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Effects of waste PET bottles aggregate on the properties of concrete

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Abstract

This paper investigates the surface microstructure of waste polyethylene terephthalate (PET) bottles lightweight aggregate (WPLA) to examine the effect of granulated blast-furnace slag (GBFS) on WPLA. The WPLA was made from the waste PET bottles and GBFS, and experimental tests were conducted on compressive strength, splitting tensile strength, modulus of elasticity, slump, and density of waste PET bottles lightweight aggregate concrete (WPLAC).

The 28-day compressive strength of WPLAC with the replacement ratio of 75% reduces about 33% compared to the control concrete in the water–cement ratio of 45%. The density of WPLAC varies from 1940 to 2260 kg/m^3 by the influence of WPLA. The structural efficiency of WPLAC decreases as the replacement ratio increases. The workability of concrete with 75% WPLA improves about 123% compared to that of the normal concrete in the water–cement ratio of 53%. The adhered GBFS is able to strengthen the surface of WPLA and to narrow the transition zone owing to the reaction with calcium hydroxide.

Keywords: Waste PET bottles lightweight aggregate; Microstructure; Granulated blast-furnace slag; Compressive strength; Workability

1. Introduction

Lightweight aggregate is an important material in reducing the unit weight of concrete complying with special concrete structures of large high-rise buildings. Generally, lightweight aggregate is made from ground granulated blast-furnace slag (GBFS), fly ash, and volcanic ash [1,2]. However, lightweight aggregate is faced with some problems: (1) the high cost of aggregate due to high incineration temperature; (2) the shrinkage and resistance to freezing and thawing because of high absorption of lightweight aggregate [3,4]. Therefore, the improvement on the quality of lightweight aggregate concrete has attracted much attention from researchers [5–7].

On the other hand, polyethylene terephthalate (PET) bottles have taken the place of glass bottles as storing vessel of beverage due to its lightweight and ease of handling and storing. As the beverage consumption increases drastically, the production of PET bottles increased exponentially as it was reported that PET bottles were produced about 87,000 tons at the end of 2002 in Korea [8].

Because the Korean Government established laws on conservation and recycling of resources to prevent environmental contamination and resource dissipation, the recycling of waste PET bottles has been designated as a priority management item [9].

Waste PET bottles had been reworked for drinking bottles by melting fusion, which turned out to be too costly. Then, waste PET bottles were insured to recycling as lightweight aggregates to reduce the rework cost. However, results have been far from satisfactory. If waste PET bottles were reused as lightweight aggregates for concrete, positive effects are expected on the recycling of waste resources and the protection of environmental containment.

Furthermore, GBFS is sufficiently able to react with calcium hydroxide to form calcium silicate hydrate (C-S-H) as a pozzolanic material. Then, the transition interfacial zone between aggregates and cement paste will be strengthened because the GBFS consumes the calcium hydroxide. The GBFS is able to improve the workability as well as the resistance to chemical attack and reduce the heat of hydration because the pozzolanic reaction is quite slow [10,11].

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Table 1
Chemical compositions of cementitious materials

Components	C (%)	GBFS (%)
SiO_2	21.60	33.33
Al_2O_3	6.00	15.34
Fe_2O_3	3.10	0.44
CaO	61.41	42.12
MgO	3.40	5.70
SO_3	2.50	2.08

Table 2
Physical properties of aggregate

Components	RS	WPLA	Coarse aggregate
Density (g/cm^3)	2.60	1.39	2.69
Bulk density (kg/m^3)	1677	844	1589
Absorption (%)	1.82	0.00	0.86
Percentage of solids (%)	64.5	60.7	58.0
Fineness modulus	2.90	4.11	7.15

In this study, lightweight aggregates were made from waste PET bottles, and GBFS was used to examine whether it is possible to improve the quality of lightweight aggregate. We investigated the quality of lightweight aggregates, conducting tests on the workability and the strength properties of concrete, analyzing the relationship between the quality of aggregates and the properties of concrete.

2. Experimental outline

2.1. Materials

Korean normal portland cement (C) and the GBFS were used as cementitious materials. The density and Blaine fineness of normal portland cement are 3.15 g/cm^3 and 3539 cm^2/g, respectively, and the density and Blaine fineness of GBFS are 2.90 g/cm^3 and 3840 cm^2/g, respectively. The characteristics of the normal portland cement and the GBFS are shown in Table 1.

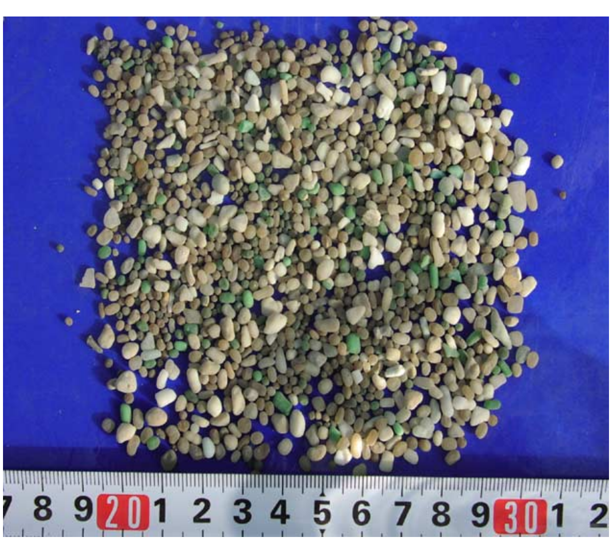

Fig. 1. Shape of WPLA.

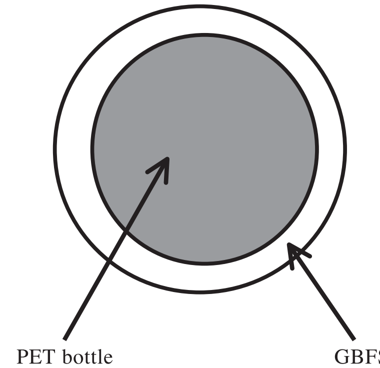

Fig. 2. Section of WPLA.

The fine aggregates are clean river sands (RS) and lightweight aggregates made from waste PET bottles (WPLA). The coarse aggregate is crushed stone aggregate with a maximum size of 20 mm. Both the fine and coarse aggregates are sufficient in satisfying the Korean Standard Specifications. The physical properties of the aggregates are shown in Table 2. Standard type of AE Water-Reducing Agent (AE) was used in this experiment, and the specific gravity and pH of AE are 1.2 ± 0.02 and 7.0 ± 1.0, respectively.

Lightweight aggregates were manufactured from the waste PET bottles according to the following procedure. The fractions of waste PET bottles cut to the range of 5–15 mm were intruded in the mixer. The inner temperature and rotate velocity of the mixer were 250 ± 10 °C and 30–50 rpm for 20 s. The GBFS was entered in the mixer with the waste PET bottles to solidify the surface of aggregates.

The density and bulk density of the WPLA are 1.39 g/cm^3 and 844 kg/m^3, respectively, and its absorption was not measured in Table 2. Fig. 1 indicates the smooth sphere shape of the WPLA. Fig. 2 shows the section of WPLA, and GBFS is uniformly covered on the surface of aggregates.

Table 3
Mixture proportions of concrete

Mix number	WPLA: (RS + WPLA)	S/a [%]	W/C	C:AE
1, 2, 3, 4	0:1, 0.25:1, 0.5:1, 0.75:1	48.4, 50.9, 53.4, 56.4	0.53	1:0.003
5, 6, 7, 8	0:1, 0.25:1, 0.5:1, 0.75:1	47.0, 49.5, 52.0, 55.0	0.49	1:0.003
9, 10, 11, 12	0:1, 0.25:1, 0.5:1, 0.75:1	45.9, 47.9, 50.9, 53.9	0.45	1:0.003

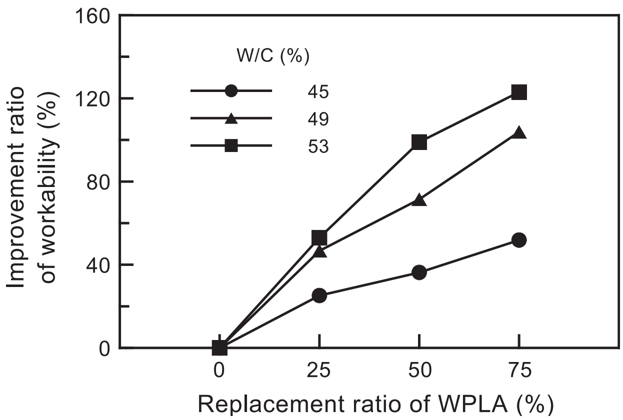

Fig. 3. Relationship between workability and replacement ratio of WPLA.

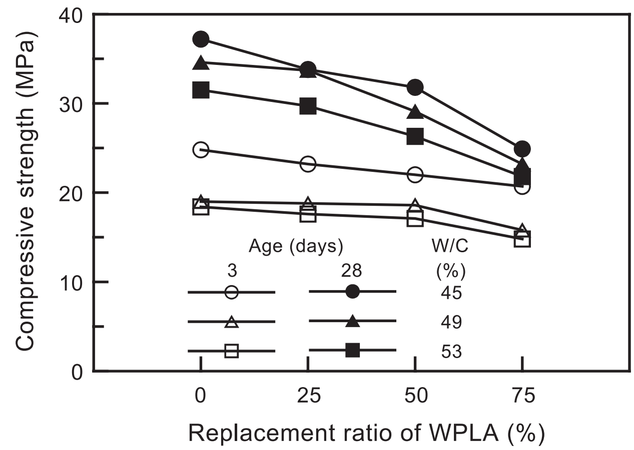

Fig. 4. Relationship between compressive strength and replacement ratio of WPLA.

2.2. Specimens' size and experimental methods

2.2.1. Strength test

Concrete specimens were cast in ϕ 100 × 200 mm steel moulds and compacted with compaction steel bar. The specimens were covered with cling film to prevent water loss for 24 h after casting and curing in water at the 23 ± 2 °C for 3, 7, and 28 days after demoulding. Before the strength testing, the specimens were capped with sulfate to prevent eccentricity. The splitting tensile strength and modulus of elasticity were measured at the age of 28 days. The density of concrete was also measured at 28 days.

2.2.2. SEM analysis

The collected samples were carbon coated and analyzed using a scanning electron microscope (SEM) in the backscattered electron mode with an accelerating voltage of 20 keV. The backscattered intensity was set to the same parameters for each sample.

2.3. Mixture proportions of concrete

Mixture proportions of concrete were planned so that the water–cement ratios were 45%, 49%, and 53%, and the replacement ratios of WPLA were 0%, 25%, 50%, and 75% by volume of fine aggregate. Table 3 shows 12 different types of mix proportions for the test samples. For all specimens, the air content was set at 4.5 ± 1%.

3. Results and discussion

3.1. Properties of fresh concrete

The relationship between the workability and the replacement ratio of the WPLA is illustrated in Fig. 3. The slump value of waste PET bottles lightweight aggregate concrete (WPLAC) increases as the water–cement ratio and the replacement ratio increase, as shown in Table 4. The improvement ratios of workability represent 52%, 104%, and 123% in comparison with that of normal concrete at the water–cement ratio 45%, 49%, and 53%, respectively. This may be attributed to not only the spherical and smooth shape but also to the absorption of WPLA.

Namely, the workability improvement achieved by containing the WPLA is capable of reducing the unit water

Table 4
Results of concrete properties

W/C [%]	WPLA/ (RS + WPLA) [%]	Density [kg/m^3]	Compressive strength [MPa]			Splitting tensile strength [MPa]	Modulus of elasticity [MPa, × 10^3]	Slump [cm]
			3 days	7 days	28 days			
53	0	2300	18.4	24.0	31.5	3.27	23.5	10.0
	25	2220	17.6	23.4	29.7	2.65	23.0	15.3
	50	2130	17.1	21.5	26.3	2.25	21.2	19.9
	75	2010	14.8	19.2	21.8	2.04	18.5	22.3
49	0	2300	19.0	27.8	34.6	3.27	23.3	10.5
	25	2230	18.8	26.7	33.7	2.76	22.8	15.4
	50	2120	18.6	24.3	29.1	2.35	18.1	18.0
	75	2000	15.8	21.6	23.2	1.94	16.7	21.4
45	0	2300	24.8	31.3	37.2	3.32	25.5	13.5
	25	2260	23.2	27.4	33.8	2.80	18.7	16.9
	50	2160	22.0	26.5	31.8	2.55	17.3	18.4
	75	1940	20.7	24.8	24.9	2.04	15.6	20.5

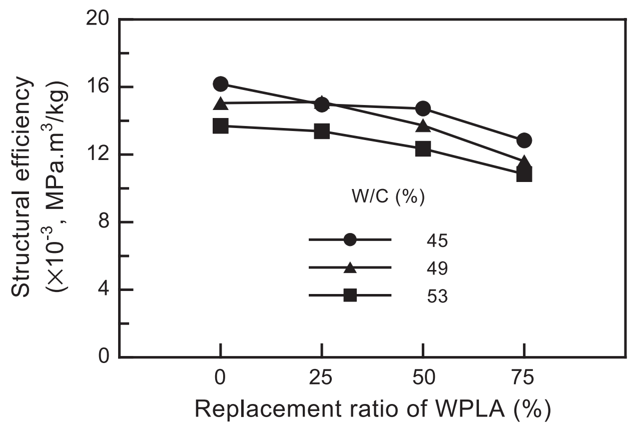

Fig. 5. Relationship between structural efficiency and replacement ratio of WPLA.

content and the water-reducing agent content. It is expected that the reduction of the unit water content could compensate for the strength reduction of the WPLAC in the case of manufacturing the concrete with the same slump.

3.2. Mechanical properties

The compressive and splitting tensile strength, the modulus of elasticity, and the density of WPLAC are illustrated in Table 4. The 28-day compressive strength varies from 21.8 to 37.2. The splitting tensile–compressive strength ratio (f_t/f_c) and the modulus of elasticity–compressive strength (E_c/f_c) of WPLAC indicate the range of 1/10–1/12 and 6.27–7.46 × 10^2, respectively. The compressive and tensile strength, and the modulus of elasticity of WPLAC

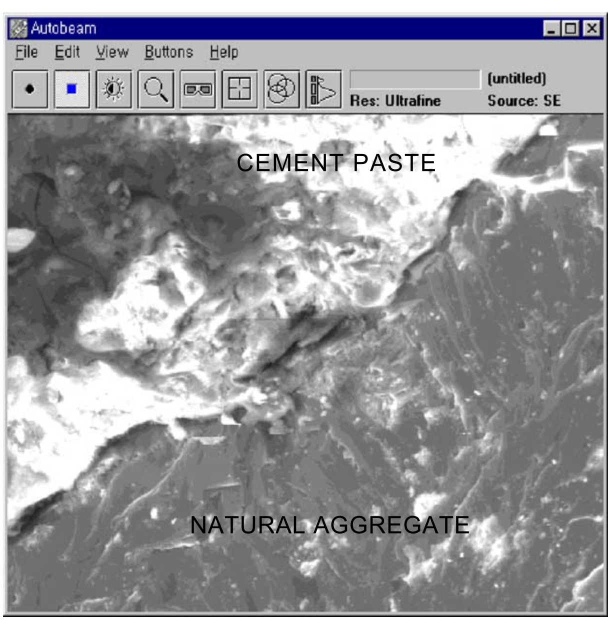

Fig. 6. Transition zone between cement paste and natural aggregate in mortar (28 days, magnified × 700).

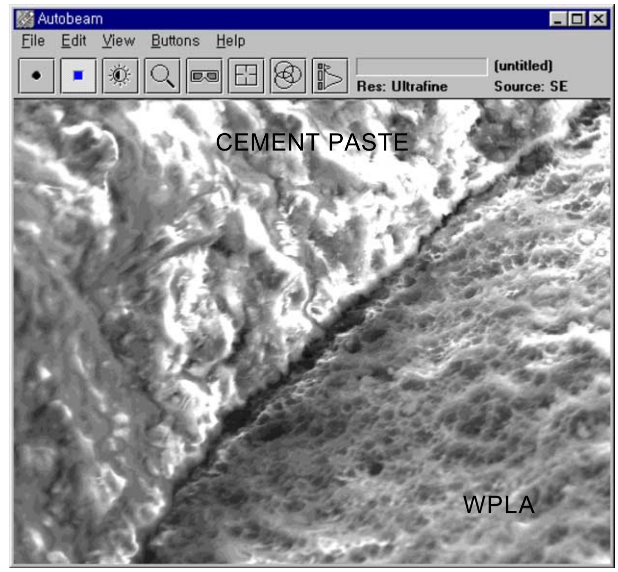

Fig. 7. Transition zone between cement paste and WPLA in mortar (28 days, magnified × 700).

are affected by the water–cement ratio and replacement ratio of WPLA. The density of WPLAC varies from 1940 to 2260 kg/m^3, indicating a saving in the self-weight between 2% and 16% compared to the density of normal-weight concrete of 2300 kg/m^3.

Fig. 4 represents the relationship between the compressive strength and the replacement ratio of WPLA. The difference of 3 days compressive strength is not represented compare to the replacement of WPLA, but the 28-day compressive strength decreases as the replacement ratio increases. The 28-day compressive strength of concrete with WPLA of 75% is reduced about 33% compared

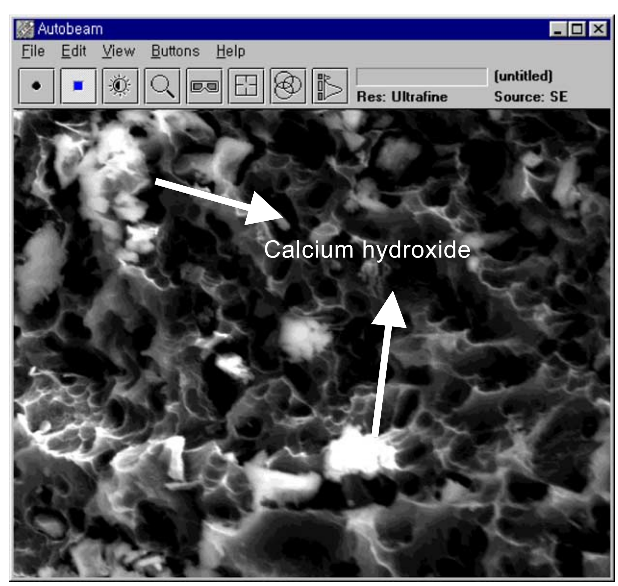

Fig. 8. Surface microstructure of WPLA in mortar (3 days; 28 days, magnified × 2000).

to that of control concrete in the water–cement ratio of 45%. It indicates that the compressive strength probably reaches an upper level for the aggregates, and the strength does not benefit much from further improvement in the matrix strength. This may be attributed to the influence of WPLA.

Fig. 5 shows the relationship between the 28-day structural efficiency (compressive strength/density ratio) [5] and the replacement ratio of WPLA. The structural efficiency decreases as the replacement ratio and water–cement ratio increase. The structural efficiency of WPLAC with the replacement ratio of 75% is about 21% lower than that of control concrete at the same water–cement ratios, and the structural efficiency of WPLAC with a water–cement ratio of 53% is about 15% lower than that of control concrete at the same replacement ratio. This may be attributed to the influence of WPLA weight and matrix strength.

3.3. Transition zone and surface microstructure of WPLA

Figs. 6 and 7 show the transition zone between the cement paste and the natural aggregate, and the WPLA in mortar at the age of 28 days. The transition interfacial zone between the WPLA and the cement paste shows a tendency to be uniformly wider than that of the natural aggregate because the WPLA was manufactured to spherical and smooth shape. Furthermore, the workability improvement increases the water–cement ratio in the transition zone of WPLA so that the transition zone was expanded [12].

Figs. 8 and 9 show the surface microstructure of WPLA in mortar at the age of 3 and 28 days.

The hydrates are slightly shown on the surface of WPLA in mortar at the age of 3 days, but densely covered on the surface of WPLA at the age of 28 days. This phenomenon indicates that the adhered GBFS on the surface of WPLA reacts with calcium hydroxide made by C_2S and C_3S, and produces C-S-H. Furthermore, the adhered GBFS is able to strengthen the surface of WPLA and narrow the transition zone because of consuming the calcium hydroxide [10,11].

The surface of WPLA shows a slightly hexagonal calcium hydroxide at the age of 3 days, but it is densely covered with C-S-H by the reactive GBFS at the age of 28 days [10,11]. It would be possible to predict that the GBFS adhered on the surface of the aggregate is capable of strengthening and improving the surface and the resistance to fire of lightweight aggregate made only with waste PET bottles.

As these results indicate, when the waste PET bottles will be reused as aggregates for concrete, we can expect not only the reduction of self-weight and absorption of concrete but also the protection of environmental pollution and the recycling of waste resources.

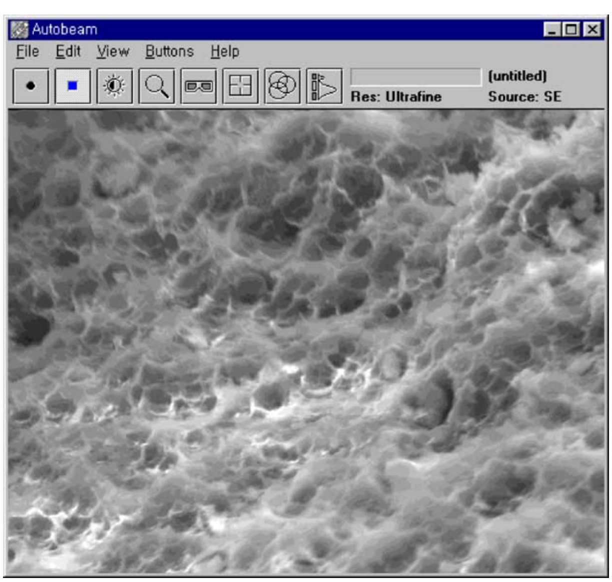

Fig. 9. Surface microstructure of WPLA in mortar (28 days; 28days, magnified ×2000).

4. Conclusions

The results of this study have led us to reach the following conclusions.

(1) The specific gravity and the bulk density of WPLA was about 50% lower than the natural aggregate, and its absorption was not measured. The WPLA was made from the waste PET bottles and GBFS on the surface of aggregates.
(2) The 28-day compressive strength and the density of WPLACs were reduced as the replacement ratio and the water–cement ratio increased. The structural efficiency of WPLAC with the replacement ratio of 75% was about 21% lower than that of the control concrete. This may be attributed to the influence of WPLA weight and matrix strength.
(3) The workability of WPLACs was improved as the replacement ratio and the water–cement ratio increased. The results demonstrate that the workability improvement of WPLAC is capable of reducing the unit water content and the water-reducing agent content.
(4) The transition zone between the WPLA and the cement paste was expanded when compared with that of the natural aggregate. It is expected that the GBFS adhered on the surface of WPLA is capable of strengthening the surface of aggregate, narrowing the transition zone compared to the surface of other lightweight aggregate without GBFS because of the consumption of calcium hydroxide.

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