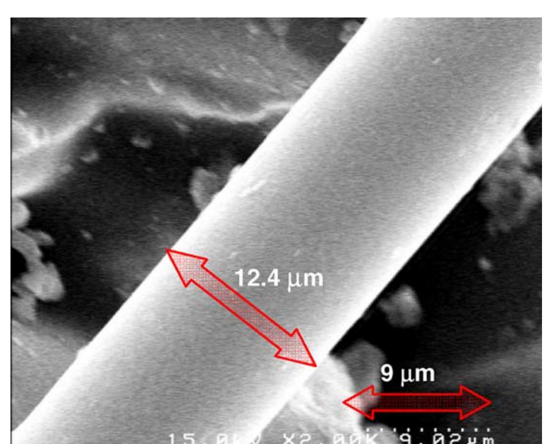

Fig. 1. SEM observation of E-glass.

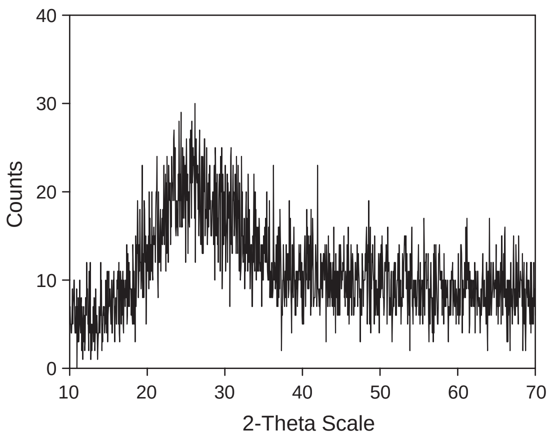

Fig. 2. X-ray diffraction spectrum of E-glass.

Table 5
Concrete mix proportions (kg/m^3)

Mix no.	E-glass content (%)	Water	Cement	S/F [a]	E-glass	Fine aggregate	Coarse aggregate
A0	0	205	205	77/19	0	979	764
A1	10	205	205	77/19	98	878	764
A2	20	205	205	77/19	194	778	764
A3	30	205	205	77/19	291	678	764
A4	40	205	205	77/19	386	579	764
B0	0	225	180	36/9	0	998	764
B1	10	225	180	36/9	99	895	764
B2	20	225	180	36/9	198	793	764
B3	30	225	180	36/9	296	691	764
B4	40	225	180	36/9	394	591	764
B5	50	225	180	36/9	490	490	764

[a] S/F: slag/fly ash.

2.2. Concrete mixes

Two control mixes are proportioned with reference to ACI 211.1 [19] and modified with various E-glass particle contents as listed in Table 5. The ggbs and fly ash are incorporated in the mix to reduce the alkali concentration and to activate the ground waste glass reaction according to the findings from previous studies [11,13]. By considering to use waste E-glass particles in the mixes as many as possible and to achieve suitable workability, two water/binder ratios of 0.68 and 1.0 were selected. The equivalent water/binder ratios are computed according to the equivalent percentage of supplementary cementitious material, which is determined by the E-glass content and particle size. As indicated in Table 6, the equivalent water/binder ratios are between 0.46 and 0.68 for Mix A and between 0.55 and 1.00 for Mix B, respectively.

2.3. Workability

The workability was evaluated by conducting slump test in accordance with ASTM C 143-03 [20]. The slumps for control mixes were 200–220 mm. As the E-glass content increases, the slump decreases due to the reduction of equivalent fineness modulus and the negative effect of cylindrical shape of glass particle as shown in Fig. 3. For concretes with glass content over 30%, high-range water reducer admixture is needed to obtain a uniform mix as shown in Fig. 4. The dosage of admixture is about 1.5% by weight of binder in this study.

Table 4
Equivalent fineness modulus for various E-glass contents

E-glass content (%) $W_g/(W_g+W_{fa})$ [a]	All E-glass as partial fine aggregate substitute	E-glass (Ø>75 μm) as partial fine aggregate substitute [b]	E-glass (Ø>150 μm) as partial fine aggregate substitute [b]
0	2.78	2.78	2.78
10	2.59	2.62	2.69
20	2.41	2.47	3.60
30	2.23	2.30	2.51
40	2.04	2.14	2.40
50	1.86	1.97	2.29

[a] g: E-glass; fa: fine aggregate.
[b] Ø: particle size.

2.4. Compressive strength test

Compressive strength test was conducted in accordance with ASTM C 39-04 [21] to evaluate the strength development of concrete containing various E-glass contents at the age of 7, 28, 91 and 365 days, respectively. Twenty Ø 100×200 mm cylindrical specimens were cast for each batch following the specifications of ASTM C 31-03 [22]. Twenty-four hours after casting, the specimens were demolded and cured in a tank with saturated lime water until testing.

2.5. Sulfate-immersion test

Sulfate-immersion test was performed with reference to ASTM C 267-01 [23] to evaluate the resistance of E-glass concretes subjected to sulfate attack, which may be resulted from seawater or contaminated ground water. The volume expansion of chemical reaction induces internal stresses, which may generate internal cracks and ultimately lead to failure. The specimens were Ø 100×200 mm cylinders which were cast and cured in saturated lime water until testing. After measuring the weight, the specimen was immersed in saturated sulfate solution

Table 6
Equivalent water/binder ratios for various E-glass contents

Mix no.	E-glass content (%)	Equivalent W/B ratio	
		E-glass (Ø<75 μm) as cementitious materials	E-glass (Ø<150 μm) as cementitious materials
A0	0	0.68	0.68
A1	10	0.66	0.61
A2	20	0.63	0.55
A3	30	0.61	0.50
A4	40	0.59	0.46
B0	0	1.00	1.00
B1	10	0.95	0.86
B2	20	0.91	0.75
B3	30	0.87	0.67
B4	40	0.83	0.60
B5	50	0.80	0.55

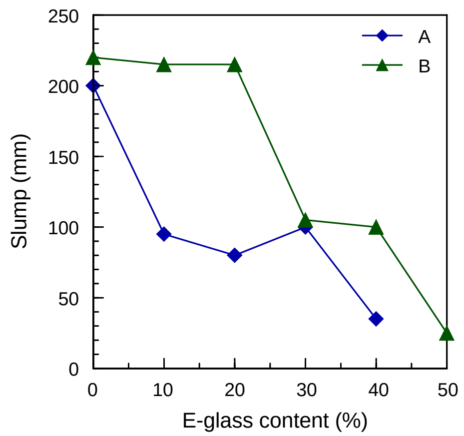

Fig. 3. Slump vs. E-glass content curves.

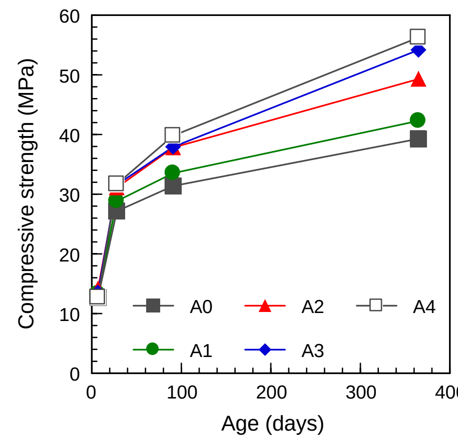

Fig. 5. Compressive strength development curves for mix A.

for 24 h and then oven-dried at 110 ± 5 °C for 24 h. The wet-and-dry procedure was repeated for five cycles and the weight loss and strength reduction of the specimen was recorded every cycle. The surface condition of the immersed specimen was also observed.

2.6. Rapid chloride penetration test (RCPT)

Rapid chloride penetration test (RCPT) was carried out according to the specifications of ASTM C 1202-97 [24]. It involves the application of 60 V in a designated electric cell to accelerate the chloride ion movement in concrete specimen. Testing specimen was Ø 100 × 50 mm circular plate, which was cut from the middle portion of a Ø 100 × 200 mm cylinder. The current was recorded every 30 min in a 6-h period. The total charge passed obtained by integrating the current with time would be used as an index to evaluate the resistance of chloride-ion penetration into concrete.

2.7. Alkali silica reaction test

Alkali silica reaction test was conducted following the standard test method of ASTM C 1260-01 [25], which permitted for detection within 16 days of the potential for deleterious alkali-silica reaction of aggregate in mortar bar. The mix proportion of mortar was 1 part of Portland cement to 2.25 parts of graded aggregate by mass and water/cement ratio was 0.47. Fine aggregate was replaced by 5, 10, 15 and 20 wt.% of E-glass particles in E-glass mortars, respectively. Mortar specimen was 25 × 25 × 300 mm prism. After demolding and taking an initial comparator reading, the specimen was placed in the water bath at 80 °C for a period of 24 h. And then all the specimens made with each aggregate sample were immersed in 1 N NaOH solution at 80 °C. Subsequent comparator readings of the specimens were made for 1, 3, 7, 10, 14 and 28 days after the zero reading. The difference from the zero comparator reading of specimen at each period was computed and recorded as an average of three samples.

3. Results and discussion

3.1. Compressive strength with various E-glass contents

The compressive strength development curves are plotted in Figs. 5 and 6 for mix A and mix B, respectively. The addition of waste E-glass particles as fine aggregate substitute in concretes

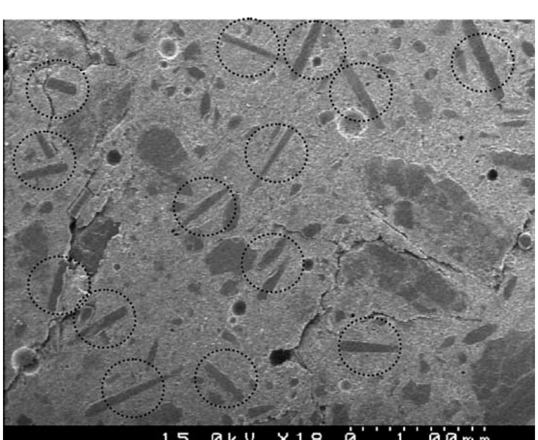

Fig. 4. Uniform distribution of E-glass in concrete.

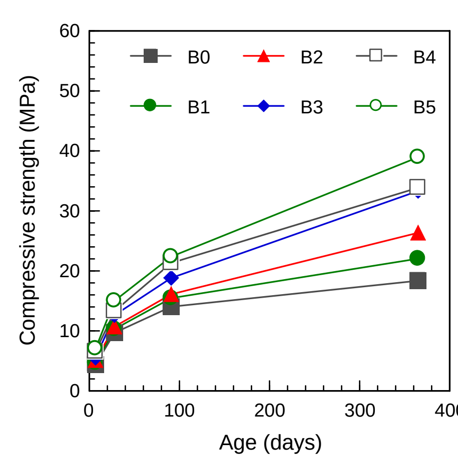

Fig. 6. Compressive strength development curves for mix B.

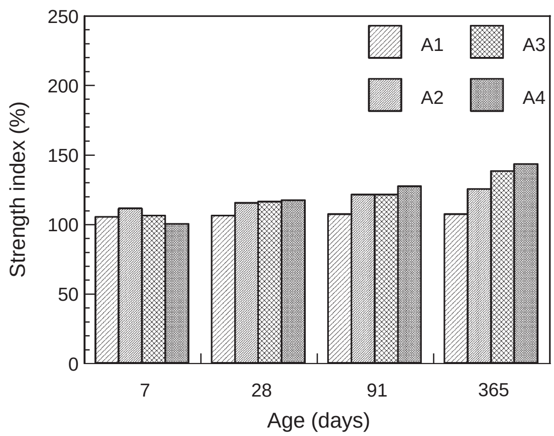

Fig. 7. Strength index for mix A.

appears to significantly improve the compressive strength from early to late ages. And, the compressive strength of E-glass concrete evidently develops even after 91 days in comparison with reference concrete. Strength index is defined as the compressive strength ratio of E-glass concrete and reference concrete and plotted as in Figs. 7 and 8. Index results indicate that E-glass particles play an important role in concrete mixes at all ages. Both hydration and pozzolanic reaction may occur in fine E-glass particles as observed by SEM and illustrated in Fig. 9, consequently affecting concrete strength development. The coarse E-glass can be used as partial aggregate replacement material and the cylindrical particles that act as the crack-arresters in concrete mixes as shown in Fig. 10, which can inhibit internal crack propagation and ultimately increases concrete strength. By taking the equivalent water/binder ratio into account, compressive strength vs. water/binder ratio curves are drawn as indicated in Fig. 11 for all specimens, respectively. Linear regression analysis is conducted to correlate concrete compressive strength with equivalent water/binder ratio. The dividing particle size of E-glass for providing cementitious property can be determined by statistical significance and it is found to be 75 μm by comparing the correlation coefficients. The particle size of 75 μm is about to pass the strength requirement of pozzolanic materials as proposed by the previous study [11] and E-glass has higher aluminosilicate content, which behaves very beneficial performance in concrete mixes.

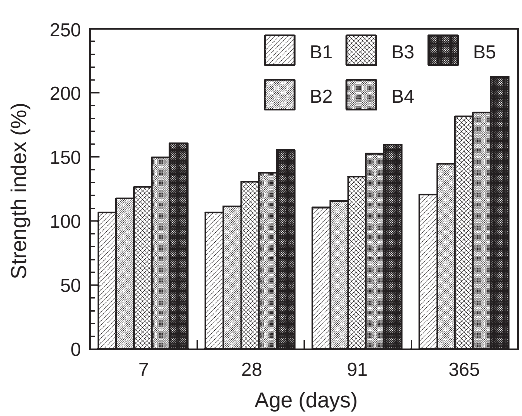

Fig. 8. Strength index for mix B.

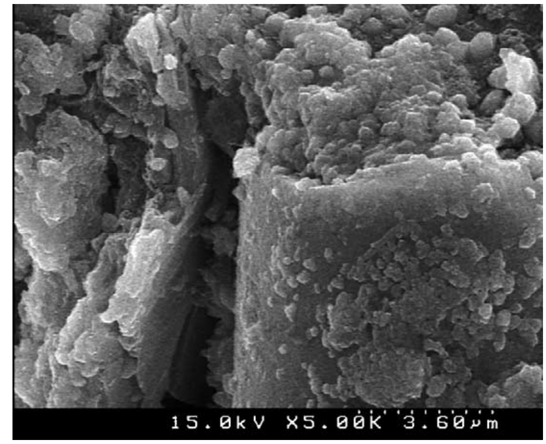

Fig. 9. Products of hydration and pozzolanic reaction of E-glass.

3.2. Sulfate resistance

After five cyclic wet-and-dry exposures, significant weight loss and strength reduction were recorded, which exhibited strong sulfate attack on specimens. Figs. 12 and 13 illustrate that

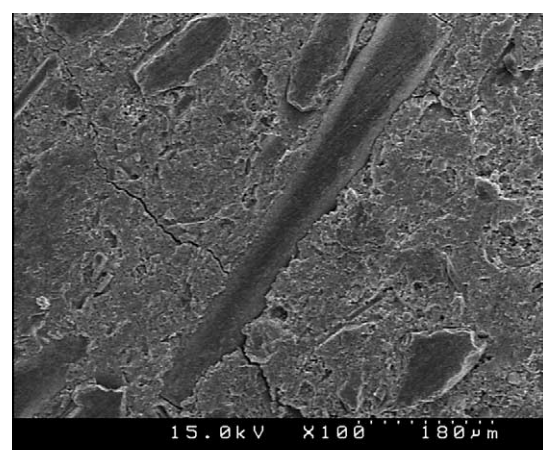

Fig. 10. Crack-arrester effect of E-glass particle.

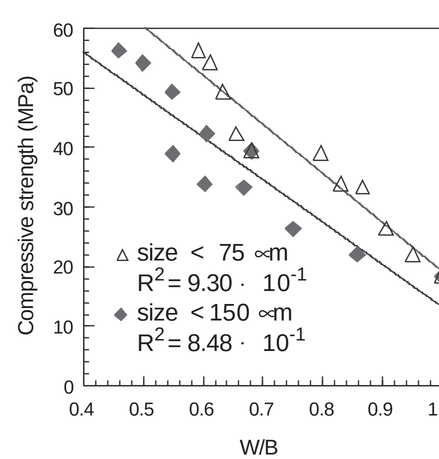

Fig. 11. Compressive strength vs. equivalent water/binder ratio curves.

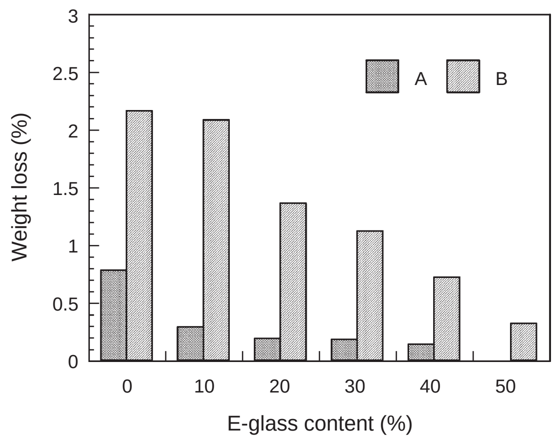

Fig. 12. Weight loss of concrete after five-cycle exposure.

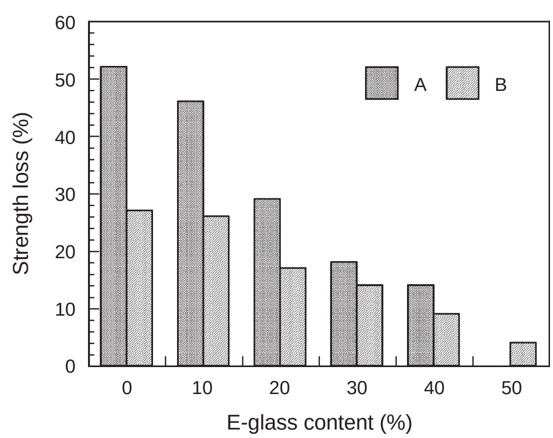

Fig. 13. Strength loss of concrete after five-cycle exposure.

an increase in E-glass content is significantly decrease weight and strength loss, particularly for the specimens with lower water/binder ratio. The surface defects of tested specimens also show a qualitative evidence of sulfate attack. The positive effect of E-glass on sulfate resistance of concrete is very prominent by the illustration in Figs. 14 and 15.

3.3. Resistance to chloride-ion penetration and Potential alkali silica reactivity

The comparative results of the total charges passed are presented in Figs. 16 and 17 for two concrete mixes. It is evident that the total charge passed decrease with an increasing E-glass content. By incorporating E-glass in mix A, the total charge passed is less than 2000 coulombs which indicates very low chloride ion penetrability in concrete specimen. Concretes with E-glass particles have a denser internal structure providing the specimen with effective barrier against chloride-ion penetration. As indicated in compressive strength results, the improvement of chloride-ion penetration resistance is more prominent in E-glass concrete with higher w/c ratio. From previous testing results, E-glass particles with a size less than 75 μm have three characteristics: high aluminosilicate content, glassy state, and finely divided state. Thus, high reactive potential and large specific surface area are provided to activate effective pozzolanic reaction in E-glass concrete mixes, which results in higher compressive strength, higher resistance of sulfate attack, and lower chloride ion penetration. However, E-glass particles with a size larger than 75 μm having less or no pozzolanic activity due to the effect of specific surface area are considered as fine aggregate and no significant positive influence on concrete performance.

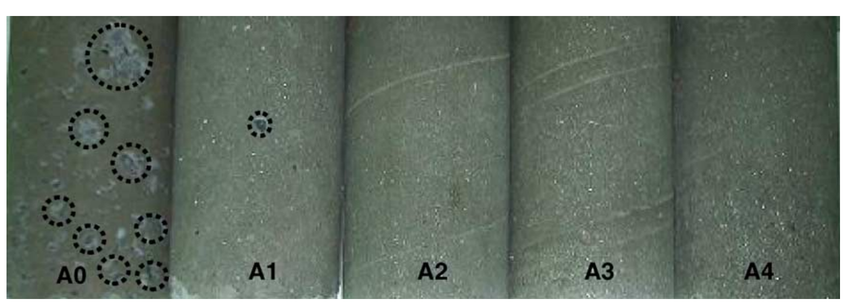

Fig. 14. Surface defect of concretes after five-cycle exposure for mix A.

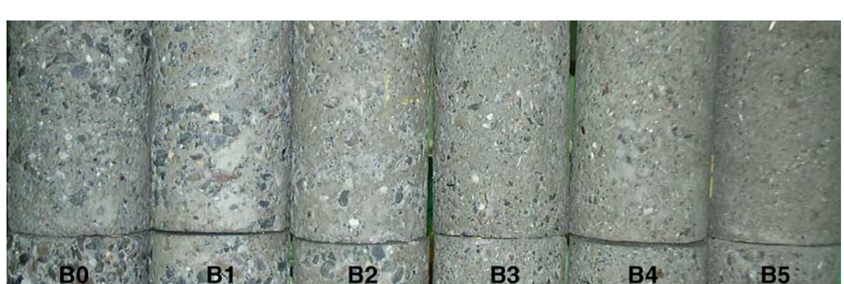

Fig. 15. Surface defect of concretes after five-cycle exposure for mix B.

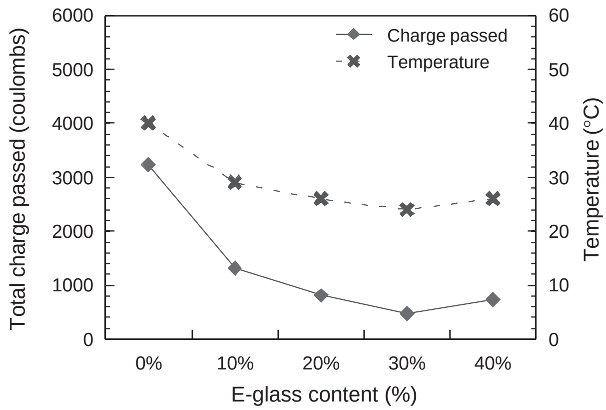

Fig. 16. Total charge passed vs. E-glass content curves for mix A.

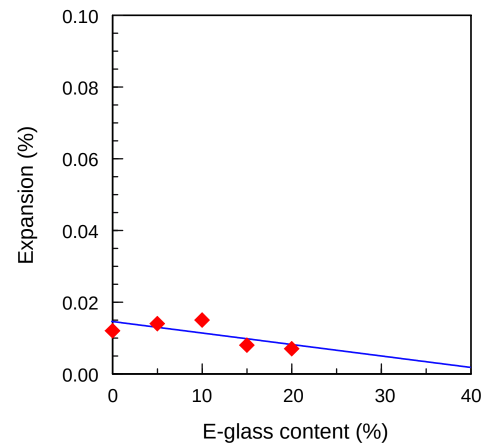

Fig. 18. Expansions of mortar bars with various E-glass contents immersed in NaOH solution.

Expansion percentages of mortar bars with various E-glass contents immersed in NaOH solution are illustrated in Fig. 18. Expansion decreased as E-glass content increased and expansions of all specimens were less than 0.10%, which indicated innocuous behavior and no potentially deleterious expansion would be caused in the E-glass specimens according to the specification of ASTM C 1260-01. This is because the equivalent alkali content (Na_2O and K_2O) of E-glass was 0.8, which was much lower than that of container glass, and increasing E-glass content in cementitious materials could inhibit expansion due to the pozzolanic effect of fine particles.

4. Conclusions

Waste E-glass obtained from electronic grade glass yarn scrap used in cementitious mixtures is environment-friendly, property-improving, and cost-effective. The compressive strength of specimen with 40 wt.% E-glass content is 17%, 27% and 43% higher than that of control specimen at age of 28, 91 and 365 days, respectively. The addition of E-glass significantly improves sulfate resistance of concrete according to the results of weight loss and strength reduction. E-glass particle can be used as partial fine aggregate replacement material as well as supplementary binding material depending on its particle size. For particle size less than 75 μm, amorphous E-glass could possess cementitious capability, which resulting from hydration or pozzolanic reaction. The coarser cylindrical glass acts as a potential crack-arrester and inhibits the internal crack propagation. The equivalent fineness modulus and equivalent water/binder ratio are proposed to explain the effect of E-glass particles on the properties of cementitious materials and the possible mechanisms. Based on the properties of hardened concrete, optimum E-glass content is found to be 40–50 wt.% in this study. However, the slump decreases as the glass content increases due to the reduction of fineness modulus, and the use of high-range water reducers is needed to obtain a uniform mix. Compared with control mix, concrete with E-glass has excellent chloride-ion penetration resistance and no adverse ASR-expansion effect. The use of E-glass particles could save the cost of cement and fine aggregate in cementitious mixtures and minimize the environmental impact due to solid waste disposal.

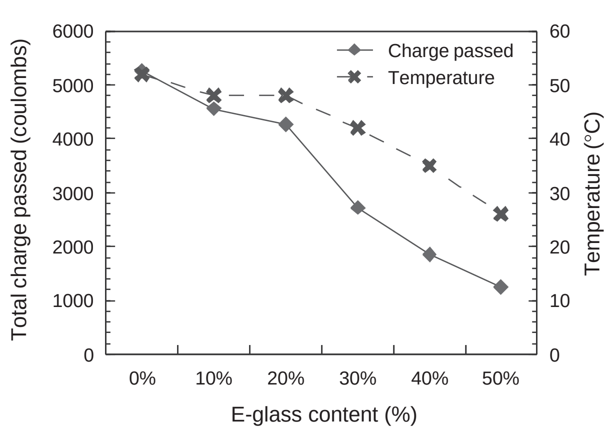

Fig. 17. Total charge passed vs. E-glass content curves for mix B.

Acknowledgements

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