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Foaming Properties of Lightweight Matrix Based with Non-Reacted Si Blast Furnace Slag†

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In this study, we examined whether the paper-ash could be used as a foaming agent for blast furnace slag-based foamed concrete. We attempted to examine the amount of hydrogen produced from paper-ash based on the mechanism of hydrogen generation caused by non-reacted Si and validated experimentally. The results of the experiment showed that the hydrogen generation caused by non-reacted Si of paper-ash was the highest at about 57 % of NaOH based on 100 % paper-ash consumption. In addition, it was found that 10.8 % of NaOH consumption was required when the paper-ash consumption amounted to 5 % of binder.

Keywords: Paper ash, Blast furnace slag, Non-reaction, Alkali activator, Non-cement.

INTRODUCTION

The amount of paper sludge, which is one of the industrial by-products generated from the paper process, has increased every year amidst the advancement of paper industry. Most paper sludge has been disposed of by landfill, marine discharge, incineration, *etc*. However, the revised enforcement regulations of waste management act prohibit the landfill of sludge from 2003, which resulted in most sludge being disposed of by incineration[1-3].

Such processing method involves the elimination of residual organic substances from the sludge and the dewatering process making only inorganic substances remain in the form of ash which is called "paper-ash".

The paper-ash is disposed of mostly by landfill and marine discharge, like the sludge. Although some paper-ash is recycled as solidification material, the amount is very little. Thus, the methods for the recycling of paper-ash need to be explored and one of such methods is to use the paper-ash as admixture in concrete. As the paper-ash has the chemical components and contents similar to those of cement, *etc*., the paper-ash has the advantage that high strength can be achieved if it is used as admixture in concrete. Moreover, paper-ash produces a lot of pores when it reacts with OH-series alkali activator, thus enabling production of foamed concrete. If the paper-ash is used in non-cement matrix for which the use of alkali activator is indispensable, the effect is expected to be huge. In this study, we intend to examine the hydrogen generation mechanism of Si for the production of blast furnace slag-based lightweight matrix that does not use cement through the formation of pores by trapping the hydrogen in binders based on the foaming of paper-ash. Additionally, it is assumed that the hydrogen generation mechanism of non-reacted Si and derived the amount of NaOH for generating maximum hydrogen gas in order to define the amount of alkaline activator required for paper-ash. To verify it, we also carried out experiments by varying the amount of NaOH.

EXPERIMENTAL

Mechanism of paper-ash foaming by non-reacted Si: Silicon is one of chemical components of paper-ash, can exhibit the strength equal to or higher than that of concrete made from cement if it exists as SiO_2. However, Si reacts with alkaline activator and generates hydrogen gas if it exists as non-reacted Si. The reaction formula of hydrogen generation by non-reacted Si can be expressed as eqn. 1 and Na_2SiO_3 and much heat are generated, as well as hydrogen.

$$Si + 2NaOH + H_2O \rightarrow Na_2SiO_3 + 2H_2 + 423.8 \text{ (kJ/mol)} \quad (1)$$

NaOH for generating NaOH and H_2 required for non-cement matrix

Addition amount of NaOH required for the blast furnace slag-based non-cement matrix: The method for calculating the amount of NaOH required for blast furnace slag-based non-cement matrix was derived by carrying out the experiment as shown in Table-1.

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TABLE-1
EXPERIMENTAL DESIGN TO DERIVE THE ADDITION AMOUNT OF NaOH REQUIRED FOR INORGANIC BINDER

Factors	Levels						
Binder type	BFS (Blast furnace slag)						1
Alkali activator	NaOH						1
Addition ratio of NaOH	1	3	6	9	12	(M)	5
	1.4	4.2	8.4	12.6	16.8	(g)	
Curing condition	Relative humidity (80 ± 5) %, Temperature (20 ± 2) °C						1
W/B	0.35						1
Test items	Compressive strength						1

First, in the experiment, the mixing water was fixed at 35 g for binders with the blast furnace slag weighing 100 g. In other words, the W/B was fixed at 0.35 and the addition amount of NaOH was set at 5 levels such as 1, 3, 6, 9, 12 (M) based on 35 g mixing water. As an item of experiment, the compressive strength was measured. The addition amount of NaOH was determined by observing the whitening phenomenon that made alkali component turn white when the test specimen was exposed to the atmosphere.

As shown in Fig. 1, the compressive strength was the highest in the test specimen added with 6 M NaOH at the age of 28 days. The test specimen added with more than 6 M NaOH showed a tendency that the strength was reduced as the addition amount increased. In addition, alkali component was not visible in the test specimens of 1, 3, 6 (M) on their surface. However, the test specimens of 9 and 12 (M) were found to have white alkali component on the surface area.

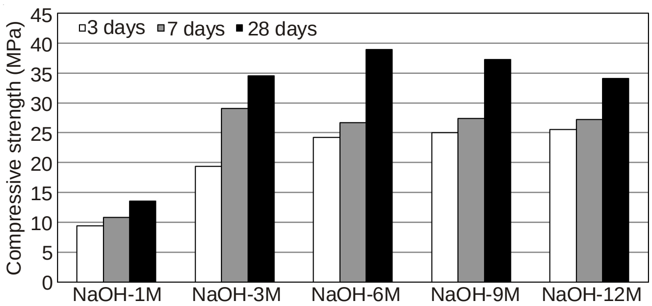

Fig. 1. Compressive strength

Therefore, the addition amount of NaOH required for blast furnace slag-based inorganic binders was determined to be 6 M based on 35 g water.

Addition amount of NaOH for generating H_2: For the non-reacted Si content in the paper-ash 100 g, the required amount of NaOH was derived by using eqn. 1 on the assumption that the non-reacted Si corresponded to the difference between the content of SiO_2 which is found in molecular state during the XRF analysis as shown in Tables 2 and 3 and the content of Si which is found in elemental state.

As the per cent mass of SiO_2 in Table-2 is 12.4 %, it is 2.07 M. Meanwhile, the per cent mass of Si in Table-3 is 25.6 % and therefore it is 9.14 M. The difference is 7.07 M, which is the molecular weight of non-reacted Si. If this is substituted in eqn. 1, the addition amount of NaOH required for maximum generation of hydrogen gas is 56.6 g as shown below:

$$\underset{\substack{7.07\ M \\ (100\ g)}}{Si(paper\ ash)} + \underset{\substack{14.14\ M \\ (56.6\ g)}}{2NaOH} + \underset{\substack{7.07\ M \\ (12.7\ g)}}{H_2O} \longrightarrow \underset{\substack{7.07\ M \\ (86.3\ g)}}{Na_2SiO_3} + \underset{\substack{14.14\ M \\ (2.8\ g)}}{2H_2}$$

Therefore, the required addition amount of NaOH is 56.6 g based on paper-ash 100 g and the water amount is 12.7 g. At this time, the amount of paper-ash used to produce non-cement lightweight matrix should be set to 5 g. The mixing ratio shown in Table-4 can be obtained if the workability is taken into consideration.

TABLE-4
MIXING OF BLAST FURNACE SLAG-BASED
NON-CEMENT LIGHTWEIGHT MATRIX (Unit: g)

W/B	W	BFS	Paper ash	NaOH
0.40	40	95	5	10.8

Experimental plan and methods: In the experiment aiming to verify the addition rate of NaOH which was derived before, the binders are blast furnace slag and paper-ash of which substitution rate was 5 %. The additive rate of NaOH was based 9 levels, such as 2.5, 7.5, 10.8 (the additive rate derived by non-reacted Si), 12.5, 17.5, 22.5, 27.5, 32.5 and 37.5 (%) for the weight of binders. The W/B was fixed at 0.40 in the same way as shown in Table-5.

As a test item, the bulk specific gravity was measured as the scale of weight reduction by the foaming performance and

TABLE-2
CHEMICAL COMPONENT OF PAPER ASH (MOLECULAR)

	Mass (%)											
Molecular	CaO	SiO_2	Fe_2O_3	Al_2O_3	Cl	MgO	SO_3	TiO_2	P_2O_5	CuO	ZnO	*etc.*
Content	58.7	12.4	8.52	6.91	3.99	3.38	1.76	1.35	0.783	0.62	0.62	0.97

TABLE-3
CHEMICAL COMPONENT OF PAPER ASH (ELEMENT)

	Mass (%)											
Element	Ca	Si	Fe	Al	Ti	Cu	Pb	Ba	Mn	Co	Sb	*etc.*
Content	46.6	25.6	13.3	7.09	3.15	1.3	0.89	0.684	0.219	0.188	0.111	0.87

TABLE-5
EXPERIMENTAL FACTORS AND LEVELS

Factors	Levels	
Binder type	BFS + PA	1
Replacement ratio of paper ash	5 %	1
Alkali activator	NaOH	1
Addition ratios of NaOH	2.5, 7.5, 10.8, 12.5, 17.5, 22.5, 27.5, 32.5, 37.5 (%)	9
Curing condition	Relative humidity (80 ± 5) %, Temperature (20 ± 2) °C	1
W/B	0.40	1
Test items	Bulk specific gravity, Compressive strength	2

based on that, the compressive strength were measured. For the test method based on bulk specific gravity, the test specimen was produced in the form of cylinder measuring 100 mm in diameter and 200 mm in height in accordance with the test method (KS F 2459) for the bulk specific gravity, moisture content, water absorption ratio and compressive strength of foamed concrete. This specimen was cured for 28 days and then its weight and volume were measured to calculate the bulk specific gravity. For the compressive strength, the test specimen was made to fit the dimension of 40 mm × 40 mm × 160 mm in accordance with the cement strength test method (KS L ISO 679). Then, the specimen was cured under constant temperature and humidity condition with the temperature of 20 ± 2 °C and humidity of 80 ± 5 % and measured to determine their compressive strength at the age of 3, 7 and 28 days.

RESULTS AND DISCUSSION

Bulk specific gravity: Regarding the bulk specific gravity, unit volume weight and compressive strength based on the addition of NaOH, it was found that the unit volume weight increased as the addition amount of NaOH varied as shown in Fig. 2. The bulk specific gravity was found to be the lowest in the specimen added with 10.8 % NaOH, the rate which was derived based on the non-reacted Si. When the addition amount of NaOH was below 10.8 %, the hydrogen generation showed a tendency of slight decrease. When the addition rate of NaOH exceeded 10.8 %, the reaction time of NaOH and non-reacted Si was shortened, causing some loss of hydrogen gas in the mixing process and thereby increasing the density.

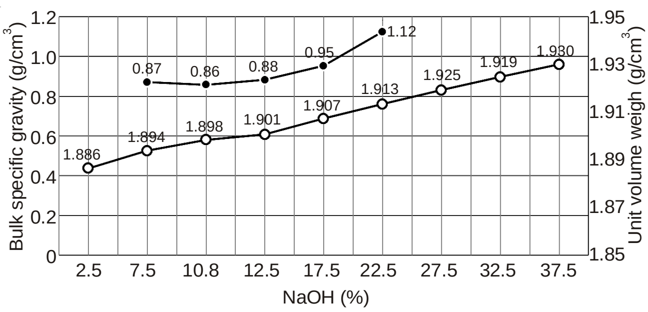

Fig. 2. Bulk specific gravity

Compressive strength: As shown in Fig. 3, the results of compressive strength test showed that the matrix added with 2.5 % NaOH exhibited high compressive strength of over 9 MPa after 28 days and showed variation in strength based on the NaOH additive rate of 10.8 % in the same way as bulk specific gravity. The difference in strength between the matrix with 2.5 % NaOH addition and the matrix with 7.5 % NaOH addition was 1/2 level. The matrix with 7.5 % NaOH addition exhibited lower compressive strength. This suggests that more than a certain amount of NaOH is required for the hydrogen gas generated by NaOH and non-reacted Si of paper-ash. The use of NaOH is considered to activate the paper-ash foaming performance under high pH environment.

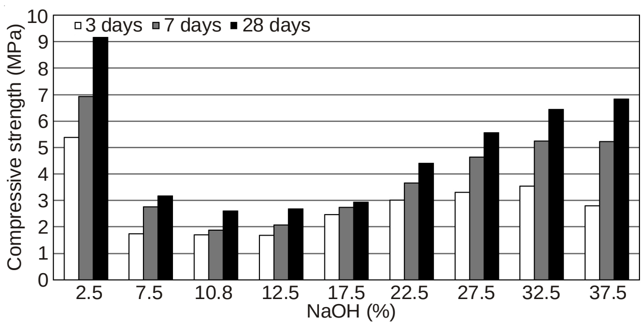

Fig. 3. Compressive strength

Conclusions

The optimum amount of NaOH is 56.5 % based on 100 g paper-ash with the required water amount of 12.7 % on the assumption of non-reacted Si through the contents of Si and SiO_2 which are detected by XRF analysis of paper-ash. However, it is necessary to increase the mixing water in light of workability and paper-ash with high absorption. In addition, the additive rate of alkali activator was 10.8 % when the paper-ash which was used corresponded to 5 % of binder. At this time, it was found that the water should be increased to 40 %. In the experiment which was performed to validate the mixing ratio derived by assuming the non-reacted Si, the bulk specific gravity was found to be the lowest in the test specimen added with 10.8 % NaOH. Thus, the use of paper-ash, which is the foaming agent of non-cement lightweight matrix as the material of foamed concrete, requires additional use of NaOH. The addition amount is 56.5 % of the paper-ash weight and the foaming performance would be adequate even when the paper-ash is used at a level below 10 %.

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