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# Expansion Properties of Mortar Using Waste Glass and Industrial By-Products

**Seung-Bum Park[1)] and Bong-Chun Lee[2)]**

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**Abstract:** Waste glass has been increasingly used in industrial applications. One shortcoming in the utilization of waste glass for concrete production is that it can cause the concrete to be weakened and cracked due to its expansion by alkali-silica reaction (ASR). This study analyzed the ASR expansion and strength properties of concrete in terms of waste glass color (amber and emerald-green), and industrial by-products (ground granulated blast-furnace slag, fly ash). Specifically, the role of industrial by-products content in reducing the ASR expansion caused by waste glass was analyzed in detail. In addition, the feasibility of using ground glass for its pozzolanic property was also analyzed. The research result revealed that the pessimum size for waste glass was 2.5~1.2 mm regardless of the color of waste glass. Moreover, it was found that the smaller the waste glass is than the size of 2.5~1.2 mm, the less expansion of ASR was. Additionally, the use of waste glass in combination with industrial by-products had an effect of reducing the expansion and strength loss caused by ASR between the alkali in the cement paste and the silica in the waste glass. Finally, ground glass less than 0.075 mm was deemed to be applicable as a pozzolanic material.

**Keywords:** waste glass, ground glass, alkali-silica reaction, ground granulated blast-furnace slag, fly ash.

## 1. Introduction

Glass has become a household item around our homes, and its waste has been increasing. One way to recycle the waste glass is to use it as a material for glass bottles. Another way is to use it as a material for concrete. In this case of recycling waste glass for concrete production, it may be used as an alternative material for regular fine aggregate or as an admixture to concrete.[1-3]

Because of shortage of natural resources, it has become increasingly difficult to obtain aggregate of good quality for concrete production, and the $CO_2$, which is emitted during cement production, has become a serious environmental issue. For these reasons, recycling the bottles made of waste glass as a material for concrete is deemed to be very effective in terms of environment and economics.

Nevertheless, it has been pointed out that using waste glass as a material for concrete production brings about the problem of decreasing the performance of concrete due to its expansion by Alkali-Silica Reaction (ASR).[4,5] Thus, this study aims to compare and evaluate the influence of the grain size of the glass ground from waste glass bottles on the concrete expansion due to ASR and on the overall strength of concrete. In this endeavor, this study aims to delineate the effect of mixing industrial by-products (fly ash and ground granulated blast-furnace slag) in the concrete along with the ground glass on the expansion by ASR and the overall strength of concrete

[1)] KCI member, Dept. of Civil Engineering, Chungnam National University, Daejeon 305-764, Korea. E-mail: park_sb@cnu.ac.kr
[2)] KCI member, Dept. of Civil Engineering, Chungnam National University, Daejeon 305-764, Korea.



## 2. Materials and experimental method

### 2.1 Materials

Ordinary Portland cement (Type I) and regular sand as fine aggregate were used in this study. The physical property and chemical composition of the cement in this study are shown in Table 1. The colors of waste glass (WG) were amber and emerald-green as they are used widely in the glass bottle and other glass products. These waste glasses were grouped by the grain size into 5~2.5 mm, 2.5~1.2 mm, 1.2~0.6 mm, 0.6~0.3 mm, 0.3~0.15 mm, 0.15~0.075 mm, and below 0.075 mm. The chemical composition of the waste glass used in this study is shown in Table 2.

The hydrated lime ($Ca(OH)_2$) of 200 mesh size and produced by domestic B company was used for the analysis of the performance of waste glass as a pozzolanic material.

Fly ash (FA) was obtained from power plant as a by-product of its operation to generate power by burning bituminous (soft) coal. Its chemical composition and physical properties are shown in Table 3.

The fine powder of ground granulated blast-furnace slag (BS) produced by domestic C company was also used in this study. Its chemical composition and physical properties are summarized in Table 4.

The ultra-fine powder of A Co. of the Republic of South Africa

**Table 1** Physical properties and chemical composition of cement.

| Chemical composition (%) | | | | | | | | | | Physical properties | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $SO_3$ | Ig.loss | Total | Specific gravity | Blaine ($cm^2/g$) | Stability (%) | Compressive strength($kgf/cm^2$) | | |
| | | | | | | | | | | | | | 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 | 3,200 | 0.02 | 221 | 298 | 389 |

**Table 2** Chemical composition of waste glass.

| Composition \ Type | Emerald-green glass(%) | Amber glass(%) |
|---|---|---|
| $SiO_2$ | 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 |

was used for silica fume (SF). Its chemical composition and physical properties are presented in Table 5.

## 2.2 Experimental method

The following experimental variables were selected to evaluate the ASR expansion of concrete by the grain size of colored waste glass and the strength and ASR expansion properties of concrete mixed in with industrial by-products plus 20% colored, ground waste glass of 2.5~1.2 mm grain size.

① Color of waste glass (amber and emerald-green)
② Grain size of waste glass (5~2.5 mm, 2.5~1.2 mm, 1.2~0.6 mm, 0.6~0.3 mm, 0.3~0.15 mm, 0.15~0.075 mm, and below 0.075 mm)
③ Industrial by-products (ground granulated blast-furnace slag, fly ash)
④ Mix ratio of industrial by-products (10%, 20%, 30%, 50%)

In addition, the feasibility of using ground waste glass as a pozzolanic material was analyzed by comparing its performance on ASR and hydrated lime-glass experiment with the performance of typical pozzolanic materials (silica fume, ground granulated blast-furnace slag).

### 2.2.1 Alkali-silica reaction experiment

The evaluation of the degree of ASR expansion due to the use of waste glass was conducted pursuant to ASTM C 1260[7] as a test for recycling waste glass as fine aggregate for concrete.

Three mortar bar specimens (25 × 25 × 310 mm) for the experiment were prepared for each mix with the ratios of water to cement (W/C) of 0.47 and aggregate to cement (S/C) of 2.25. After 24 hours of standard curing and another 24 hours of immersion in water at 80°C, the specimens were stored in a closed container filled with 1 N NaOH solution at 80°C. The change in length of the mortar bar specimen was measured with a comparator of the accuracy within 0.002 mm right after the specimens were taken out of the storage container for 14 days.

### 2.2.2 Lime-glass experiment

An experiment was performed pursuant to ASTM C 593[6] to analyze the applicability of waste glass as a pozzolanic material. In other words, 180 g of hydrated lime, 260 g of mineral admixtures (glass, silica fume, fly ash, slag), and 1,340 g of standard sand were mixed in. The flow of water was calibrated to 65~75% through a flow experiment, and, then, square pillar specimens of 50×50×50 mm were prepared. The specimens were then stored in a closed container and cured for 7 days at 54±2°C and for additional 21 days at 23°C. The compressive strength of the mortar bar specimens was measured at 7 days and 28 days.

### 2.2.3 Compressive strength experiment for mortar

50 × 50 × 50 mm specimens were prepared pursuant to the 'Compressive Strength Test Method for Cement Mortar' of KS L

**Table 3** Chemical composition and physical properties of fly ash.

| Chemical composition (%) | | | | | | | | Physical properties | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $SO_3$ | Ig. loss | Specific gravity | Blaine ($cm^2/g$) | Particle size(mm) |
| 65.3 | 25.50 | 4.25 | 1.20 | 0.98 | 0.21 | 1.03 | 3.63 | 2.1 | 3,124 | $4.2\times10^{-2}$ |

**Table 4** Chemical composition and physical properties of ground blast-furnace slag.

| Chemical composition (%) | | | | | | | | Physical properties | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $SO_3$ | Ig. loss | Specific gravity | Blaine ($cm^2/g$) | Particle size (mm) |
| 35.20 | 15.90 | 0.46 | 42.21 | 5.85 | 0.12 | 0.11 | 0.05 | 2.83 | 3,000 ~4,000 | 1.0~1.6 |

**Table 5** Chemical composition and physical properties of silica fume.

| Chemical composition (%) | | | | | Physical properties | | |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | Ig. loss | Specific gravity | Blaine ($cm^2/g$) | Particle size($\mu m$) |
| 92.5 | 1.68 | 2.51 | 0.56 | 0.31 | 2.21 | 263,000 | 1.36 |

5105 in order to conduct a compressive strength test for the cement mortar mixed with waste glass and industrial by-products. The specimens were immersed in 1 N NaOH solution for 14 days at 80°C under the same condition as specified by ASTM C 1260 before being measured of their compressive strength.

#### 2.2.4 SEM inspection

The mortar bars mixed with various grain size of waste glass and industrial by-products were cut, and the cut surface was repetitively ground with sand paper and then coated with gold. The prepared specimens were then subjected to SEM (scanning electron microscopy) to observe the products of ASR (alkali-silica reaction) around the waste glass mixed in the hardened cement as well as the mortar bar surface.

## 3. Experimental result and analysis

### 3.1 Expansion property of waste glass by the grain size

Since alkali-silica reaction involves a reaction between solid (reactant aggregate) and liquid (alkali solution), the surface area of reactant aggregate is an important factor in the degree of expansion of the concrete due to ASR.

The waste glass replaced ordinary sand by the weight of 20 % in order to investigate of the effect of its grain size on the expansion due to ASR. Then, the expansion of the concrete was measured by the grain size (5~2.5 mm, 2.5~1.2 mm, 1.2~0.6 mm, 0.6~0.3 mm, 0.3~0.15 mm, 0.15~0.075 mm, and below 0.075 mm) of the waste glass. The expansion of the mortar bar

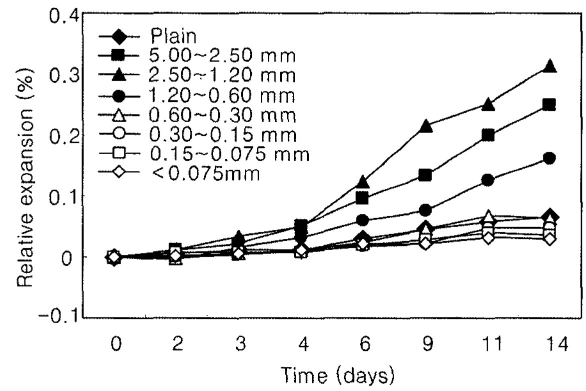


**Fig. 1** Expansion time histories for mortar bars (amber glass).

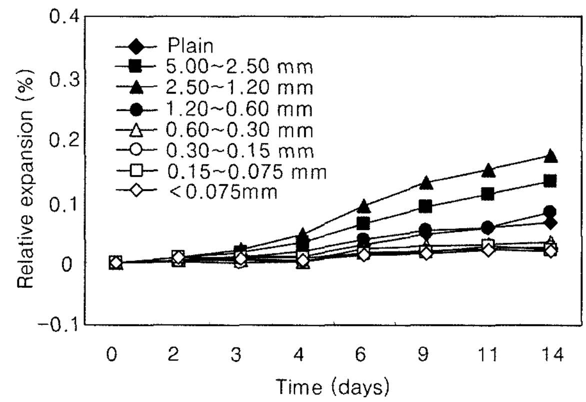


**Fig. 2** Expansion time histories for mortar bars (emerald-green glass).

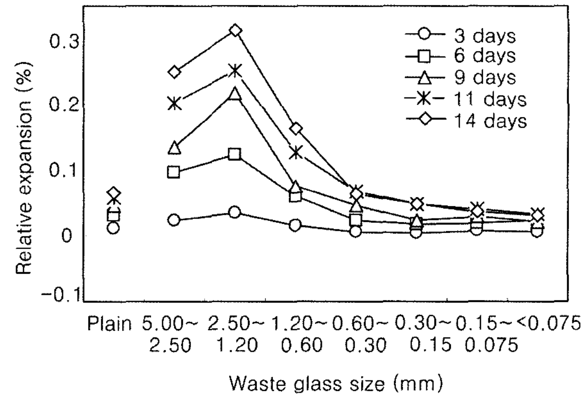


**Fig. 3** Expansion of mortar bars (amber glass).

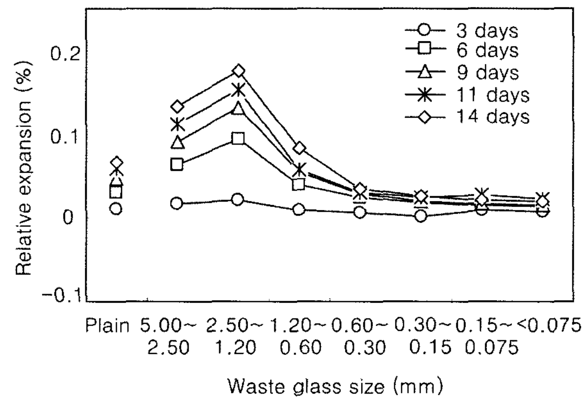


**Fig. 4** Expansion of mortar bars (emerald-green glass).

specimens with time is shown in Figs. 1 and 2 by the color and the grain size of the waste glass. The expansion with respect to the color and age of the mortar bar specimens is shown in Figs. 3 and 4.

The color of the waste glass was an important factor in determining the degree of expansion due to ASR. Emerald-green waste glass exhibited lower expansion relative to amber waste glass. The pessimum size for the waste glass was observed to be 2.5~1.2 mm at the age of 14 days regardless of the color as evidenced by the largest relative expansion. This difference in relative expansion by the color can be explained as it follows. The waste glass is colored emerald-green by the addition of $Cr_2O_3$. This oxidized compound deters the expansion. This reasoning supports the finding of Weihua Jin's research[18] that reported $Cr_2O_3$ reduced the expansion due to ASR. The mechanism of $Cr_2O_3$ to restrain ASR can be explained by the hypothesis of Prezzi et al[19]. that proposed the expansive pressure caused by electrical double-layer repulsion is was inversely proportional to the ionic value. Thus, the gel containing $Cr^{3+}$ can result in less expansion. Additionally, the relative expansion showed the tendency to decease gradually as the grain size became less than 1.5~1.2 mm. The amber waste glass exhibited relative expansion of 0.037% and 0.03% for the grain size of 0.15~0.075 mm and below 0.075 mm, respectively. This is about 85~88% less than the relative expansion of amber waste glass of 1.5~1.2 mm grain size and also less than that of plain specimen. The expansion of mortar showed the trend to increase gradually with time for all grain sizes.

In general, the expansion due to ASR depends largely on the grain size of reactant aggregate. However, Diamond et al. reported that the relative expansion ratio increased as the grain size of opal, which was the reactant aggregate mixed in mortar bar, decreased from 50 μm to 20 μm, but the expansion ceased to increase with the grain size below 20 μm in their experiment. Hobbs and French et al.[9,10] reason for the existence of this pessimum grain size as the following. The quantity of gel formed from alkali-silica reaction increases with the increase in the surface area of the reactant aggregate, but the quantity of alkali and water as the other reactants for ASR is reduced with the increase in the surface area of the reactant aggregate. However, the experiment pursuant to ASTM C 1260 revealed that the relative expansion ratio showed the tendency to decrease gradually when the grain size of waste glass was over 2.5~1.2 mm even though the quantity of alkali was kept increasing. Thus, this observation can be better explained by the reason below. As the grain size of waste glass becomes smaller, a pozzolan reaction by the waste glass takes place locally along with the ASR. Photo 1 shows the SEM image of the interface between mortar paste and waste glass of 2.5~1.2 mm grain size. The formation of gel due to ASR around the waste glass and cracks due to the mortar expansion by ASR can be confirmed in the image.

Photo 2 shows the image of the surface of mortar bar mixed with waste glass of the grain size below 0.075 mm. It should be noted that the gel formation due to ASR and cracks have not taken place. Thus, it follows that the performance degradation due to ASR can be prevented by the use of waste glass of minute grain size. Moreover, the possibility of developing waste glass into a useful admixture to concrete is wide open.

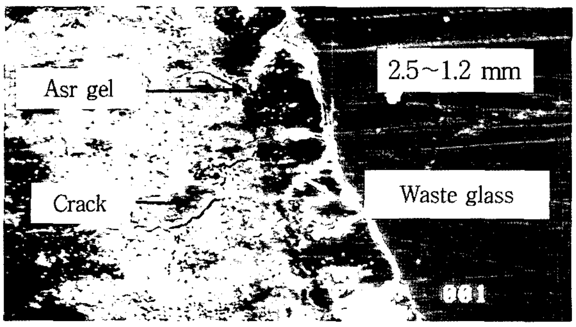


**Photo 1** SEM image of mortar bar.

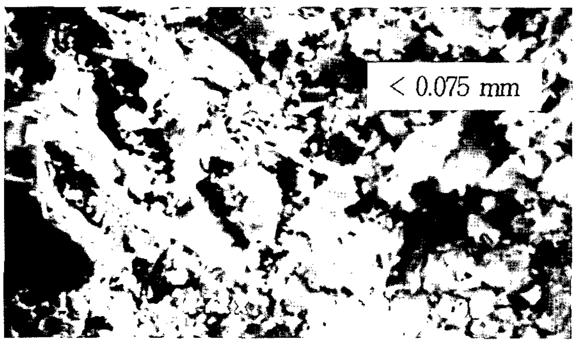


**Photo 2** SEM image of mortar bar.

## 3.2 Expansion property of mortar mixed with industrial by-products

### 3.2.1 Expansion property of mortar mixed with industrial by-products

It has been reported that the concrete strength decreases when waste glass is used at or over 30% as fine aggregate for concrete.[11] Thus, the expansion property of the mortar bar specimens by various mix ratio of industrial by-products was analyzed as an alternative solution to restrain the detrimental expansion caused by the pessimum grain size (2.5~1.2 mm) of colored waste glass mixed in the mortar at 20% by weight.

Figs. 5 and 6 show the relative expansion ratios of the mortar specimen by various mix ratios (10~50%) of fly ash and ground granulated blast-furnace slag mixed in the specimen along with the colored waste glass of 20% by weight with the grain size of 2.5~1.2 mm, which was determined to be the pessimum size from the aforementioned ASR.

Fig. 5 reveals that the amber waste glass exhibited higher relative expansion ratio overall than emerald-green waste glass. The relative expansion ratio tended to decrease with the increase in mix ratio of ground granulated blast-furnace slag to surpass below the relative expansion ratio of 0.1% (the ratio specified to be the standard value of safety by ASTM C 1260) at the mix ratio of ground granulated blast-furnace slag at or above 30%. Additionally, the mixing of ground granulated blast-furnace slag resulted in the decrease in the relative expansion ratio by about 11~86% compared to the case of using amber waste glass of 2.5~1.2 mm grain size only.

Addition of fly ash showed the trend of decreasing expansion ratio gradually with its increasing mix ratio similar to the case of adding ground granulated blast-furnace slag regardless of the color

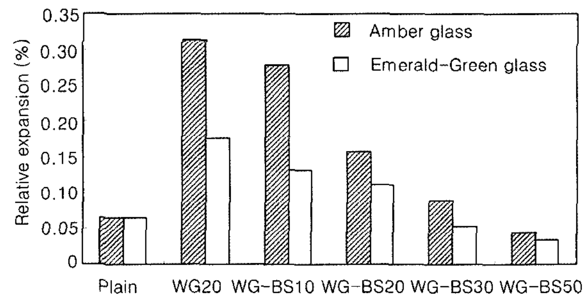


**Fig. 5** Expansion of mortar bars containing WG and BS.

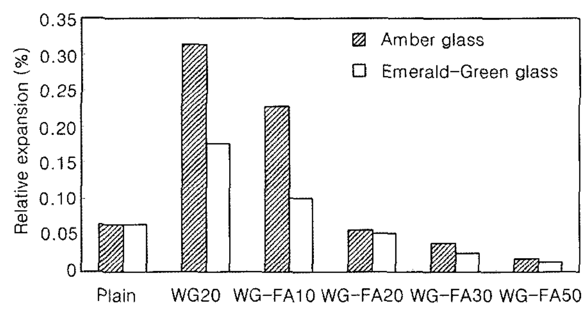


**Fig. 6** Expansion of mortar bars containing WG and FA.

of the waste glass. It resulted in the decrease in the relative expansion ratio of the mortar bar specimen by about 27~94% compared to the case of mixing amber waste glass of 2.5~1.2 mm grain size only. Thus, it follows that it is only appropriate to add fly ash in the amount 20% or in excess of 20% for the case of follows that it is only appropriate to add fly ash in the quantity of 20% or in excess of 20% by weight for the case of using colored waste glass of 20 % by weight.

Given the same mix ratio of industrial by-products, fly ash was more effective in restraining the expansion than ground granulated blast-furnace slag. Thus, it is deemed that the use of industrial by-products is effective in restraining the expansion due to ASR induced by the mixing of waste glass.

Davies et al.[12] reports that dilution of alkalinity in concrete is the main mechanism of industrial by-products to restrain the expansion owing to the high specific surface area. Qian et al.[13] reasoned that, because ground granulated blast-furnace slag has relatively high alkalinity, the matrix of hydration of the slag and cement attracts OH, $Na^+$, and $K^+$ ions, resulting in the delay of their movement to the reactant aggregate. This delay effect is enhanced with higher replacement ratio by industrial by-products.

Thus, it is found that the effect of restraining the expansion due to ASR will be greater with higher mix ratio of industrial by-products by the mechanisms of dilution of alkalinity, delay effect of movement of alkaline ions, and the densely packed structure of the industrial by-products mixed in the cement mortar.

### 3.2.2 Strength property of mortar mixed with industrial by-products

The influence of the mix ratio of industrial by-products (ground granulated blast-furnace slag, fly ash) on the compressive strength of mortar mixed with amber or emerald-green waste glass was analyzed.

Figs. 7 and 8 show the result of compressive strength test on the mortar bar specimens mixed with 20% waste glass of 2.5~1.2 mm grain size and various mix ratios of industrial by-products after being immersed in NaOH solution for 14 days at 80°C.

The cases of mixing in waste glass only and additional addition of 10% ground granulated blast-furnace slag exhibited low strength compared to the plain mortar specimen regardless of the color of the waste glass. However, the strength increased with increasing mix ratio of ground granulated blast-furnace slag to manifest the highest strength at 30% mix ratio of ground granulated blast-furnace slag. The influence of the color of the waste glass was only marginal for the mix ratio of ground granulated blast-furnace slag at or above 20%. Additionally, the characteristics of strength influenced by various mix ratios of fly ash showed a similar trend with the case for ground granulated blast-furnace slag and reached the peak strength at the mix ratio of 20% fly ash. Given the same mix ratio of industrial by-products, fly ash manifested higher strength than ground granulated blast-furnace slag.

The reason that the strength is increased with the addition of industrial by-products is construed to be due to the fact that the addition of industrial by-products reduces the expansion due to ASR induced by the mixing of waste glass, resulting in less degree and occurrence of crack.

Figs. 9 and 10 depicts the relationship between compressive strength and expansion ratio of the mortar, which is mixed with 20 % waste glass and is immersed in NaOH solution at 80°C, by increasing mix ratio of industrial by-products.

While the expansion ratio decreased with increasing mix ratio of industrial by-products compared to the case of mixing waste glass of 2.5~1.2 mm grain size only, the compressive strength ratio

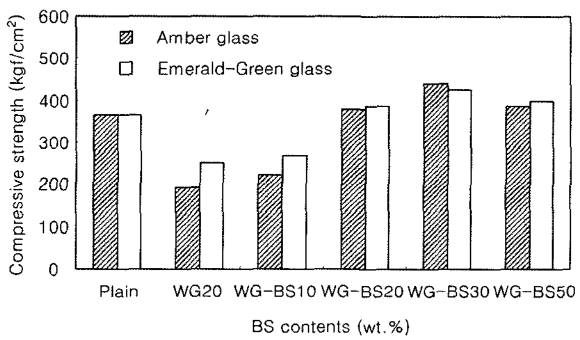


**Fig. 7** Compressive strength according to BS contents.

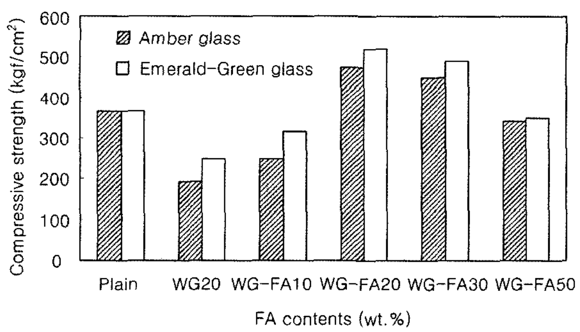


**Fig. 8** Compressive strength according to FA contents.

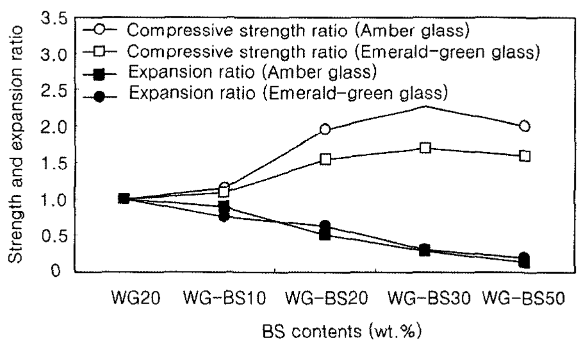


**Fig. 9** Compressive strength ratio and expansion ratio.

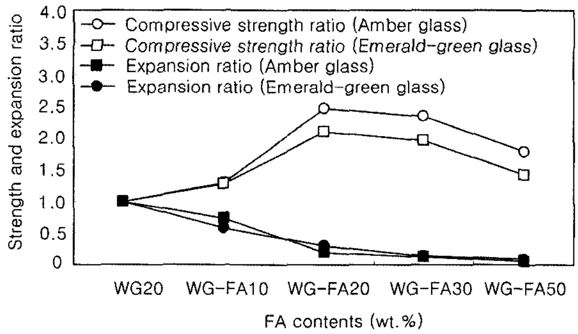


**Fig. 10** Compressive strength ratio and expansion ratio.

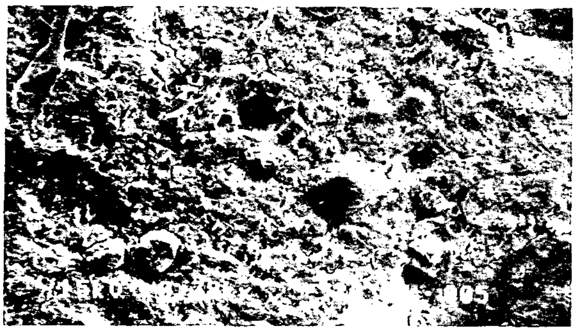

**Photo 3** SEM image of mortar bar (BS 20%).

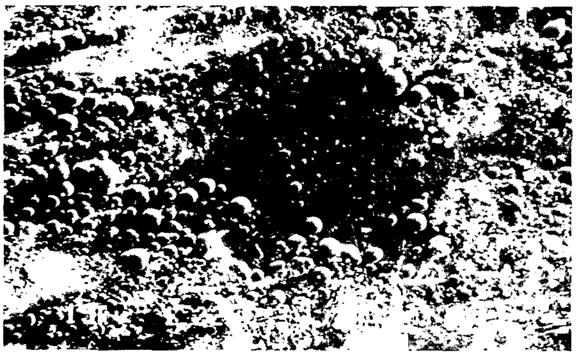

**Photo 4** SEM image of mortar bar (FA 20%).

reached the peak for the mix ratios of 30% for ground granulated blast-furnace slag and 20% for fly ash and did not increase further with higher mix ratios of industrial by-products. Thus, it follows that mixing of industrial by-products in large quantity is effective in restraining the expansion due to ASR but is not as effective in the manifestation of higher strength.

Photos 3 and 4 are the SEM images of the surface of the mortar bar specimen mixed with industrial by-products and waste glass of 2.5~1.2 mm grain size. The formation of gel due to ASR was not observed in this image of mortar specimen mixed with industrial by-products, and the image showed the mortar bar generally in good shape. Particles of fly ash mixed in the mortar at 20% could be seen around the waste glass in the SEM image of Photo 4, and the formation of gel, which was seen in the SEM image of Photo 1 for the case of mixing waste glass of 2.5~1.2 mm grain size only, was not observed.

## 3.3 Feasibility analysis of ground waste glass for the use as an admixture

The smaller the grain size of the waste glass was, the less expansion due to ASR and less loss of strength was observed. This section deals with an experiment pursuant to ASTM C 539 in an effort to analyze the possibility of using amber ground waste glass as a pozzolanic material. Additionally, the performance of the ground waste glass as a concrete admixture was compared to the performance of typical pozzolanic materials such as silica fume, ground granulated blast-furnace slag, and fly ash through expansion and compressive strength tests.

### 3.3.1 Lime-glass test for ground waster glass

Fig. 11 illustrates the result of experiment pursuant to ASTM C 593 to evaluate the possibility of using ground waste glass as a

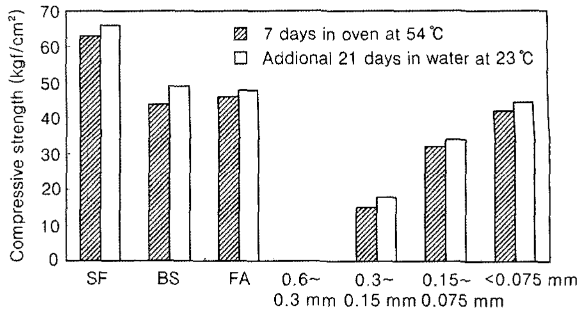


**Fig. 11** Compressive strength of lime-mineral additive mixtures

pozzolanic material. The compressive strength measured after 7 days of curing in the oven kept at 54°C and the value measured after additional curing in water at 20°C satisfied the specifications of ASTM C 539. The ground waste glass of 0.6~0.3 mm grain size showed unsatisfactory shape during the preparation of the mortar specimen and failed to manifest the required strength measured at 7 days and 29 days.

Additionally, the mortar bars mixed with waste glass of 0.3~0.15 mm and 0.15~0.075 mm grain sizes manifested good strength compared to that mixed with waste glass of 0.6~0.3 mm grain size, but their strength was not enough to meet the standard strength value set by ASTM C 539. The compressive strength of the mortar specimen with ground waste glass of grain size below 0.075 mm exceeded the standard value. It follows then that the waste glass of minute grain size below 0.075 mm has the performance capacity of a pozzolanic material, but the strength of the mortar mixed with it manifested lower strength than that mixed with existing pozzolanic materials.

Yixin et al.[14] reported that fluorescent glass of 38 μm grain size could be possibly used as a pozzolanic material. Moreover, they reasoned that the cause for the ground waste glass to exhibit less pozzolanic reaction compared to other pozzolanic materials was due to the relatively smaller amount of its main constituent compounds ($SiO_2$, $Al_2O_3$, $Fe_2O_3$).

Since changing the main constituent compounds ($SiO_2$, $Al_2O_3$, $Fe_2O_3$) of waste glass to make it a better pozzolanic material is difficult due to the unique characteristics of glass production, a viable alternative would be to grind the waste glass to make its grain size smaller and finer.

### 3.3.2 Expansion and strength properties of ground waste glass

The change in expansion ratio with time for the mortar, of which the cement was replaced 20 % by weight with ground waste glass and pozzolanic materials (fly ash, ground granulated blast-furnace slag) is shown in Fig. 12.

The expansion of all test specimens including the plain specimen surpassed and was below the standard value of 0.1% expansion ratio as deemed safe by ASTM C 1260. Nevertheless, the mortar mixed with 20% ground granulated blast-furnace slag had relatively less reduction in the expansion compared to other pozzolanic materials. The mortar mixed with waste glass exhibited greater reduction in the expansion ratio compared to untreated, ordinary mortar by 61~65%. Moreover, the mortar mixed with waste glass of the grain size below 0.075 mm exhibited a reduction in the expansion ratio almost equal to that of

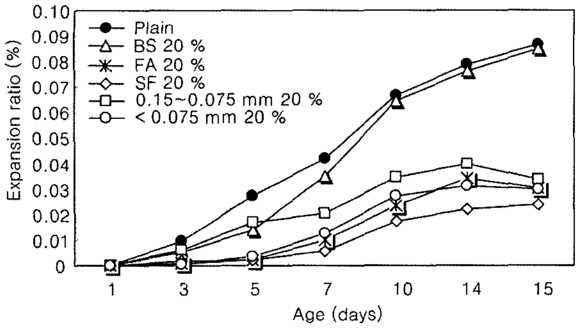


**Fig. 12** Expansion time histories for mortar bar.

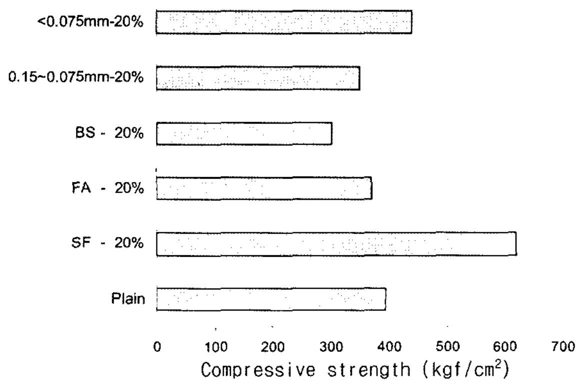


**Fig. 13** Compressive strength of mortar containing 20% mineral additives.

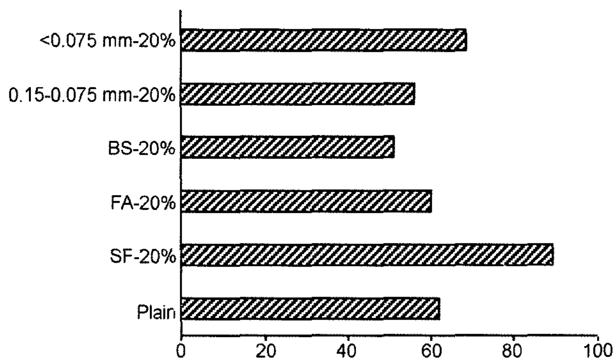


**Fig. 14** Flexural strength of mortar containing 20% mineral additives.

fly ash. This effect of waste glass in restraining the expansion is reported by the studies of Meyer, Baxter, and Yixin et al.[14-16]

Figs. 13 and 14 show the results of compressive strength and flexural strength of mortar, of which the cement was replaced with pozzolanic materials and ground waste glass by 20% of the weight and was immersed in NaOH solution for 14 days at 80°C. The compressive strength of the mortar mixed with 20% silica fume manifested far greater strength than the mortar mixed with other additives. The case of adding fly ash or ground granulated blast-furnace slag to the mortar specimen resulted in the manifestation of lower compressive and flexural strength compared to the untreated, plain mortar specimen. However, the case of adding ground waste glass of the grain size below 0.075 mm to the mortar specimen showed about 10% greater strengths compared to case of plain specimen. The manifestation of good strengths by replacing the cement with ground waste glass is construed by the fact that the high content of $Na_2O$ in waste glass and the pozzolanic reaction at high temperature contributed to the increase in strength. In addition, Jawed and Skalny[17] explained that the strength is increased because the alkalinity in the concrete acts as the catalyst for the formation of calcium silicate hydrate (C-S-H) at early stage.

Thus, the result of analyzing the possibility of using ground waste glass as an admixture for concrete show that the grain size of ground waste glass is an important factor of influence on pozzolanic reaction test (lime-glass test), expansion ratio, and strength property. Furthermore, the mixing of waste glass of the grain size below 0.075 mm showed a very favorable performance result compared to the performance of typical pozzolanic materials (fly ash, ground granulated blast-furnace slag). It follows that using the waste lass with this performance property as an admixture to the concrete could save the space for the land-fill of waste glass and could help in the prevention of environmental pollution by decreasing the emission of $CO_2$ by saving the amount of cement used.

## 4. Conclusions

The following conclusions are derived from the results of this experiment, which evaluated the properties of expansion and strength by the color and grain size of waste glass, and mix ratio of industrial by-products, etc. as well as the analysis of the possibility to use ground waste glass as a pozzolanic material.

1) The experiment on ASR expansion characteristics by the grain size of waste glass followed the specifications of ASTM C 1260. The result revealed that the pessimum grain size for waste glass was found to be 2.5~1.2 mm regardless of the color of waste glass.

2) As the grain size of waste glass became smaller than 2.5~1.2 mm, the ASR expansion ratio showed the tendency to decrease gradually. The expansion ratios of the mortar specimens mixed with amber waste glass of the 0.15~0.075 mm and below 0.075 mm grain sizes were 0.037% and 0.03%, respectively. These values were 85% ~88% lower than the expansion ratio of the mortar mixed with amber waste glass of 2.5~1.2 mm grain size and also lower than the plain mortar not mixed with waste glass.

3) The comparison of the images of SEM photos for the mortar mixed with waste glass of grain sizes of 2.5~1.2 mm and below 0.075 mm revealed that the formation of gel due to ASR was not observed for the case of waste glass below 0.075 mm in grain size unlike the case of waste glass of 2.5~1.2 mm grain size.

4) When industrial by-products were added in the mortar mixed with amber waste glass of 2.5~1.2 mm grain size, the expansion ratio was reduced by 11~86% and 27~94% with the addition of ground granulated blast-furnace slag and fly ash, respectively. Considering the characteristics of strength exhibited by the mortar specimens, it was deemed that the mix ratios of 30% for ground granulated blast-furnace slag and 20% for fly ash were the most appropriate.

5) The result of the experiment, which followed the specifications of ASTM C 593 to analyze the possibility of using waste glass as a pozzolanic material, revealed that only the mortar mixed

with ground waste glass of the grain size below 0.075 mm unsatisfactorily exceeded the standard value of safety as specified by ASTM C 593.

6) The case of using ground waste glass of the grain size below 0.075 mm as a concrete admixture presented good results of reducing the expansion by 65% more and of increasing the strength by about 10% greater than the case of untreated, plain mortar specimen. Thus, it was found that the use of waste glass of the grain size below 0.075 mm as a pozzolanic material was not only possible but also desirable in consideration of economic and environmental issues.

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