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SCIENCE DIRECT

Cement and Concrete Research 33 (2003) 1749–1754

CEMENT AND CONCRETE RESEARCH

Influence of the fineness of sewage sludge ash on the mortar properties

Shih-Cheng Pan[a], Dyi-Hwa Tseng[a,*], Chih-Chiang Lee[a], Chau Lee[b]

[a]Graduate Institute of Environmental Engineering, National Central University, Chungli 32054, Taiwan, ROC

[b]Department of Civil Engineering, National Central University, Chungli 32054, Taiwan, ROC

Received 12 September 2001; accepted 21 April 2003

Abstract

Sewage sludge ash (SSA) is a recycled material and can be used in cement mortar as pozzolan. To improve the mortar properties, this research utilized mechanical grinding to adjust the fineness of SSA. Finely ground SSA with Blaine fineness of 500–1000 m^2/kg was added to mortar to replace 20% of portland cement. The initial and final setting times of SSA–cement paste simultaneously prolonged when SSA fineness increased. Because of the lubricant effect and morphology improvement, the workability of SSA mortar increased when fineness increased. In addition, the pozzolanic activity of SSA and the compressive strength of mortar increased when SSA fineness did. The strength activity index (SAI) value approximately increased 5% when SSA fineness increased per 100 m^2/kg. According to the results, the application of mechanical grinding to adjust SSA fineness was an effective modification to improve SSA mortar properties including workability and compressive strength.

Keywords: Sewage sludge ash; Fineness; Pozzolanic activity; Workability; Compressive strength

1. Introduction

To solve the water pollution problems in urban areas, many sewerage systems and sewage treatment plants have been constructed and operated all over the world. Through the sewerage systems and treatment plants, the sewage and wastewater discharged from households and industries are collected and purified. However, in the sewage treatment plants, large quantities of sewage sludge are produced. To control the environmental impact caused by sewage sludge disposal, the interest of reusing sewage sludge is continuously rising. Many technologies have been developed to reuse sewage sludge beneficially and economically. Among those technologies, utilization of the incinerated residues of sewage sludge, i.e., sewage sludge ash (SSA), has been investigated by many researchers. Previous works revealed that SSA exhibits pozzolanic activity [1–5]. Therefore, SSA can potentially be used in concrete or mortar to partially replace portland cement.

Although the SSA can be used as a mineral admixture, there are two major disadvantages when SSA is used in mortar. First, the pozzolanic activity of SSA is lower than that of some common pozzolans such as fly ash. Tay and Show [3] found that the strength activity index (SAI) of SSA with portland cement was between 57.6% and 67.2%. On the other hand, the SAI value of F-class fly ash was between 96% and 134% [5,6]. Because the SAI value of SSA was smaller than that of fly ash, the effectiveness of using SSA in mortar was lesser than that of fly ash. Second, the water demand of SSA mortar is higher than that of ordinary cement mortar [4,6,7]. Pan et al. [5] found that the addition of SSA affected the mortar workability. This phenomenon is primarily due to the porous and irregular morphology of SSA. Consequently, it is difficult to adequately maintain water-to-cement ratio and workability of SSA mortar simultaneously.

Regarding the two disadvantages mentioned, adequate modification and treatment of SSA should be applied before reusing this material in mortar. In recent research works, increasing the fineness by mechanical grinding has been used to enhance the pozzolanic activity of fly ash and natural pozzolan [8–10]. When ground fly ash (GFA) is used in mortar, an improvement of the compressive strength is obtained compared to original fly ashes [10]. However, GFA reduces the workability of mortar compared to original fly ashes, because the ground process destroys the spherical shape and lubricant effect of original fly ashes [11]. Although mechanical grinding is effective to improve the

* Corresponding author. Tel./fax: +886-3-4226944.
E-mail address: dhtseng@ncuen.ncu.edu.tw (D.-H. Tseng).

0008-8846/$ – see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0008-8846(03)00165-0

compressive strength of fly ash mortar, it is seldom investigated in the application of SSA mortar. For this reason, this study intended to adjust the fineness of SSA by mechanical grinding. The pozzolanic activity of finely ground SSA was evaluated. In addition, the influence of SSA fineness on mortar and paste properties, including workability, time of setting, and compressive strength were also investigated.

2. Materials and methods

2.1. Preparation of SSA

The sewage sludge used in this study was sampled from Pa-Li Wastewater Treatment Plant (PLWWTP), Taipei City. The PLWWTP is a typical sewage treatment plant with preliminary and primary treatment processes. The sampled dewatered sludge cake was incinerated at 700 °C during 3 h by a modular incinerator. The coarse SSA collected from the incinerator was then finely ground in a ball mill. In addition to grinding time, other control factors in each grinding batch including ash volume, ball volume, and bowl rotation speed were selected as 280 g, 1 kg, and 80 rpm, respectively. In this study, the grinding time of SSA was selected as 10, 20, 30, 60, 120, 180, and 360 min, respectively. The fineness of SSA was expected to increase with increasing grinding time. Therefore, a total of seven samples of finely ground SSA with different fineness were obtained. The chemical composition of the SSA used in this study is summarized in Table 1.

2.2. Preparation of SSA mortar

The preparation and curing of SSA mortar in this study generally follows the ASTM C109 and ASTM C311 test methods. In each batch of SSA mortar preparation, the mix proportion was 1375 g of graded sand, 400 g of ordinary portland cement (OPC), and 100 g of finely ground SSA. To study the influence of SSA, one batch of control mortar without adding any SSA was also prepared. To the batch of control mortar, 1375 g of graded sand and 500 g of OPC were mixed. According to a preliminary trial, the mixing water used in each batch was 300 g. The mortar specimens obtained in this study were 5-cm cubes. There were six mortar cubes obtained from each batch. The mortar cubes were cured in saturated limewater at 23 °C and tested for compressive strength at the age of 7 and 28 days, respectively.

Table 1
Chemical composition of SSA

Primary composition, %								
SiO_2	Al_2O_3	Fe_2O_3	CaO	P_2O_5	MgO	SO_3	Na_2O	K_2O
50.6	12.8	7.21	1.93	1.67	1.48	2.38	0.32	1.70

Heavy metals, g/kg								
Ag	As	Cr	Cu	Mn	Ni	Pb	Se	Zn
0.049	0.023	0.564	1.09	0.44	0.72	0.18	N.D.	2.62

N.D., not detected.

2.3. Tests for SSA and mortar properties

The tests of finely ground SSA in this study included Blaine fineness, specific gravity, BET specific surface area, crystalline constituent, and microscopic observation. The tests of Blaine fineness and specific gravity generally conformed to ASTM C204 and ASTM C188 test methods, respectively. Regarding the tests of specific surface area, crystalline constituent, and microscopic observation of SSA, methods of nitrogen adsorption, X-ray diffractometry (XRD), and scanning electron microscopy (SEM) were used, respectively.

For mortar specimens, the workability of fresh mortar was tested by the flow table method. The test apparatus and procedures of mortar workability, i.e., flow table spread (FTS), conformed to ASTM C230 specifications and ASTM C109 test method, respectively. The FTS of fresh mortar was calculated as follows:

$$\text{FTS}\ (\%) = \text{increase in average base diameter of mortar mass} \quad (1)$$

The test of compressive strength of hardened mortar generally followed the ASTM C109 test method. According to the ASTM C311 test method, the SAI (in percent) was used to evaluate pozzolanic activity of finely ground SSA. In this study, the SAI of SSA was calculated as follows:

$$\text{SAI}\ (\%) = 100 \times (\text{SC}/\text{SC}_0) \quad (2)$$

where SC is the average compressive strength of SSA mortar at curing age of 7 or 28 days, in which 20% of OPC was replaced by finely ground SSA, and SC_0 is the average compressive strength of control mortar at the same curing age as SSA mortar.

To observe the effect of SSA fineness on cement hydration, the setting properties of SSA–cement paste were determined. As well as in SSA mortar, the mass of SSA and OPC in SSA–cement paste was 100 and 400 g, respectively. According to ASTM C191 test methods, the Vicat needle was used to determine the initial and final setting of SSA–cement paste. According to a preliminary trial of normal consistency, 175 g of water was added to each batch during the preparation of SSA–cement paste.

3. Results and discussion

3.1. Effect of grinding on SSA properties

The test results of Blaine fineness, specific gravity, and specific surface area of SSA are indicated in Table 2. When

Table 2
Properties of finely ground SSA

Properties	SSA grinding time, min						
	10	20	30	60	120	180	360
Blaine fineness, m^2/kg	496	780	846	975	979	993	872
Specific gravity	2.48	2.61	–[a]	2.54	2.45	2.67	2.60
BET specific surface area, m^2/kg	11,588	10,906	11,774	11,020	11,666	11,521	12,487

[a] Not determined.

the grinding time varied from 10 to 360 min, the variation of specific gravity and specific surface area of SSA was insignificant. On the other hand, when grinding time was between 10 and 60 min, the fineness of SSA increased with the increase of grinding time. However, when grinding time was between 60 and 180 min, the SSA fineness did not increase significantly. When grinding time further extended to 360 min, the SSA fineness decreased to 872 m^2/kg. The maximum value of SSA fineness was approximately 1000 m^2/kg, which indicated the limit of grinding ability of the ball mill used in this study.

In addition to Blaine fineness, the values of specific surface area and specific gravity of SSA did not significantly vary with grinding time. As shown in Table 2, the specific surface area of SSA was between 10,900 and 12,500 m^2/kg and was much larger than those of Blaine fineness. This can be primarily explained by the porous nature of SSA. In other words, inner pores rather than the outer surface of SSA particles primarily exhibit the specific surface area. The increase of outer surface caused by fracture or split of SSA particles is relatively insignificant to pore surface area. For this reason, mechanical grinding has no effect on altering the specific surface area and specific gravity of SSA.

The SEM images of SSA with and without grinding are shown in Fig. 1. As shown in Fig. 1a, the particle size of coarse SSA without grinding was generally greater than 200 μm. As shown in Fig. 1b, c, and d, the original large particles of SSA were fractured into smaller pieces after 10–30 min of grinding. After 60 min of grinding, the particle size of SSA was primarily between 50 and 100 μm (Fig. 1e). After 180 min of grinding, the size of SSA particles approximately decreased to 20–30 μm (Fig. 1g). In addition to particle size, the shape of the SSA varied from originally irregular particles into more spherical-like particles. Also, many finer grains peeled off from SSA particles. According to direct estimation from Fig. 1, the size of these finer grains were primarily between 1 and 2 μm. As shown in Fig. 1h, when the grinding time prolonged to 360 min, particles larger than 50 μm appeared again. This phenomenon was possibly due to the compaction and agglomeration of fractured particles and peeled grains in the ball mill. This mechanism also explains the decrease of SSA fineness when grinding time extended from 180 to 360 min, which was mentioned previously.

The XRD spectra of SSA with different grinding times are shown in Fig. 2. The predominant crystalline constituents of all SSA samples are identically quartz and moganite. Both of these minerals contain primarily silicon dioxide (SiO_2). In addition, no significant difference among the XRD spectra indicated that the mechanical grinding did not change the crystalline constituents of SSA.

3.2. Effect of SSA fineness on cement setting

The initial and final setting times of SSA–cement paste is shown in Fig. 3. When SSA fineness was 500 m^2/kg, the

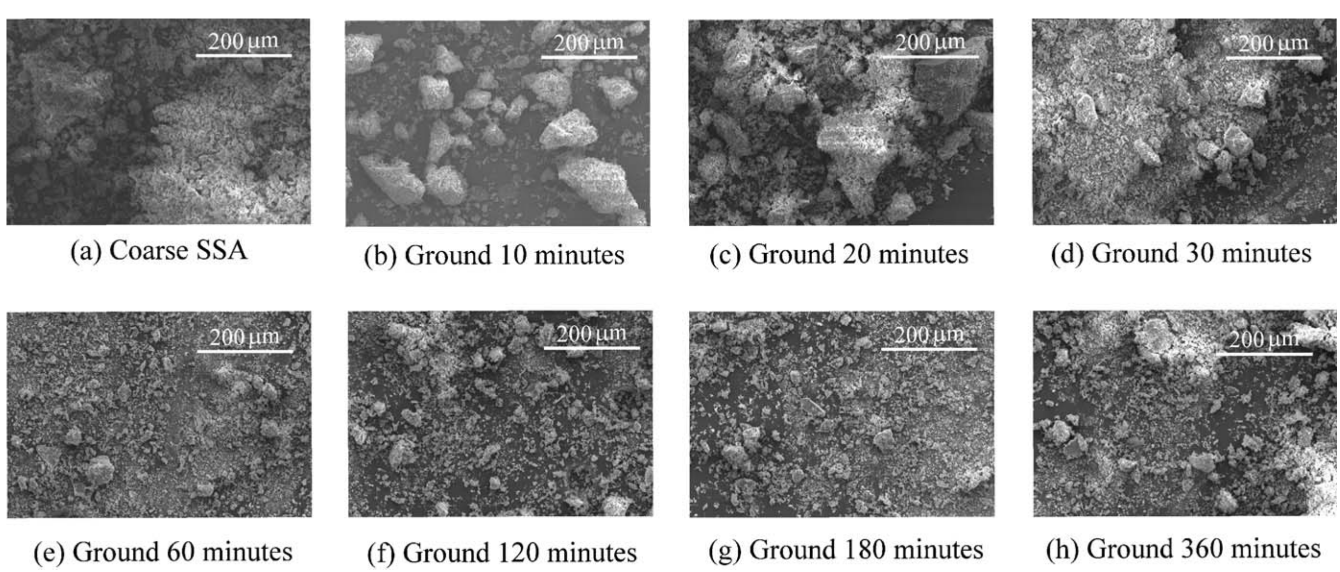

Fig. 1. SEM images of finely ground SSA with different grinding times.

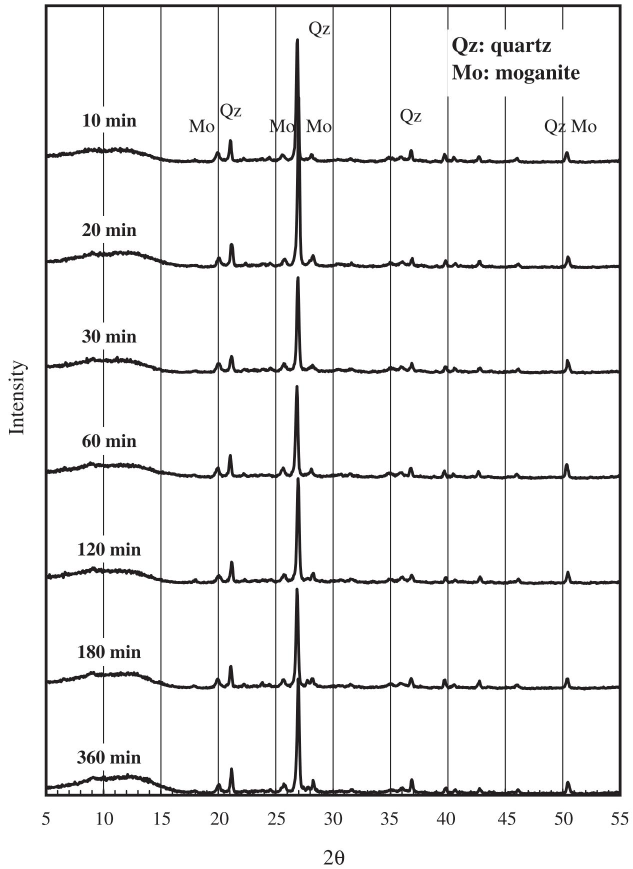

Fig. 2. X-ray diffraction spectra of finely ground SSA with different grinding times.

initial and final setting of SSA–cement paste was about 3 and 4 h, respectively. However, the typical initial and final setting of OPC paste occurs in 2–4 and 5–8 h, respectively [12]. The final setting time of SSA–cement paste was slightly shorter than that of typical values. Tay and Show [3] found that the hydration rate of aluminum oxide in SSA is faster than that of calcium silicates in OPC. In addition, the aluminum oxide content in SSA, i.e., 12.8%, is greater than the aluminum oxide content (6%) in OPC. For these reasons, the SSA–cement paste exhibited shorter final setting time than OPC paste.

When SSA fineness increased to 780–1000 m^2/kg, the initial and final setting times of SSA–cement paste prolonged to about 3.5–5 and 7–8 h, respectively. In general, the setting time of SSA–cement paste increased with the increase of SSA fineness. This phenomenon can be explained by the reaction that occurs at the cement and pozzolan particle surface during early hydration [13,14]. At the beginning of hydration, the calcium ions are adsorbed at the outer surface of SSA particles and are not able to adsorb onto the pore surface of SSA due to the blocking of pores. Because grinding increased the outer surface of SSA particles, the amount of adsorbed calcium ions increased with the increase of SSA fineness. The increase of adsorbed calcium ions inhibits calcium concentration buildup and nucleation in fresh paste during early hydration. Consequently, the dormant period, i.e., the initial setting time of SSA–cement paste, prolongs. In addition, the final setting time of SSA–cement paste also extended because the initial setting time prolonged.

3.3. Effect of SSA fineness on mortar workability

As shown in Fig. 4, the flow table spread of fresh SSA mortar was primarily between 64% and 89%. These values of flow table spread of SSA mortar were generally lower than that of control mortar (104%). This was primarily due to the irregular porous morphology and the water adsorption into SSA pores [5]. However, increasing the fineness of SSA by mechanical grinding was found to improve the workability of SSA mortar. The reason for this improvement can be further explained through the following two aspects.

3.3.1. Water distribution

Zhang et al. [15] revealed that the amount of filling water in fresh paste was proportional to the flowability or work-

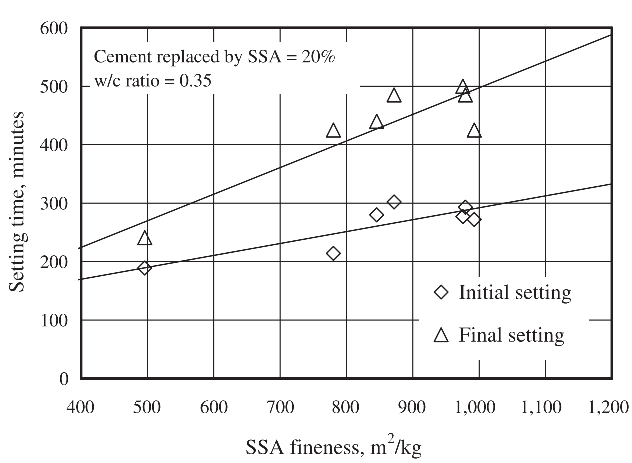

Fig. 3. Effect of SSA fineness on setting properties of SSA–cement paste.

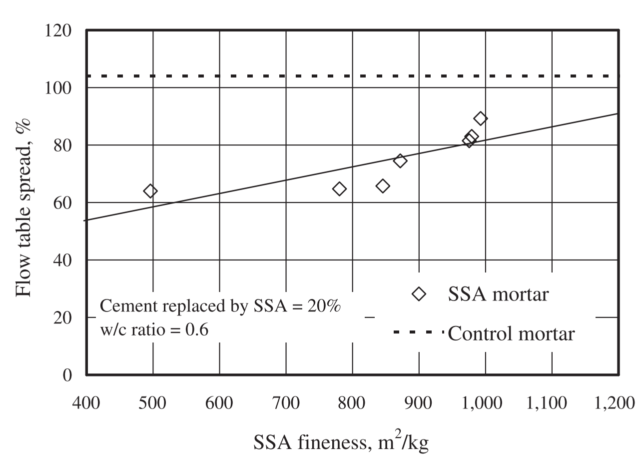

Fig. 4. Effect of SSA fineness on mortar workability.

ability of mortar. In this study, the increase of SSA fineness resulted in more water adsorbed onto the outer surface of SSA particles. However, the overall increment of adsorbed water on SSA was insignificant due to the limited additional outer surface provided by grinding. In addition, the amount of adsorbed water in pores of SSA was approximately constant because grinding did not increase the pore surface area. Consequently, the amount of filling water in fresh SSA mortar did not significantly decrease when SSA fineness increased.

3.3.2. Lubricant effect and particle morphology

Peris-Mora et al. [16] found that the increase of fly ash fineness could reduce internal friction in fresh mortar. This phenomenon, named "lubricant effect," should be able to improve the workability of SSA mortar in this study. Additionally, mechanical grinding altered the morphology of SSA particles from irregular into more spherical-like. Consequently, the mechanical grinding provided additional improvement to SSA mortar workability caused by the reduction of particle interlocking and friction in fresh paste.

According to the preceding discussion, the mechanism of improving mortar workability was primarily due to the lubricant effect and morphology improvement caused by increasing SSA fineness. However, due to the porous and water adsorption nature of SSA, the optimal workability of SSA mortar was still lower than that of control mortar.

3.4. Effect of SSA fineness on mortar strength and pozzolanic activity

Table 3 lists the test results of compressive strength of hardened SSA mortar and control mortar. The compressive strength of all mortar specimens increased when the curing age extended from 7 to 28 days. In addition, the 7- and 28-day compressive strength of SSA mortar generally increased with the increase of grinding time of SSA at the same replacement ratio (20%) to cement. This result indicated that the increase of SSA fineness could effectively improve the compressive strength of SSA mortar at early and later curing ages. However, similar to workability, the optimal compressive strength of SSA mortar was lower than that of control mortar at the same curing ages. This was primarily due to the lesser content of pozzolanic active matter, i.e., the amorphous silicon oxide, in SSA, than that in pure cement.

Table 3
Compressive strength of hardened SSA mortar and control mortar

Curing age, days	SSA mortar compressive strength, MPa							Control mortar compressive strength, MPa
	SSA grinding time, min							
	10	20	30	60	120	180	360	
7	11.5	14.1	11.5	12.5	20.4	19.7	19.2	27.9
28	18.4	22.0	22.3	27.9	26.7	27.5	29.5	38.1

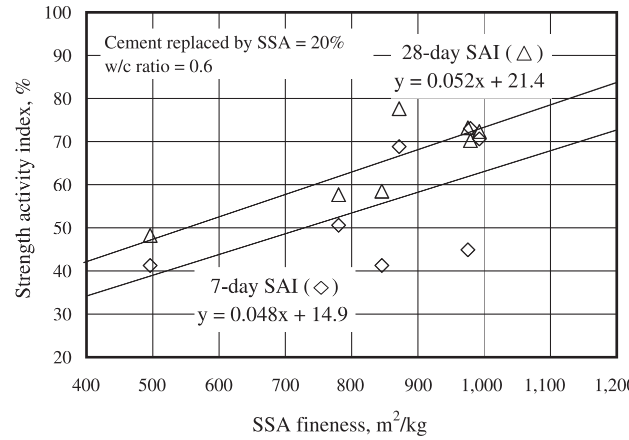

Fig. 5. Effect of fineness on pozzolanic activity of SSA.

Based on the test results of mortar compressive strength, the pozzolanic activity, i.e., SAI values of SSA, are calculated and shown in Fig. 5. In general, the 7- and 28-day SAI of finely ground SSA also increased with the increase of SSA fineness. This result indicated that the pozzolanic activity of SSA was proportional to the outer surface area rather than the pore surface area. As mentioned previously, the pores of SSA particles were blocked during early hydration. Consequently, the pozzolanic reaction primarily occurred at the outer surface and did not appear in the pore space of SSA. In addition, as shown in Fig. 5, the SAI and Blaine fineness of SSA can be correlated to a linear relationship. From the slope of regression lines, it was found that the SAI value approximately increased 5% when SSA fineness increased per 100 m^2/kg. Accordingly, for the mortar with 20% of cement replacement and water-to-cement ratio of 0.6, the 7- and 28-day compressive strength approximately increased 1.4 and 1.9 MPa, respectively, when SSA fineness increased per 100 m^2/kg. These increments in compressive strength of SSA mortar are similar to the results of Day and Shi [8].

4. Conclusions

This study investigated the possibility of improving mortar properties by adjusting the fineness of SSA. The use of mechanical grinding could increase the fineness and pozzolanic activity of SSA but did not alter its crystalline constituents, specific surface area, and specific gravity. When the fineness of SSA increased, the workability of SSA mortar increased due to the lubricant effect and morphology improvement. On the other hand, the compressive strength of SSA mortar increased with increase of SSA fineness, primarily due to the improvement of pozzolanic activity cause by grinding and the increase of the outer surface of SSA particles. These results show that the application of mechanical grinding to adjust SSA fineness was an effective modification to improve SSA mortar properties.

Acknowledgements

The authors greatly appreciate the financial support of National Science Council, Republic of China to this study. (Project number: NSC 88-2211-E008-030).

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