Pergamon

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Cement and Concrete Research 34 (2004) 1145–1152

CEMENT AND CONCRETE RESEARCH

Studies on expansion properties in mortar containing waste glass and fibers

Seung-Bum Park*, Bong-Chun Lee

Department of Civil Engineering, Chungnam National University, Daejeon, 305-764 South Korea

Received 18 December 2002; accepted 1 December 2003

Abstract

The utilization of waste glass in concrete can cause cracking and weakening due to expansion by alkali–silica reaction (ASR). In this study, ASR expansion and properties of strength were analyzed in terms of waste glass content, glass color (brown, green), fibers (steel fiber, polypropylene fiber) and fiber content, in anticipation of reducing ASR expansion.

Results showed that green waste glass was more usable than brown because its expansion was less than that of brown glass. Using the accelerated ASTM C 1260 test of waste glass, no pessimum content was found. Furthermore, when fibers and waste glass were combined, there was an effect on the reduction of expansion and strength loss due to ASR between the alkali in the cement paste and the silica in the waste glass. In particular, adding 1.5 vol.% of steel fiber to concrete containing 20% waste glass reduced the expansion ratio by 40% and increased flexural strength by up to 110%, a vast improvement when compared with using only waste glass (80 °C H_2O curing) by itself.

Keywords: Alkali–aggregate reaction; Durability; Expansion; Glass; Fiber reinforcement

1. Introduction

The amount of waste glass has gradually increased over recent years due to an ever-growing use of glass products. Most colorless waste glasses have been recycled effectively. On the other hand, colored waste glasses, with their low recycling rate, have been dumped into landfill sites.

However, with a shortage of landfill sites, landfilling them is becoming more and more difficult. Additionally, landfilling of waste glasses is undesirable because they are not biodegradable, which makes them environmentally less friendly. Considering these facts, the reutilization of colored waste glasses has drawn more attention in recent years. Current reprocessing costs of waste glasses for special use is rather high. However, when waste glasses are reused in making concrete, the production cost of waste glasses for concrete will go down through the development of reprocessing technology and the extension of reprocessing facilities, which will make concrete containing waste glasses economically viable.

Studies have been done on the possibility of reusing waste glasses as asphalt additive or road filler [1 2]. Waste glasses were used as aggregates for concrete [3–5]. However, the applications were limited due to the damaging expansion in the concrete caused by alkali–silica reaction (ASR) between high-alkali pore water in cement paste and reactive silica in the waste glasses. The chemical reaction between the alkali in Portland cement and the silica in aggregates forms silica gel that not only causes cracks upon expansion, but also weakens the concrete and shortens its life [6]. Recently, studies have been carried out to suppress the ASR expansion in concrete and find methods to recycle waste glasses [7 8].

Therefore, this study compared and analyzed the ASR expansion characteristics according to the color of waste glasses (green and brown), which were generally generated in Korea, and their contents (mixing ratio). It also revealed the expansion and strength characteristics of concrete due to ASR by mixing reinforcing steel fibers or polypropylene fibers [9] to suppress the expansion by ASR when using waste glasses as aggregates. Finally, this study

* Corresponding author. Tel.: +82-42-821-5674.
E-mail address: park_sb@cnu.ac.kr (S.-B. Park).

0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2003.12.005

Table 1
Comparison of the alkali–silica reactivity tests [20]

Test appellation	ASTM C 1260	ASTM C 227	Microbars
Sample design	Mortar bars: w/c=0.47 Aggregates: fixed gradation, sand/cement=2.25	Mortar or concrete bars, w/c not specified Aggregates: fixed gradation, sand/cement=2.25	Mortar bars: w/c=0.3 Sand: fixed gradation, sand/cement suggested
Measurement conditions	In a 1 N NaOH solution at 80 °C	At 100% RH and 38 °C	At 150 °C in 10% KOH solution
Criteria of expansion	Deleterious if expansion >0.2% at 14 days	Deleterious if expansion >0.1% at 6 months, expansion >0.05% at 3 months	Deleterious if expansion >0.11% at 3 days

presents basic data for the effective utilization of waste glasses.

2. Research significance

There is significant interest in the development of environmentally friendly concrete with waste. Using waste glass as a construction material is a good way to help the environment. However, its applications were limited due to the damaging expansion in the concrete caused by an ASR. Such internal expansion can be suppressed by fibers.

3. Analysis of ASR test methods

ASR test methods such as ASTM C 1260, ASTM C 227 and the French microbar method [10] have been applied to an ASR test on mortar or concrete test specimens containing aggregates. Table 1 compares the characteristics of these three test methods. Despite numerous studies done on ASR, a satisfactory method to determine potential ASR expansion in concrete has yet to be developed [11]. ASTM C 227 requires a relatively longer test period and is considered to be less stringent against potentially reactive aggregates [12 13]. On the other hand, when compared to ASTM C 227, ASTM C 1260 is applied to more stringent testing due to its severe requirement of strong alkaline NaOH solution and higher temperature. Therefore, it does not represent all the conditions of concrete in real situations, but it draws much attention due to its shorter test period and enhanced reliability of ASR.

Table 3
Chemical and physical properties of waste glass

Properties		Type: Green glass	Brown glass
Chemical composition	SiO_2(%)	71.3	72.1
	Al_2O_3(%)	2.18	1.74
	Na_2O+K_2O(%)	13.07	14.11
	$CaO+MgO$(%)	12.18	11.52
	SO_3(%)	0.053	0.13
	Fe_2O_3(%)	0.596	0.31
	Cr_2O_3(%)	0.44	0.01
Physical properties	Specific gravity	2.50	2.52
	Water absorption(%)	0.41	0.40

4. Materials and test methods

4.1. Materials

In this study, general Portland cement (Type 1) and standard sand from Jumunjin in Korea for fine aggregates were used. Table 2 shows the physical and chemical properties of the cement. As a reactive aggregate, this study used the colored soda lime glasses that are widely used for glass bottles and glassware. The green and brown glasses, which are currently being poorly recycled, were crushed into the size of aggregates suitable for ASTM C 1260 testing (Table 5).

Table 3 reveals the chemical composition of these waste glasses. Steel or polypropylene (PP) reinforcing fiber was used to suppress the ASR expansion. The steel fiber manufactured by a domestic company had hooks at both ends, and the PP fiber by the company was of net type. Table 4 shows the physical characteristics of the reinforcing fibers.

4.2. Mix and test method

The mix proportions were selected to evaluate the ASR expansion and strength characteristics of mortar containing colored waste glasses, as well as those used when reinforcing fiber, with the following parameters: (1) color of the waste glasses (green or brown); (2) content of the waste glasses [WG/(WG+S)]: 10, 20, 30, 50 or 100 wt.%); (3) type of reinforcing fibers (steel or PP); and (4) content of the fibers (steel: 0.5–1.5 vol.%, PP: 0.1–0.5 vol.%). When

Table 2
Physical and chemical properties of cement

Chemical properties (%)										Physical properties				
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Ignition loss	Total	Specific gravity	Blaine (cm^2/g)	Compressive strength (N/mm^2): 3 days	7 days	28 days
21.24	5.97	3.34	62.72	2.36	0.13	0.81	1.97	1.46	100	3.14	3200	22	29	38

Table 4
Physical characteristics of fibers

Properties	Fiber type	
	Steel fiber	PP fiber
Fiber length (mm)	36	25
Equivalent diameter (mm)	0.6	0.1
Specific gravity	7.85	0.9
Tensile strength (N/mm^2)	441	255
Modulus of elasticity (kN/mm^2)	196	3.5

mixing fibers with concrete, workability, fiber ball, etc., of fresh concrete are considered. Usually, the optimum mixing rate of steel fiber is 0.5–1.5 vol.% and of PP fiber is 0.1–0.5 vol.%. This test was conducted in accordance with ASTM C 1260 to check the recyclability of the waste glasses and to evaluate their influence on the ASR. For each individual mix, the fine aggregates and waste glasses were crushed in order to meet requirements for the particle size as shown in Table 5. Three mortar specimens were made for each mixing with W/C 0.47 and S/C 2.25. Normal procedure was to cure them for 24 h, immerse them in water for 24 h, and then store them in 1 N NaOH solution at 80 °C in a closed container. Changes in the length of the mortar bars were checked for the next 14 days after their surface was dried by using a comparator, a length comparison measuring device with an accuracy less than 0.002 mm.

Compressive strength test for mortar specimens of 5×5×5 cm in size containing waste glasses and reinforcing fiber was conducted in accordance with KS L 5105. The mortar specimens were immersed in 80 °C 1 N NaOH solution and 80 °C water, conditions as required by ASTM C 1260, for 14 days prior to testing.

Flexural strength test for mortar specimens of 4 ×4×16 cm in size containing waste glasses and reinforcing fiber was conducted under similar conditions as those used in compressive strength test. The bars were immersed in 80 °C 1 N NaOH solution or 80 °C water for 14 days.

5. Results and discussion

5.1. Analysis of the expansion characteristic of mortar containing waste glasses

The expansion–time history curve made by the measurements complying with ASTM C 1260 in terms of the colors

Table 5
Grading requirements (ASTM C 1260)

Sieve size		Mass, %
Passing	Retained on	
4.75 mm	2.36 mm	10
2.36 mm	1.18 mm	25
1.18 mm	600 μm	25
600 μm	300 μm	25
300 μm	150 μm	15

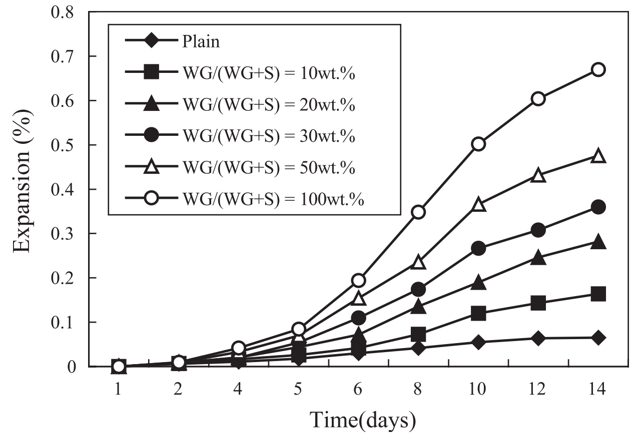

Fig. 1. Expansion time histories for mortar bars (brown glass).

of waste glasses (green or brown) and their contents (0–100%) are shown in Figs. 1 and 2.

Mortar bars with waste glasses mixed in display a relatively higher expansion rate than plain bars with no waste glasses. Mortar bars containing brown waste glass showed higher expansion rates than bars containing green waste glass.

All mortar bars except 10% brown waste glass exceeded an expansion rate of 0.2% as required by ASTM C 1260, while the bars containing green waste glass showed an expansion rate within 0.2% up to 30% of its content.

Fig. 3 shows expansion rates for mortar bars according to the contents of green and brown glass, respectively. The expansion rates noticeably increased with an increase in waste glass content, regardless of the types of waste glasses used. The expansion rate of mortar bars containing brown glass is 2.5–10.3 times higher than that of plain mortar bars having no waste glass. The bars containing green glass showed an expansion rate of 1.8–3.9 times than plain mortar bars, which is less than that of the mortar bars with brown glass. This may be due to the Cr_2O_3, which is generally added to the glass to create a greenish hue and is considered to repress the expansion. This is similar to the

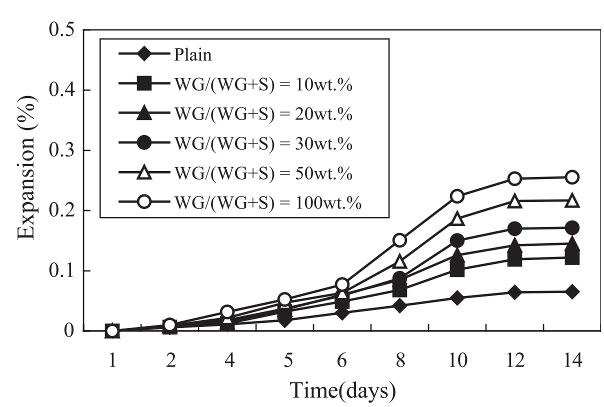

Fig. 2. Expansion time histories for mortar bars (green glass).

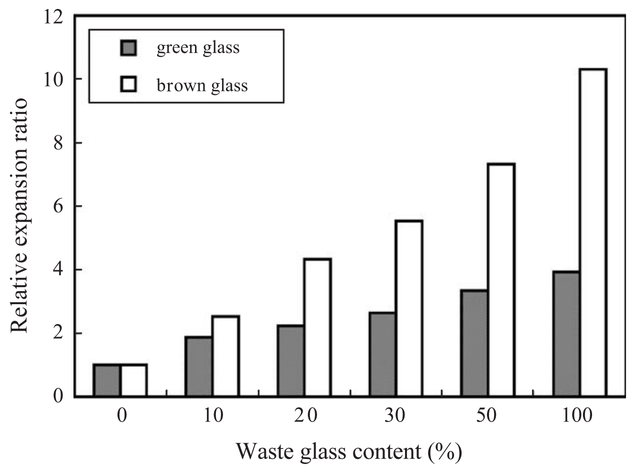

Fig. 3. Expansion ratio for mortar bars.

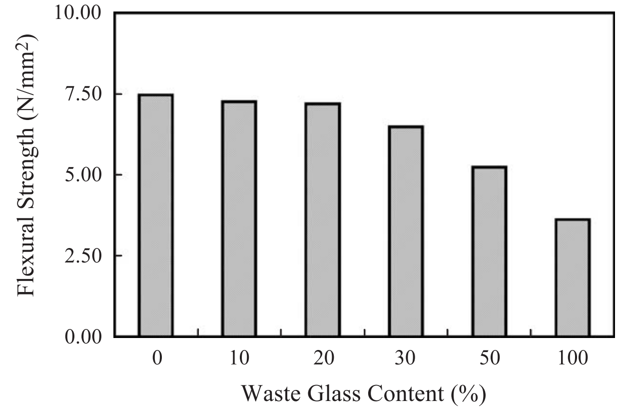

Fig. 5. Flexural strength according to waste glass content (brown glass).

results of the study done by Jin [14], who found that the expansion rate decreases as the Cr_2O_3 increases. This ASR-suppressing mechanism of Cr_2O_3 seems to support the hypothesis of Prezzi et al. [18] that the expansive pressure resulting from electrical double-layer repulsion is inversely proportional to the ionic valence. Thus, the gel containing Cr^{3+} appears to be less expansive.

Evidence from numerous studies has shown that there is a certain concentration or proportion of reactive aggregate present in an otherwise inert aggregate that causes a maximum expansion in concrete made from it. This proportion of reactive material producing a maximum expansive effect is referred to as the "pessimum proportion" [19].

The mortar bar expansion tests using existing test methods by ASTM C 227 have reported that the pessimum value for ASR was generated when the reactive aggregate compound reaches 50% of the mixing rate [15–17]. In this ASTM C 1260 test, no pessimum was generated as the expansion rate continued to increase along with an increase in the amount of mixing waste glass. This may be due to the unlimited supply of alkali in the 1 N NaOH solution when applying ASTM C 1260 test.

5.2. Analysis of the strength characteristic of mortar containing waste glasses

Analysis of mortar strength was done for the mortar bars containing brown waste glass, which showed a high expansion rate during expansion analysis.

Figs. 4 and 5 show the compressive and the flexural strength of the mortar in terms of the content of brown glass at 14 days. The mortar bars were treated in accordance with ASTM C 1260 and then immersed in NaOH solution at 80 °C for 14 days. The compressive and the flexural strength gradually decreased by 2–49% and 3–51%, respectively, with an increase in the content of brown glass. Weakening effect increased when the content of brown glass exceeded 20%.

It is believed that such a decrease in mortar strength is due to cracks created by expansion pressure caused by the ASR generated from the silica in waste glasses, and the decrease in adhesive strength between the surface of the waste glass and the cement paste.

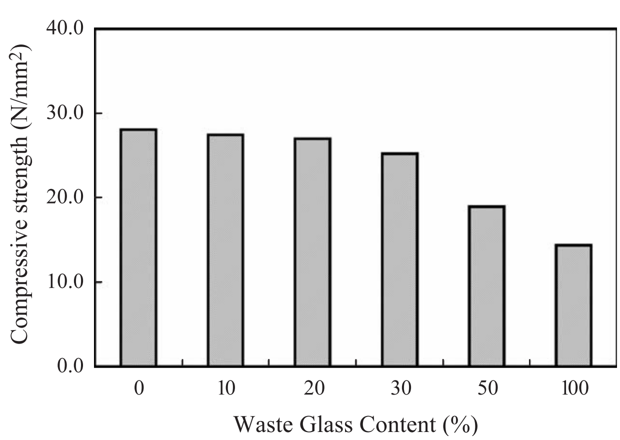

Fig. 4. Compressive strength according to waste glass content (brown glass).

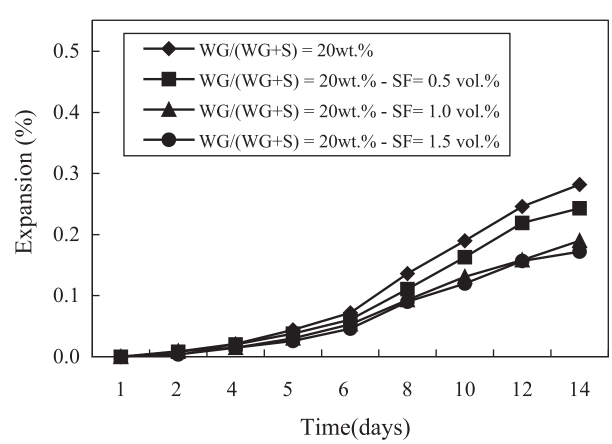

Fig. 6. Expansion time histories for mortar bars (brown glass+SF).

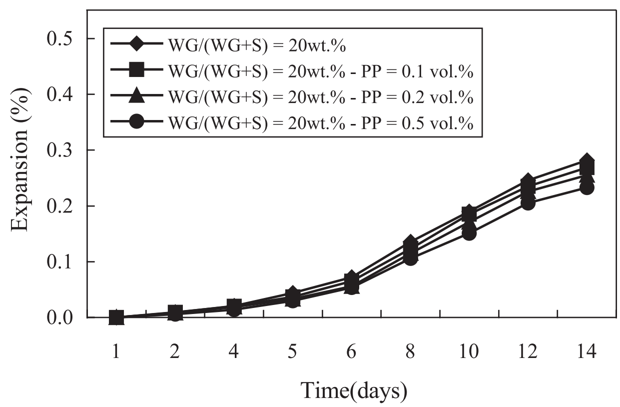

Fig. 7. Expansion time histories for mortar bars (brown glass+PP).

5.3. ASR characteristics of mortar containing reinforcing fiber

The internal pressure created by ASR gel causes ASR expansion and cracks in the mortar containing waste glasses. Such internal expansion can be suppressed by randomly distributing discontinuous single fibers. The ASR expansion and mortar strength were analyzed by varying reinforcing fibers (steel fiber or PP fiber) and their content.

Figs. 6 and 7 display the expansion time history curve for mortar bars having different contents of steel fiber (0.5–1.5 vol.%) and PP fiber (0.1–0.5 vol.%), respectively, with the content of brown glass fixed at 20%. They show that the ASR expansion decreases with an increase in the contents of both fibers. With a steel fiber content of more than 1.0 vol.%, the relative expansion rate defined by ASTM C 1260 was suppressed under 0.2%.

The PP fibers did not bring the expansion rate down below 0.2%, which necessitates additional suppressive measures such as adding extra PP fiber, blast furnace slag or fly ash when using PP fibers.

Figs. 8 and 9 display the expansion time history curve for mortar bars containing 20% green glass in combination with steel or PP fibers. As in the above case using brown glass, the expansion rate decreased with an increase in the contents

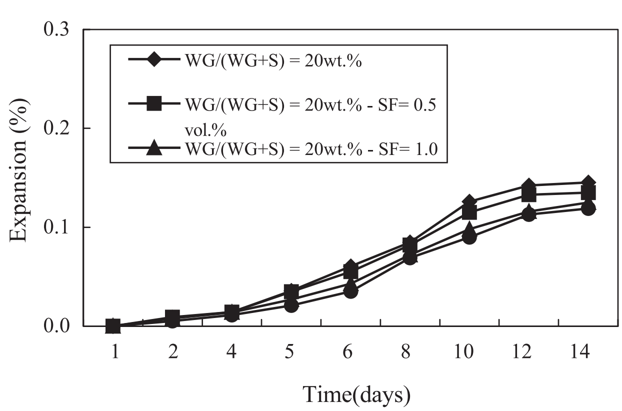

Fig. 8. Expansion time histories for mortar bars (green glass+SF).

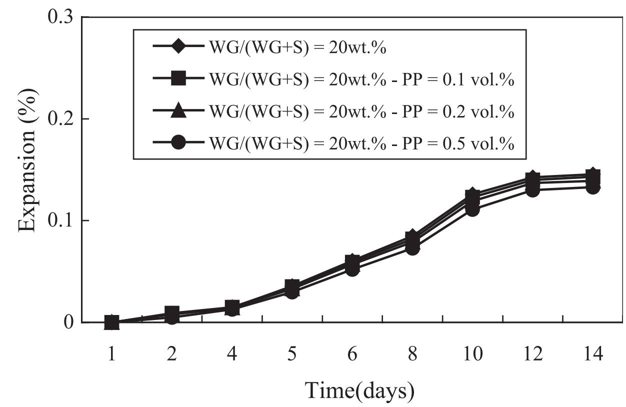

Fig. 9. Expansion time histories for mortar bars (green glass+PP).

of both fibers, but showed a lower expansion suppression effect than the brown glass.

Fig. 10 shows the comparison of expansion rates of mortar bars containing both waste glasses and fibers to those of mortar bars containing only waste glasses. The expansion suppression effect of the reinforcing fiber was more prominent in the brown glass than in the green glass. With its content increasing, the steel fiber achieved 13–40% of expansion suppression rate when mixed with brown glass, and 8–19% when mixed with green glass. In the case of the PP fiber, expansion was suppressed by 5–18% when mixed with brown glass, and by 2–9% when mixed with green glass.

5.4. Strength characteristics of mortar containing reinforcing fiber

An analysis was made on the strength characteristics of the mortar containing reinforcing fibers as well as on brown glass that showed high expansion rates in the expansion testing.

Figs. 11 and 12 show the compressive and flexural strength of the mortar bars with mixing ratio of steel fiber. The mortar bars were immersed in 80°C NaOH solution and in 80 °C water, respectively, for 14 days prior to testing. With waste glass content at 20%, the addition of steel fiber

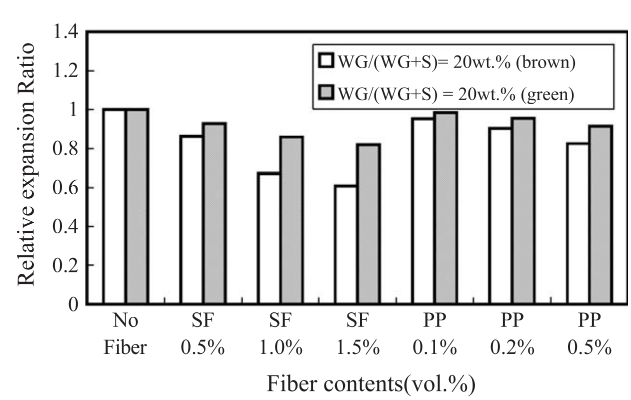

Fig. 10. Expansion ratio according to fiber content.

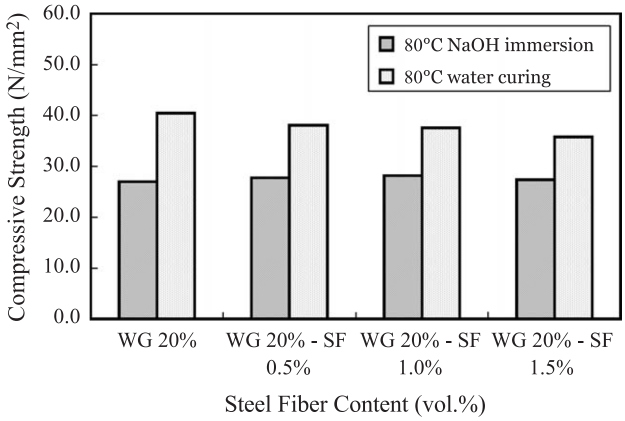

Fig. 11. Compressive strength according to SF content.

did not significantly affect the compressive strength. Compressive strength of mortar bars dipped in the NaOH solution was generally weaker than the ones dipped in water due to the expansion caused by the ASR reaction. Flexural strength of the mortar bars immersed in the NaOH solution was lower than that of the mortar bars immersed in water. However, an increase in the content of steel fiber gradually enhanced the flexural strength, while the difference in the strength in both cases became less significant.

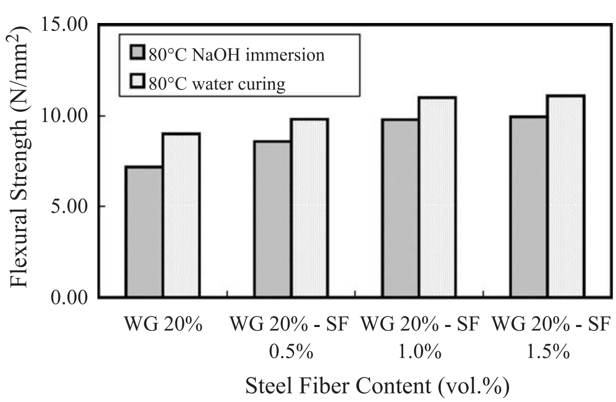

Fig. 12. Flexural strength according to SF content.

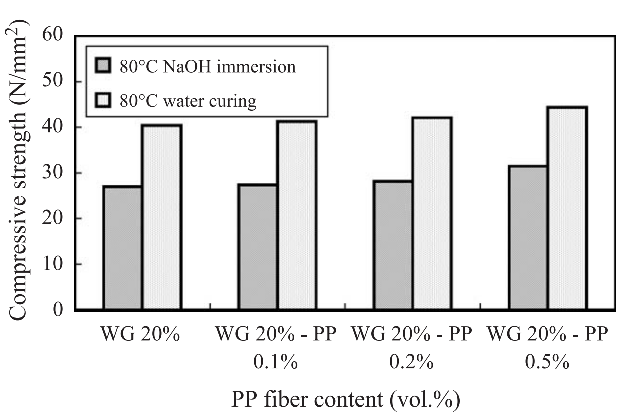

Fig. 13. Compressive strength according to PP content.

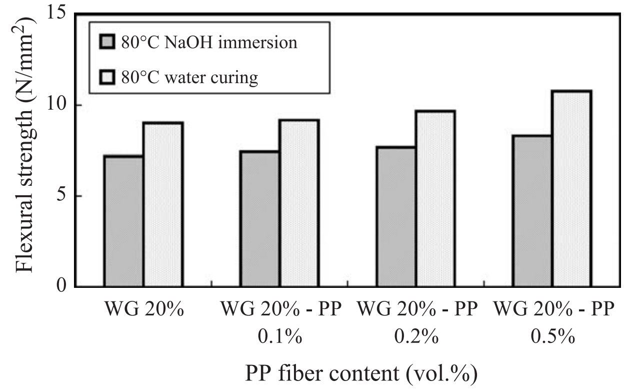

Fig. 14. Flexural strength according to PP content.

Figs. 13 and 14 show both the compressive and flexural strength of the mortar bars with mixing ratio of PP fiber.

Similarly, the PP fiber content did not affect the compressive strength significantly, while the flexural strength more or less increased as the PP fiber content increased.

Figs. 15 and 16 demonstrate the following findings: (1) the relationship between the expansion ratio of the 80 °C

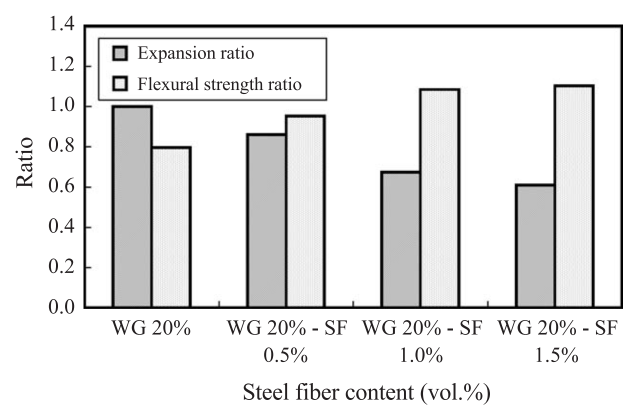

Fig. 15. Expansion and strength ratio according to SF content.

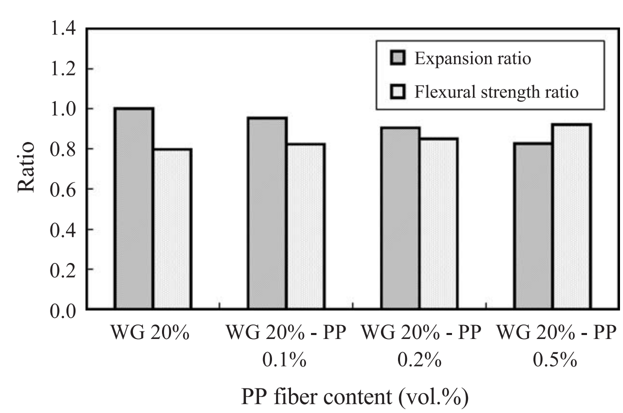

Fig. 16. Expansion and strength ratio according to PP content.

NaOH-treated mortar bars containing brown waste glass (20%) and both types of fiber of varying contents and (2) the flexural strength ratio of the mortar bars immersed in 80 °C NaOH based on the flexural strength of the mortar bars containing waste glass (20%) that were measured after the mortar bars had been cured in the 80 °C water. In general, an increase in the fiber content meant a decrease in the expansion ratio and an increase in the flexural strength.

When mixing steel fiber by 1.5 vol.% in addition to waste glass, the expansion rate was reduced by 40% than when mixing waste glass alone. Immersing the mortar bars containing only waste glass in the NaOH solution caused a 20% loss in flexural strength. However, when mixing steel fiber by 1.5 vol.%, the flexural strength increased by 10%. The addition of PP fiber had similar effects on the expansion ratio and flexural strength. Increasing the content of PP fiber by 0.1–0.5 vol.% suppressed the expansion rate by 5–18%, but decreased the flexural strength by 8–18%. The ASR expansion and subsequent decrease in mortar strength caused by the use of waste glasses is known to be effective in suppressing the expansion and strength decrease because of the enhanced adhesion of cement paste and suppression effect of the matrix by reinforcing fibers.

6. Conclusions

This study intended to find effective ways to reutilize the hard to recycle colored waste glasses as concrete aggregate. Analysis of the problematic ASR expansion and strength characteristics of concrete containing recycled waste glasses and reinforcing fiber gave the following results:

(1) The expansion rate by ASR in accordance with ASTM C 1260 showed an increasing tendency with increase in the content of waste glasses regardless of their type. Brown waste glass showed a greater expansion rate than green glass. Additionally, a pessimum caused by mixing waste glasses was not observed, which is considered to be due to the unlimited supply of alkali in the NaOH solution.

(2) The compressive and flexural strength of mortar containing brown waste glass decreased as the waste glass content increased. The strength noticeably decreased when the glass content was more than 20%.

(3) With the content of waste glass being 20% and that of steel fiber 0.5–1.5 vol.%, the expansion rate of the mortar bars decreased by about 13–40%. With the content of waste glass being 20% and that of PP fiber 0.1–0.5 vol.%, the expansion rate of the mortar bars decreased by 13–40%.

(4) When the mortar bar containing 20% waste glass was dipped in the 80 °C NaOH solution, its flexural strength decreased below the reference flexural strength (80 °C H_2O curing) by 20%. However, when the content of steel fiber was 1.5 vol.%, the flexural strength increased above the reference strength by 10%, while the mortar bars with 0.5 vol.% of PP fiber showed about 8% strength decrease below the reference strength.

(5) The addition of reinforcing fibers to the mortar bars proved to be effective in suppressing the expansion and strength decrease caused by ASR when waste glasses were mixed into it.

Acknowledgements

This work was supported by SISTeC sponsored by Korea Science and Engineering Foundation.

References

[1] J. Refined, Development of non-traditional glass markets, Resour. Recycl. (1991) 18–21.

[2] J. Uchiyama, Long-term utilization of the glass reasphalt pavement, Pavement (1998) 3–89.

[3] C.D. Johnson, Waste glass as coarse aggregate for concrete, J. Test. Eval. 2 (5) (1974) 344–350.

[4] O. Masaki, Study on the hydration hardening character of glass powder and basic physical properties of waste glass as a construction material, Asahi Ceramic Foundation Annual Research Report, 1995.

[5] S.B. Park, Development of Recycling and Treatment Technologies for Construction Wastes, Ministry of Construction and Transportation, Seoul, 2000.

[6] R.N. Swamy, The Alkali–Silica Reaction in Concrete, Van Nostrand Reinhold, New York, 1992.

[7] S. Naohiro, The strength characteristics of mortar containing glass powder, The 49th Cement Technology Symposium. JCA, Tokyo, (1995) 114–119.

[8] I. Kyoichi, K. Atobumi, Effects of glass powder on compressive strength of cement mortar, College of Engineering, Kantou Gakuin University, Study Report 40 (1) (1996) 13–17.

[9] S.B. Park, Development of Energy Conserving High Performance Fiber Reinforced Concrete and Instruction for Design and Construction for the Reinforced Concrete, Ministry of Construction and Transportation, Seoul, 1998.

[10] A. Criaud, C. Vernet, C. Defosse, The microbar method, an accelerated expansion test for evaluating aggregate, assessment of Canadian aggregate. Workshop Canadian Developments in Testing Alkali–Aggregate Reactivity. Ministry of Transportation, Toronto, 1990.

[11] P.E. Grattan-Bellew, A critical review of accelerated ASR tests, in: A. Shayan (Ed.), Proceedings of the 10th International Conference on Alkali–Aggregate Reaction in Concrete, Melbourne, Australia (1996) 27–38.

[12] R. Helmuth, Alkali–aggregate reactivity: an overview of research, National Research Council, Strategic Highway Research Program, SHRP-C-3342, 1993.

[13] D.C. Stark, Immersion test to identify cement alkali levels and pozzolans to prevent ASR, in: A. Shayan (Ed.), Proceedings of the 10th International Conference on Alkali–aggregate Reaction in Concrete, Melbourne, Australia, (1996) 355–361.

[14] W. Jin, Alkali–silica reaction in concrete with glass aggregate, thesis for degree of Doctor of Science, Columbia University, 1998.

[15] T.E. Stanton, Expansion of concrete through reaction between cement and aggregate, Proc. Am. Soc. Civ. Eng. 66 (1940) 1781–1811.
[16] H.E. Vivian, The effects on mortar expansion of reactive component in the aggregate, studies in cement–aggregate reactions, Part 10, CSIRO Bull. 256 (1947) 13–20.
[17] M. Berra, R. Di Maggio, T. Mangialardi, A.E. Paolini, Fused quartz as a reference reactive aggregate for alkali–silica reaction studies, Adv. Cem. Res. 7 (1995) 21–32.
[18] M. Prezzi, P.J.M. Monteiro, G. Sposito, The alkali–silica reaction: Part I. Use of double-layer theory to explain behavior of reaction-product gels, ACI Mater. J. 94 (1) (1997) 10–17.
[19] M.A. Ozol, The pessimum proportion as a reference point in modulation alkali–silica reaction, Proceedings of a Symposium on Alkali–Aggregate Reaction, Preventive Measures Reykjavik (1975) 113–130.
[20] C.F. Ferraris, Alkali–silica reaction and high performance concrete, NISTIR 5742, 1995.