Available online at www.sciencedirect.com
ScienceDirect
Cement & Concrete Composites 29 (2007) 128–135
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Properties of concrete made with alkali-activated fly ash lightweight aggregate (AFLA)

Byung-wan Jo, Seung-kook Park *, Jong-bin Park

Structural Engineering Lab., Department of Civil Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea

Received 4 October 2005; received in revised form 28 August 2006; accepted 22 September 2006
Available online 7 November 2006

Abstract

An experiment was performed to investigate the properties of the hardened paste of fly ash by alkali activation and to determine the possible use of the paste in the production of lightweight aggregates. The highest compressive strength was 33.9 MPa, for paste with 10% NaOH, 15% sodium silicate, and 5% MnO_2, cured at room temperature after 24 h of moisture curing at 50 °C. The hardened paste of fly ash was granulated to produce AFLA (alkali-activated fly ash lightweight aggregate). AFLA exhibited specific gravity (SSD, OD), water absorption, unit weight, and solid volume percentages of 1.85 (SSD), 1.66 (OD), 11.8%, 972 kg/m^3, and 58.6%, respectively. The results of the heavy metals leaching test met US EPA regulations. The concrete using AFLA exhibited a compressive strength of 26.47 MPa and good freeze–thaw resistance at 6.0% entrained air content.

Keywords: Fly ash; Alkali activation; Artificial lightweight aggregate; Lightweight concrete

1. Introduction

Lightweight aggregates are popular for use in concrete because they offer some improved physical properties compared with normal-weight aggregates, including reduced dead weight, higher insulating coefficients, and superior sound-dampening qualities. Conventional lightweight aggregates are made by heating clay, shale, or slate to temperatures in excess of 1000–1200 °C in a rotary kiln. This process produces a high-quality lightweight aggregate that is structurally strong, physically stable, durable, environmentally inert, highly insulative, and lightweight [1]. Originally, lightweight aggregates were composed of natural materials extracted from the earth; but, as demand for lightweight aggregates increased, natural resources became depleted. To produce alternative lightweight aggregates, common rocks and minerals are altered, usually by elevated temperatures. With modern, artificially produced lightweight aggregates, it is possible to produce lightweight concrete with compressive strength comparable to that of normal-weight concrete. Lightweight concretes are commonly used in the construction of buildings, bridge deck pavements, and, in a more limited role, for entire bridge superstructures [2–4].

In addition, industrialization has generated excess waste materials that are now being examined as potential sources of raw materials for the production of lightweight aggregates. The high demand for construction materials and building products make them a favorable medium for recycling materials [15]. Consequently, recycling of waste materials in the construction industry has become increasingly popular since the early 1980s. Fly ash is the fine portion of coal combustion by-products produced at power-generating stations and typically collected from the flue gases by electrostatic precipitators. Aggregates made from these sources are generally called recycled artificial lightweight aggregates. As with recycled aggregates, fly ash artificial lightweight aggregates transform what once was a liability

* Corresponding author. Tel.: +82 2 2220 0327; fax: +82 2 2292 0321.
E-mail address: plus_skpark@yahoo.com (S.-k. Park).

0958-9465/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2006.09.004

into an asset. Reuse of waste material also limits landfill use and the mining required for aggregates.

Alkaline activators have been widely reported to produce rapid hardening and high compressive strengths. Wang and Scrivener have shown that the type of activator affected the properties of the alkali-activated slag and recommended sodium silicate [5]. Davidovits reported that alkali-activated material possesses excellent mechanical properties, does not dissolve in acidic solutions, and does not generate any deleterious alkali-aggregate reaction even in the presence of high alkalinity [7]. Fernandez–Jimenez reported that the most significant factor in the development of alkali-activated slag mortars with good mechanical strengths is the nature of the alkaline activator [8]. Bakharev reported that slag concrete, activated by liquid sodium silicate, had the best mechanical properties. The activators were liquid sodium silicates (4–7% Na, mass of slag) and a multi-compound activator ($NaOH + Na_2CO_3$) (8% Na, mass of slag) [9]. Some of the past research results on the behavior of alkali-activated material are contradictory. Palomo, Grutzeck, and Blanco have shown that the curing temperature, curing time, and type of activator affected the compressive strength, while the solution-to-fly ash ratio was not a relevant parameter [10]. Bakharev, Sanjayan, and Cheng reported that the main products of degradation in sulfate attack are gypsum and ettringite in the case of Portland cement concrete and gypsum in the case of alkali-activated slag concrete. Portland cement concretes showed significant expansion, cracking, and loss of concrete, while alkali-activated slag concretes were not expanded but cracked in the sulfate attack test [11].

This work presents an investigation into the new lightweight aggregate made from fly ash. In this experiment, the hardened paste of fly ash was manufactured by alkali activation [5]. The pastes were composed of fly ash, sodium silicate (Na_2SiO_3), NaOH, and MnO_2. The paste of fly ash was cast to investigate the optimum composition, curing condition, and strength of the hardened paste. XRD and SEM techniques were used to understand the hardening mechanisms of the hardened paste of fly ash.

The hardened paste of fly ash was granulated to produce the alkali-activated fly ash artificial lightweight aggregates (AFLA). Specific gravities, absorption capacities, sieve analysis, environment stability, and other properties of the AFLA were determined. Concrete was made with the AFLA, and its mechanical and freezing–thawing properties were investigated.

Results are compared with those of traditional and other artificial lightweight aggregates. Potential future applications and the composition of AFLA are discussed.

2. Materials and experiment

2.1. Fly ash

The chemical composition of the fly ash is given in Table 1. The calcium content was low (<3%), and the sum ($Al_2O_3 + SiO_2 + Fe_2O_3$) was more than 92.3%, which means that this ash belongs to ASTM Class F ash. The X-ray diffractogram of the ash (Figs. 3 and 4) shows the presence of a glassy phase with two major crystalline phases of quartz and mullite. This low-calcium ash shows diffused halo maxima at $2\theta = 20$–27° (Cu Kα radiation). The scanning electron micrograph of the fly ash (Fig. 1 and 2) shows both spherical particles and irregular-shaped grains. It should be pointed out that the fly ash used in this study has a high fraction of reactive oxides ($Al_2O_3 + SiO_2 + Fe_2O_3 > 92.3\%$), which means that it has high reactivity with sodium silicate and thus potentially possesses high strength [5].

2.2. Binders

Sodium silicate (liquid 40%) was used as a combining agent for the fly ash. NaOH (with liquid 33%, 98% purity, and 12 mol) was used as an oxidizing agent to increase the combining reactivity of fly ash and $Ca(OH)_2$, as well as to enhance the dissolution of silica in fly ash. MnO_2 was also used to improve strength. The small amount of normal portland cement was used to increase strength (see Table 2).

2.3. Test of hardened paste of fly ash

After dry mixing of fly ash and cement for 2 min, sodium silicate, NaOH, and water were poured into the mixer to complete mixing for 3 more minutes. The water to solids ratio was 23.6% (by weight) in consideration of workability. Fly ash mixtures were cast in $50 \times 50 \times 50\ mm^3$ steel molds for physical and mechanical tests. During casting, all of the specimens were compacted by rodding and vibration. During the first 24 h, the specimens were left in the molds. The experimental variable and mixtures are tabulated in Tables 3 and 4. In order to verify the effectiveness of activators and curing conditions on the strength of pastes, the pastes were mixed with various activators. The strength characteristics and stability of different mixtures of hardened paste of fly ash were analyzed under different curing conditions after 7 days. Higher curing temperature generally results in greater compressive strength; however, beyond a certain curing temperature (45–60 °C), the strength of alkali-activated materials does

Table 1
Properties of fly ash and Portland cement (unit: %)

Type	Specific gravity	Fineness (cm^2/g)	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Fly ash	2.20	3150	3.5	57.09	24.66	10.5	2.58	1.37	0.94
Portland cement	3.15	3360	1.2	21.4	5.1	2.9	64.0	1.6	2.0

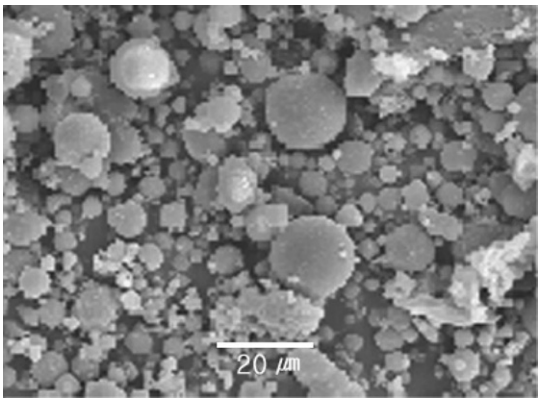


Fig. 1. Grain shape of fly ash.

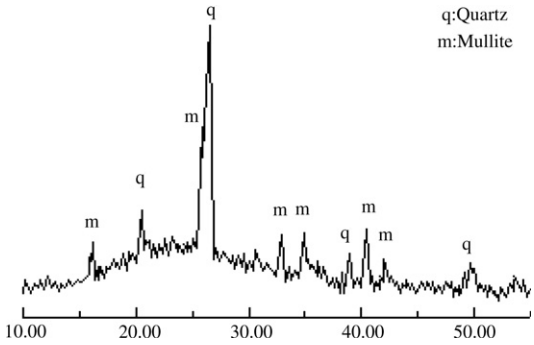


Fig. 3. XRD analysis of fly ash.

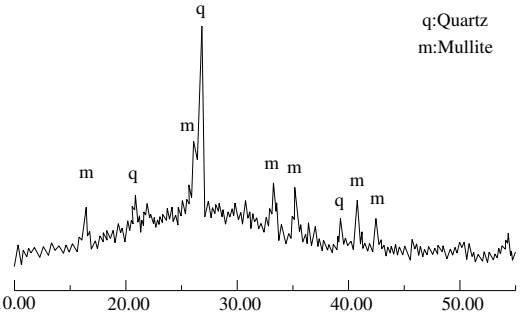


Fig. 4. X-ray diffractogram of hardened paste of fly ash.

not change significantly as cuing temperature increases [8,10]. Unlike normal concrete, fly ash paste has no standard curing condition. Therefore, the fly ash paste was measured at various curing conditions and mixtures (see Table 4). Also, MnO_2 was added to the mixtures, and the compressive strength of the specimen was measured.

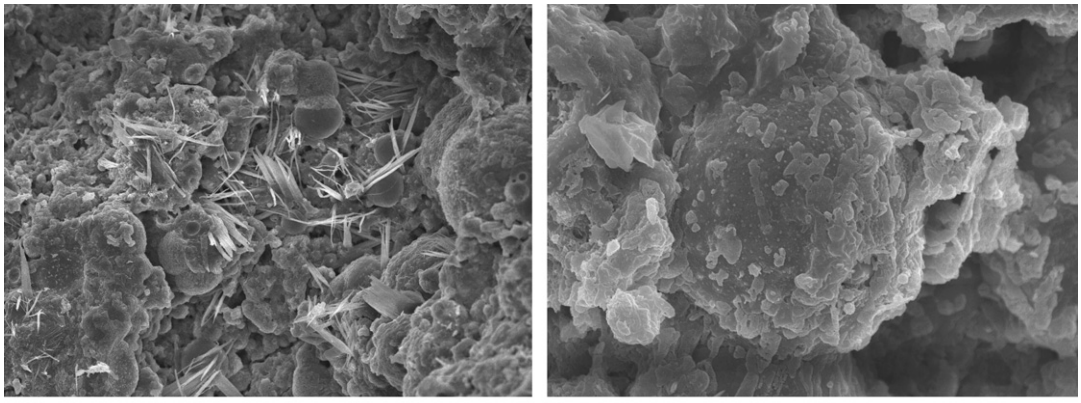
In this experiment, the amounts of binders and adding agents were controlled. The hardening of fly ash by cement is not an essential part of this study, so the amount of cement was limited to 10%. The amount of sodium silicate was also limited, because a small amount will not affect the combination of fly ash particles, a large amount causes an irrelevant and unnecessary increase in strength.

2.4. AFLA testing

AFLA was produced not by existing high temperature sintering methods, but by alkali activation of fly ash hardening aided by a combining agent. The hardened paste of fly ash was granulated to produce the specified nominal maximum aggregate size. The specific gravity, water absorption (ASTM C 127), size distribution (ASTM C 136), unit weight (ASTM C 29), and solid volume percentage of AFLA were determined [17–19]. The aggregate crushing value provides a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. The crushing value (BS 812) was measured to determine AFLA's resistance to a static load, and the qualities of AFLA compared with natural aggregate and various artificial lightweight aggregates [23]. The leaching test was performed with AFLA, according to the Toxicity Characteristic Leaching Procedure (Method 1311) of the

Table 2
Specification of sodium silicate (Na_2SiO_3)

Specific gravity	SiO_2	Na_2O	SiO_2/Na_2O
1.406	25.61%	7.53%	3.40



(a) Reaction products of fly ash mortar (b) Surface of fly ash particle

Fig. 2. Scanning electron micrograph of hardened paste of fly ash.

Table 3
Fly ash mixtures (unit: percentage to the fly ash)

Specimen	Cement (%)	NaOH (%)	Sodium silicate (%)	MnO_2 (%)	Compressive strength (MPa), at 7-days	Curing conditions
C1–N1–S1	5	5	5		1.06	B
C1–N1–S2			10		1.29	
C1–N1–S3			15		2.17	
C1–N2–S1		10	5		1.42	
C1–N2–S2			10		2.47	
C1–N2–S3			15		2.89	
C1–N3–S1		15	5		1.23	
C1–N3–S2			10		1.90	
C1–N3–S3			15		2.36	
C2–N1–S1	10	5	5		1.53	
C2–N1–S2			10		2.42	
C2–N1–S3			15		2.98	
C2–N2–S1		10	5		1.82	
C2–N2–S2			10		2.92	
C2–N2–S3			15		3.86	
C2–N3–S1		15	5		1.59	
C2–N3–S2			10		2.62	
C2–N3–S3			15		3.18	
C1–N2–S2–M1	5	10	10	5	30.4	C-2
C1–N2–S2–M2				10	28.9	
C1–N2–S3–M1			15	5	31.8	
C1–N2–S3–M2				10	31.0	
C2–N2–S2–M1	10	10	10	5	32.5	
C2–N2–S2–M2				10	30.1	
C2–N2–S3–M1			15	5	33.9	
C2–N2–S3–M2				10	31.2	

Table 4
Curing conditions for fly ash paste

Specimen	Curing conditions [curing age: 7-days (168 h)]	Compressive strength (MPa) at 7-days
A	72 h of curing at room temperature after 96 h of water curing at 15 °C	6.4
A-1	156 h of curing at room temperature after 12 h of water curing at 50 °C	12.0
A-2	144 h of curing at room temperature after 24 h of water curing at 50 °C	18.8
A-3	120 h of curing at room temperature after 48 h of water curing at 50 °C	20.0
A-4	96 h of curing at room temperature after 72 h of water curing at 50 °C	18.0
B	168 h of curing at room temperature after demolding	3.9
C-1	156 h of curing at room temperature after 12 h of moisture curing at 50 °C (more than 90% relative humidity)	20.7
C-2	144 h of curing at room temperature after 24 h of moisture curing at 50 °C (more than 90% relative humidity)	24.6
C-3	120 h of curing at room temperature after 48 h of moisture curing at 50 °C (more than 90% relative humidity)	24.9
C-4	96 h of curing at room temperature after 72 h of moisture curing at 50 °C (more than 90% relative humidity)	25.8

Type of mixture is C2–N2–S3.

US Environmental Protection Agency (EPA). Toxicity Characteristic Leaching Procedure (TCLP) is leaching test used in the laboratory to determine whether waste is considered hazardous. For the test, extraction was carried out at a 20:1 liquid to solid ratio [16].

2.5. Strength and freezing–thawing test of concrete

Cylindrical specimens (100×200 mm) were made with different lightweight aggregates, tested for compressive strength, and subjected to the freezing–thawing test. Lightweight concrete cylinders were cast following the ASTM C 192 [21]. For freezing–thawing testing, $75 \times 75 \times 400$ mm^3 specimens were cast in each mixture with 1.5%, 4%, and 6% air content. In the freezing–thawing tests, specimens were frozen and thawed in water following Procedure A of ASTM C 666 [22]. Their weight and fundamental transverse frequency were measured for the computation of relative dynamic modulus of elasticity after specific numbers of freezing–thawing cycles. Each specimen was

Table 5
Concrete mixtures

Type of aggregate	Entrained air content (%) t	W/C (%)	S/a (sand percentage)	Unit quantity (kg/m^3)				Admixture ($C\times\%$)
				Water (W)	Cement (C)	Sand (S)	Gravel (G)	
JLA, GLA	4	45	58	155	352	838	595	0.2
AFLA	1.5/4/6	45	58	155	352	838	595	0/0.2/0.5
NA	4	45	45	158	350	808	1007	0.2

G_{max}: JLA (clay artificial lightweight aggregate produced in Japan) = 15 mm, GLA (clay artificial lightweight aggregate produced in Germany) = 16 mm AFLA = 19, NA (natural coarse aggregate) = 19 mm.

subjected to freeze–thaw cycles until either its relative dynamic modulus of elasticity reached 60% of its initial value or the number of total cycles reached 300 (whichever occurred first). The mixtures of concrete prepared for test are listed in Table 5. The specimens were cast in two layers and were compacted on a vibrating table. After casting, all molded specimens were covered with plastic sheets and water saturated burlap and left in the casting room for 24 h. They were then demolded and the specimens were transferred to the moist curing room at 23 ± 2 °C and 100% relative humidity until required for testing.

3. Results and discussion

3.1. The hardened paste of fly ash

When the sodium silicate content increased from 5% to 10%, the strength increased by 0.30–1.1 MPa (22–73%), and as the content of the sodium silicate increased from 10% to 15%, the strength increased another 0.5–1.0 MPa (20–30%). However, when the sodium silicate content increased more than 20%, hardening was impeded. On the other hand, the strength was not practically developed when the sodium silicate content was less than 3%. Therefore, the appropriate sodium silicate content was taken as 15%. The binder that increased strength the most was sodium silicate. This is believed to be due to the characteristics of sodium silicate that produces a bonding force rapidly with moisture evaporation. It was concluded that sodium silicate was the binder that increased the hardened paste's compressive strength the most.

Sodium silicate is a mixture of sodium silicate and water. First, it hydrolyzes when mixed with water:

$$[Na_2O \cdot nSiO_2 + (2n+1)H_2O \leftrightarrow 2NaOH + nSi(OH)_4] \quad (1)$$

Subsequently, NaOH reacts with acidic compounds such as Al_2O_3, Fe_2O_3, and SiO_2 in the fly ash at the appropriate temperature. The products of reactions may be in an amorphous phase or a low-ordered crystalline structure that does not exhibit distinguishable peak in the XRD pattern (see Fig. 4). The hardened pastes composed of fly ash and binders are mostly Na_2O–Al_2O_3–SiO_2, and contain small amounts of CaO, MgO, and FeO_2. Finally, Na_2O–Al_2O_3–SiO_2 is bonded with another hydrolysis product of fly ash such as silica gel and gives the hardened paste a high strength (see Fig. 2) [12].

Generally, fly ash is found in an amorphous phase, which is etched by NaOH. When SiO_2 or Al_2O_3 undergoes a pozzolanic reaction, they were attacked by OH^- ion, which is attached to Si or network structure atom. The oxygen atoms get separated by OH^- ions, and through this reaction, the hydration reaction progresses as silicate, or another oxy anion is taken from the original structure. Therefore, NaOH was used for enhancing the reaction of fly ash with $Ca(OH)_2$. The addition of NaOH to the paste increases the dissolution rate of silica from the fly ash, which increases the paste reactivity [6].

When the NaOH content was 10%, the strength was 0.30–0.9 MPa higher than when it was 5%. When the content of NaOH was increased to 15%, the compressive strength decreased by about 0.5 MPa. Therefore, the appropriate content of NaOH was taken as 10%.

The strength development of fly ash was relatively slow compared with cement, because the strength development occurs by a pozzolanic reaction. Therefore, in this study, cement was added to increase initial strength. When the cement content was 10%, the strength was about 0.5–1.0 MPa higher than when it was 5%. It is considered that improvement in strength was due to the early hydration reaction caused by the addition of cement.

An appropriate temperature is necessary for the paste of fly ash to be in an amorphous phase or low-ordered crystalline structure by a reaction between NaOH and an acidic compound, such as Al_2O_3, Fe_2O_3 and SiO_3. Therefore, the compressive strength was measured after 7 days of curing according to the curing conditions given in Table 4 for the mixture type of C2-N2-S3 that was selected in the compressive strength test.

The compressive strength development characteristics of the specimens under various conditions are summarized in Table 4. Notably, the compressive strength of a specimen that underwent water and moisture curing was about 562% higher than one that underwent room temperature curing. The strength of the specimen that underwent moisture curing was higher than the one that underwent water curing, and the strength increased with curing times for both curing processes. Beyond 24 h of moisture curing, however, the compressive strengths did not change significantly with curing time; beyond 48 h of water curing, the compressive strength started to decrease with curing time.

This result was also dependent on the dissolution of sodium ilicate and NaOH, which are soluble in water under water curing. Thus, curing condition affects the strength development. It was observed that the optimum curing method was C-2.

After MnO_2 was added, the strength increased to a maximum of 8.24 MPa. Table 3 shows the strength increase resulting from the addition of MnO_2. The strength when MnO_2 content was 5% was higher than when it was 10%. Therefore, 5% MnO_2 was the most appropriate content. The highest strength obtained for C2-N2-S3-M1 was 33.9 MPa, and that for C2-N2-S2-M1 was 32.5 MPa.

When MnO_2 was not added, the strength increased 20–30% as the sodium silicate content was increased from 10% to 15%. However, when MnO_2 was added, the strength increased only 4–7% when sodium silicate content was increased, a much smaller value than when only MnO_2 was added. Therefore, it was determined that C2-N2-S3-M1 was the most appropriate mixture proportion for the hardened paste of fly ash by alkali activation.

MnO_2, known as a reactive oxide, has high reactivity with sodium silicate. Transition metals such as Mn, are hard and have high densities [13,14]. Hence, strong bonding is achieved because the MnO_2 (which has a high reactivity) reacts with the mixtures. It was concluded that the strength of the hardened paste of fly ash was increased by adding MnO_2. The utilization of the industrial by-product MnO_2 offers economic and environmental advantages and can satisfy mechanical requirements.

3.2. Test results of aggregates

The saturated surface dry (SSD) and oven dry (OD) specific gravities of AFLA were 1.85 and 1.66, respectively. These values are somewhat higher than those of other artificial lightweight aggregates. It was hypothesized that the sintered artificial lightweight aggregate has a larger internal void than that of AFLA. AFLA exhibited a water absorp-

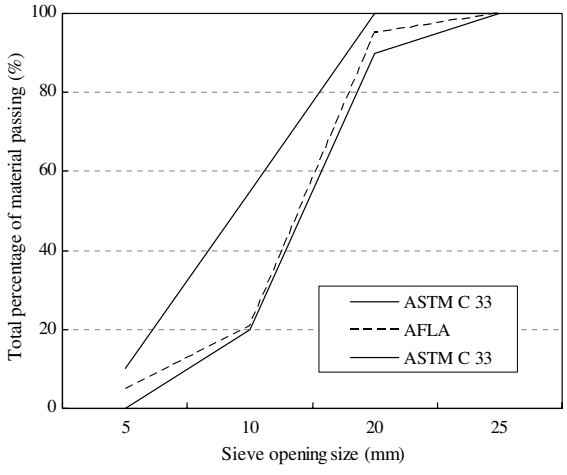


Fig. 5. Sieve analysis of AFLA.

Table 6
Properties of aggregates

Aggregate	Specific gravity (SSD) (g/m^3)	Specific gravity (OD) (g/m^3)	Crushing value (kN)	Unit weight (g/m^3)	Solid volume percentage (%)	Compressive strength of concrete at 28-day (MPa)
JLA	1.43	1.32	8.5	789	59.8	27.5
GLA	1.25	1.10	8.2	678	61.6	29.0
AFLA	1.85	1.66	6.5	972	58.6	26.7
NA	2.71	2.54	23	1626	64.0	33.0

Table 7
Heavy metals leaching test results (unit: mg/L)

Element	Cadmium (Cd)	Chromium (Cr)	Lead (Pb)	Arsenic (As)	Copper (Cu)
Test result #1	BDL	0.018	BDL	BDL	BDL
Test result #2	BDL	0.017	BDL.	BDL	BDL.
Test result #3	BDL	0.017	BDL	BDL	BDL
Regulatory threshold	1	5	5	5	5

BDL: below detection limit; Cd: <0.001 mg/l; Pb: <0.005 mg/l; As: <0.005 mg/l; Cu: <0.001.

tion of 11.8% and a angular shape. The grain size distribution of AFLA met ASTM C 33 requirement for the use of artificial lightweight aggregate as structural lightweight concrete (Fig. 5) [20].

The unit weights of AFLA, JLA, and GLA were 972, 789, and 678 kg/m^3, respectively. The solid volume percentages of artificial lightweight aggregates were similar because they have a round shape and a smooth surface. However, the solid volume percentage of AFLA was relatively lower than those of other artificial lightweight aggregates, because AFLA's grain shape was more angular.

A crushing value test was performed to investigate the resistance of the aggregate against static compressive load. This test result indicates the load magnitude when the percentage of crush was 10%. The crushing strengths of the other artificial lightweight aggregates used in these tests were 58.9–83.4 kN while that of AFLA was 63.8 kN. The natural aggregate exhibited a strength of 225.6 kN, which was higher than those of artificial aggregates. It is estimated that crushing value of the artificial aggregates was lower than that of the natural aggregates because of the artificial aggregate's porous structure (see Table 6).

The heavy metals leaching test of AFLA was performed according to the US EPA's TCLP (Toxicity Characteristics Leaching Procedure) regulation. Results of the TCLP test conducted in the study are presented in Table 7. A relatively high concentration of chromium in the solutions was found in the samples tested. Concentrations determined in the solutions of AFLA (2–4th row of the table) were far below the regulatory limits (5th row).

4. Compressive strength and freeze–thaw durability of concrete

Due to the internal voids, the strengths of the artificial lightweight aggregates were generally lower than those of natural aggregates. After 28 days, the strength of the specimen that used NA (natural aggregate) was 33.0 MPa, and that of a batch of AFLA was 26.7 MPa (19% lower than the NA specimen). Nevertheless, it is expected that AFLA will find use in lightweight concrete (Fig. 6).

The effects of air content on compressive strength and freezing–thawing are shown in Table 8. The compressive strength of the concrete with 6% entrained air content

Fig. 6. Grain shape of AFLA.

Table 8
Freezing–thawing test results

No.	Aggregate	Air (%)	Last cycle	Ratio of dynamic modulus of elasticity (%)	Durability factor (%)	Compressive strength (MPa)
At 28-days						
CF0	AFLA	1.5	271	60	54.2	26.7
CF1	AFLA	4	300	78	78.0	23.9
CF2	AFLA	6	300	92	92.0	22.4
CN	NA	4	300	91	91.0	33.0

was about 16% lower than that of concrete with 1.5% air content. According to Neville, a durability factor of above 60 is probably satisfactory [24]. However, some industrial companies require a durability factor of 90, which indicates significant resistance against freeze–thaw [25]. The durability factor of the specimen with 4.0% air entrainment, which corresponded to marginal freeze–thaw resistance, was 78, and that of the specimen with 6.0% air entrainment, which suggested good freeze–thaw resistance, was 92.

This study investigated the properties of AFLA and concrete using AFLA. However, more properties need to be examined, including long-term stability and durability and fire resistance of AFLA. Finding appropriate applications will include considering the properties of concrete containing AFLA. The low compressive strength obtained in concrete using AFLA may limit widespread application as a structural concrete. Potential applications will likely include earth-retaining structures, lower-strength concrete fill, and paving materials.

5. Conclusion

The following conclusions may be drawn from results of this study:

1. The optimal proportions of sodium silicate, NaOH, and MnO_2 can be determined effectively from the tests of the hardened paste of the fly ash. The optimal proportions

of fly ash and binders were 10% cement, 15% sodium silicate, 10% NaOH, and 5% MnO_2. The highest compressive strength of 33.9 MPa was obtained for the fly ash paste cured at room temperature after 24 h of moisture curing at 50 °C.

2. The hardened pastes composed of fly ash and binders may be the compounds of the Na_2O–Al_2O_3–SiO_2, and may contain small amounts of CaO, MgO, and FeO_2, and so exhibit a high strength. Also, MnO_2 and pozzolanic reactions increase the compressive strength of hardened pastes.
3. Water-cured hardened pastes of fly ash have a lower strength than moisture-cured pastes because of the elution of the binders. Beyond 72 h of water curing, the compressive strength of paste decreases due to the increase of elution. A particular minimum curing temperature (at least 50 °C) also effectively increased the paste's strength.
4. AFLA exhibited specific gravity (SSD, OD), water absorption, unit weight, and solid volume percentages of 1.85 (SSD), 1.66 (OD), 11.8%, 972 kg/m^3, and 58.6%, respectively. The crushing strengths of AFLA and other artificial lightweight aggregates were 63.8 kN and 58.9–83.4 kN, respectively.
5. The results of the heavy metals leaching test of AFLA met the regulatory requirements of the US EPA's Toxicity Characteristic Leaching Procedure.
6. Concrete using AFLA exhibited a compressive strength of 26.5 MPa and good freeze–thaw resistance at 6.0% entrained air content.

References

[1] Swamy RN, Wu L. The ingredients for high performance in structural lightweight aggregate concrete. Struct Lightweight Aggregate Concr 1995:628–39.

[2] Swamy RN, Jiang ED. Pore Structure and carbonation of lightweight concrete after 10 years exposure. ACI Special Publ 1993;136:377–95.

[3] Swamy RN, Lambert GH. Mix design and properties of concrete made from PFA coarse aggregates and sand. Int J Cem Comp Lightweight Concr 1983;5(4):263–75.

[4] Swamy RN, Lambert GH. The microstructure of Lytag aggregate. Int J Cem Comp Lightweight Concr 1981;3(4):273–82.

[5] Wang S-D, Scrivener KL. Hydration products of alkali activated slag cement. Cem Concr Res 1995;25(3):561–71.

[6] Joseph RP, Gary TR. Aqueous reaction of fly ash and $Ca(OH)_2$ to produce calcium silicate absorbent for flue gas desulfurization. Environ Sci Technol 1988;22(11):1299–304.

[7] Davidovits J. Chemistry of geopolymeric systems, terminology. In: Geopolymer'99 international conference, France, 1999. p. 9–40.

[8] Fernandez-Jimenez A, Palomo JG, Puertas F. Alkali-activated slag mortars mechanical strength behaviour. Cem Concr Res 1999;29(8):1313–21.

[9] Bakharev T, Sanjayan JG, Cheng Y-B. Effect of admixtures on properties of alkali-activated slag concrete. Cem Concr Res 2000;30(9):1367–74.

[10] Palomo A, Grutzeck MW, Blanco MT. Alkali-activated fly ashes, a cement for the future. Cem Concr Res 1999;29(8):1323–9.

[11] Bakharev T, Sanjayan JG, Cheng Y-B. Sulfate attack on alkali-activated slag concrete. Cem Concr Res 2002;32(2):211–6.

[12] Xie Z, Xi Y. Hardening mechanisms of an alkaline-activated class F fly ash. Cem Concr Res 2001;31:1245–9.

[13] Cotton FA, Wilkinson G, Gaus PL. Basic inorganic chemistry. 3rd ed. John Wiley and Sons; 1994. p. 165–87, 503–9, 512–7.

[14] Mackay KM, Mackay RA, Henderson W. Introduction to modern inorganic chemistry. fifth ed. Nelson Thornes; 1996.

[15] Environmental Protection Agency. Nitrogen oxides reduction program: final rule for phase II (Group 1 and Group 2 Boilers). US, EPA, July 31, 2000.

[16] Environmental Protection Agency. Toxicity characteristic leaching procedure: method 1311. U.S., EPA, revised March 2003.

[17] ASTM C 127. Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate. ASTM International, West Conshohocken, PA, 2004.

[18] ASTM C 136. Standard test method for sieve analysis of fine and coarse aggregates. ASTM International, West Conshohocken, PA, 2005.

[19] ASTM C 29. Standard test method for bulk density (''unit weight'') and voids in aggregate. ASTM International, West Conshohocken, PA, 2003.

[20] ASTM C 33. Standard specification for concrete aggregates. ASTM International, West Conshohocken, PA, 2003.

[21] ASTM C 192. Standard practice for making and curing concrete test specimens in the laboratory. ASTM International, West Conshohocken, PA, 2005.

[22] ASTM C 666/C 192M. Standard test method for resistance of concrete to rapid freezing and thawing. ASTM International, West Conshohocken, PA, 2003.

[23] BS 812, Aggregate crushing value (TCV) testing aggregates: Part 111 – methods for determination of ten percent fines aggregate crushing value. British Standards Institute, 1990.

[24] Neville AM. Properties of concrete. Pitman Publishers; 1995.

[25] Henderson RWR. Grace company, private communication, 1994.