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Study on cement mortar and concrete made with sewage sludge ash

F. C. Chang, J. D. Lin, C. C. Tsai and K. S. Wang

ABSTRACT

This study investigated the feasibility of reusing wastewater sludge ash in construction materials to replace partial materials. Wastewater sludge sampled from thermal power plant was burned into sludge ash at 800°C in the laboratory. The sludge incineration ash has low heavy metal including Pb, Cd, Cr and Cu, so it belongs to general enterprise waste. The chemical composition of sludge incineration ash was summed up in SiO_2, CaO, Fe_2O_3 and MgO. Then the wastewater sludge ash is also found to be a porous material with irregular surface. When the sludge ash was used to replace mortar or concrete cement, its water-adsorption capability will result in the reduction of mortar workability and compressive strength. Cement is being substituted for sludge ash, and 10 percent of sludge ash is more appropriate. Sludge ash is reused to take the place of construction materials and satisfies the requests of standard specification except for higher water absorption.

Key words | construction materials, resource, thermal power sludge ash

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INTRODUCTION

A large amount of waste sludge is produced annually in Taiwan. Waste sludge largely consists of silicon, calcium, aluminum and iron oxides, all of which are similar to other raw materials in cement. The use of sewage sludge ash (SSA) in cement-based materials as cement or sand replacements is one strategy for disposing of such waste (Paya *et al.* 1999; Monzo *et al.* 2003; Pan *et al.* 2003; Cheeseman & Virdi 2005). Monzo *et al.* (2003) show that sewage sludge ash reduces the workability of fresh mortars and tends to increase the setting time of cements. Most studies showed that sludge ash increased the number of the gel pores and absorbed water easily. Due to the poor mechanical properties of sludge ash in mortar, the compressive strength of the mortar was influenced. Moreover, because of the low pozzolanic activity in sludge ash, the compressive strength of the ash-cement mortar was reduced. To improve the mortar properties, Pan *et al.* (2003) added 20% of sewage sludge ash with a fineness of 500–1,000 m^2/kg to motor to replace portland cement. The initial and final setting times were delayed, and both the pozzolanic activity and the compressive strength were improved with increasing ash fineness. Lin *et al.* (2008) indicate that the amount of water needed at standard consistency increased as more nano-SiO_2 was added. Moreover, a reduction in setting time became noticeable for smaller ash particle sizes. The compressive strength of the ash-cement mortar increased as more nano-SiO_2 was added. The use of sludge ash in cement mortar also increases sulphate resistance due to interaction between sulphate and sludge ash to form denser structure of ettringite and aluminate hydrate that fill pores in the paste (Luo *et al.* 2008).

A literature analysis shows that the effects of sewage sludge ash on mortars or concrete properties are more or

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less noticeable, depending on the characteristics of the specific sewage sludge ash used in each study. Previous studies are available about the utilization of sewage sludge ash in cement-based materials, but no comparison has been made with reference concrete, so it is not possible to evaluate the potential application of sewage sludge ash. The inherent variability of this kind of residue remains one of the most important reasons for avoiding a systematic generalization of the results. So the aim of this work is to provide supplementary knowledge about the effect of sewage sludge ash on cement and concrete. The influence of sewage sludge ash on mortar properties, including workability, time of setting, pozzolanic activity and compressive strength were evaluated. In addition, the properties of sewage sludge ash concrete were also investigated.

MATERIALS AND METHODS

Materials

The sewage sludge used in this study was sampled from thermal power plant in Taiwan. The wastewater treatment plant of thermal power plant is a typical sewage treatment plant with preliminary and primary treatment processes. The sampled dewatered sludge cake was incinerated at 800°C during 3 h by a modular incinerator. The coarse SSA collected from the incinerator was then pulverized and sieved to < 0.075 mm. Portland type I cement was used in this study. The physical and chemical properties of the sewage sludge ash used in this study are in Table 1.

Methods

The preparation and curing of sewage sludge ash mortar in this study follows the ASTM C109 (1999) and ASTM C311 (2002) test methods. The mix proportion was 4,175 g of graded sand, 1,500 g of portland cement, and 0, 10, 20, and 30% finely ground sewage sludge ash replacement by weight. The mortar specimens obtained in this study were 5-cm cubes. There were three 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 3, 7, 28, 56 and 90 days, respectively. The workability and time of setting tests were developed in line with ASTM C109 (1999) and ASTM C191 (1999), respectively. The test of compressive strength of hardened mortar followed the ASTM C109 (1999) test method. According to the ASTM C311 (2002) test method, the SAI (%) was used to evaluate pozzolanic activity of finely ground sewage sludge ash.

The preparation and curing of sewage sludge ash concrete in this study follows the ACI 211.1 (1991) test methods. The mix proportion was 960 g of coarse aggregate, 880 g of fine aggregate, 310 g of portland cement, and 0, 10, 20, and 30% finely ground sewage sludge ash replacement by weight. The concrete specimens obtained in this study were 15 cm (diameter) × 30 cm (height) cylinder. There were three concrete cylinders obtained from each batch. The concrete cylinders were cured in saturated limewater at 23°C and tested for compressive strength at the age of 3, 7, 28, 56 and 90 days, respectively. The test of compressive strength of cylindrical concrete specimens followed the CNS 1232 (2002) test method.

Table 1 | Physical and chemical properties of the sewage sludge ash

		Fineness (m^2/kg)				Specific gravity (cm^2/g)				
Item	**pH**	**0%***	**10%**	**20%**	**30%**	**0%**	**10%**	**20%**	**30%**	
Physical	12.2	3.10	3.06	3.03	3.00	3,100	3,190	3,650	3,860	
Heavy metal	Leaching concentration (mg/L)					Total concentration (mg/L)				
	Pb	Cd	Cr	Cu	Zn	Pb	Cd	Cr	Cu	Zn
	0.52	0.33	2.09	ND†	0.32	214.1	24.9	94.5	93.9	797.7
Composition (%)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3
	20.10	1.90	4.47	17.20	12.98	30.49	1.57	0.06	0.25	1.83

*0%: 0% sewage sludge ash with 100% portland cement, 10%: 10% sewage sludge ash with 90% portland cement, 20%: 20% sewage sludge ash with 80% portland cement, 30%: 30% sewage sludge ash with 70% portland cement.
†ND not detected.

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RESULTS AND DISCUSSION

Effects of sewage sludge ash on mortars

In order to study the influence of the amount of sewage sludge ash replacing cement, the workability of sewage sludge ash-cement mortar was measured in the 0–30% replacement range. Figure 1 shows flow table spread values versus the percentage of sewage sludge ash in mortars containing 900 and 750 ml water volumes, i.e. 0.6 and 0.5 water/(cement + sewage sludge ash) ratios. In this experiment, a decrease of flow table spread has been observed when sewage sludge ash percentage increases for both water volumes studied. This behavior can be explained taking into account the irregular morphology of sewage sludge ash particles (Monzo *et al.* 2003). For high replacement levels (30%), very low workability mortars were obtained in all cases.

The initial and final setting times of sewage sludge ash-cement paste is shown in Table 2. An increase of initial and final setting times has been observed when sewage sludge ash percentage increases. The initial and final setting times is consistent with typical portland cement paste (2–4 and 5–8 h, respectively) (Mindess & Young 1981). The slower hydration rate of sewage sludge ash-cement mortar is due to the lower fineness of SSA than Portland type I cement (Table 1).

Figure 2 shows the test results of compressive strength of hardened sludge ash mortar and the standard of Portland type I cement mortar. The compressive strength of all mortar specimens increased when the curing age extended from 3 to 90 days. At 3 days curing age the compressive strength of hardened mortar was 10% sludge ash mortar >20% sludge ash mortar > control mortar >30% sludge ash mortar. At 7 days curing age the compressive strength of hardened mortar was 10% sludge ash mortar > control mortar >20% sludge ash mortar >30% sludge ash mortar. At 28, 56 and 90 days curing age the compressive strength of hardened mortar was control mortar >10% sludge ash mortar >20% sludge ash mortar >30% sludge ash mortar. The strength activity index (SAI) of SSA with portland cement was 95.1 and 81.2% at 7 and 28 days, respectively. Moreover, the compressive strength of 20 and 30% sludge ash mortar was lower than the regulation mortar at 28 days curing age. Therefore, the sludge ash conformed to the specification of ASTM C618-Class C fly ash (SAI > 75%) and belonged to pozzolanic and cementitious materials (ASTM C618 2005).

The sludge ash would also enhance the early strength of sludge ash mortar (Figure 2). However, when replacement of sewage sludge ash accounted for more than 20% of the original material used in making mortar, compressive strengths of the mortar specimens were reduced, due to a low pozzolanic reaction active index. This is due to the content of amorphous silicon oxide in SSA being less than that in pure cement. Moreover, the SAI value of SSA was smaller than that of Class F fly ash, the effectiveness of using SSA in mortar was less than that of Class F fly ash.

Table 2 | The initial and final setting times of sewage sludge ash-cement paste

Sewage sludge ash (%)	Indoor temperature (°C)	Initial setting time (min)	Final setting time (min)
0	23.5	159	294
10	23.5	167	304
20	23.5	180	318
30	23.5	196	339

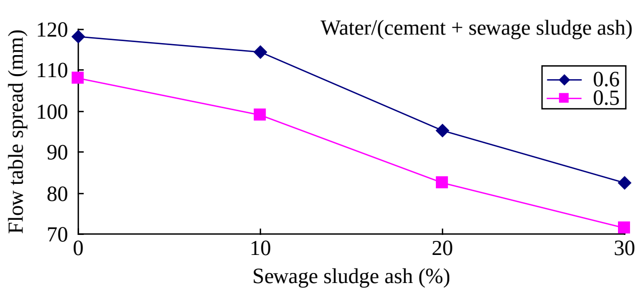

Figure 1 | Variation of flow table spread values versus sewage sludge ash percentage.

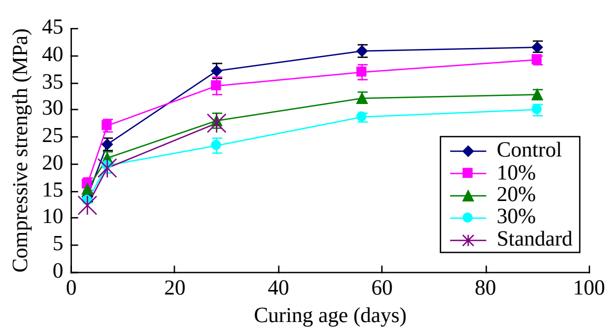

Figure 2 | Compressive strength of hardened sewage sludge ash mortar.

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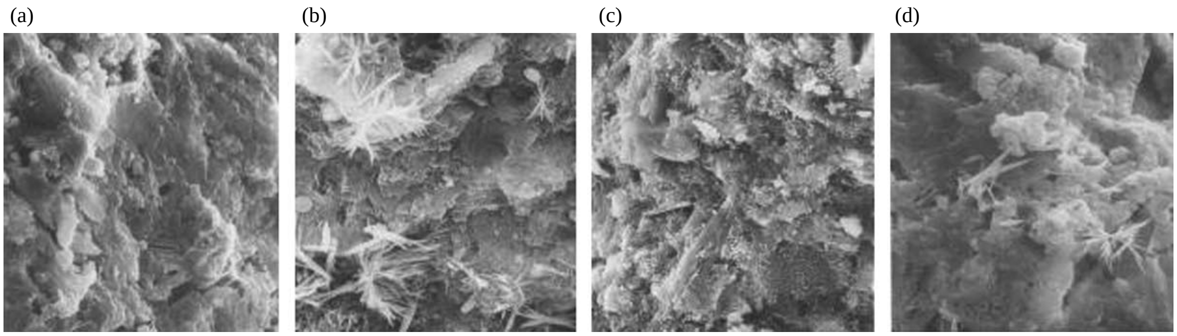

Figure 3 | SEM images of sludge ash mortar at 28 days curing age. (a) Control mortar; (b) 10% sludge ash mortar; (c) 20% sludge ash mortar and (d) 30% sludge ash mortar.

In order to understand the influences of sewage sludge ash on the micro-structures of the cement mortar, samples obtained from the central part of mortar specimens were analyzed by SEM, particularly focusing on hydrates of the C-S-H gel and monosulfoaluminate crystals. Figure 3 shows SEM images for specimens with different amounts of sludge ash when cured at 28 days. When part of the cement was replaced by sludge ash, the C-S-H gel became relatively fine and poor agglomeration was observed. Smaller monosulfoaluminate crystals were also seen. This implies that sludge ash interfered with the growth of hydration and crystallization, which resulted in a lower compressive strength of the mortar specimens.

Effects of sewage sludge ash on concrete

The physical and chemical properties of the coarse and fine aggregate used in this study are in Table 3. These aggregates conformed to the standard of nature aggregate. When the design 28-day compressive strength was 20.6 MPa, the slump of freshly mixed concrete at 0, 10, 20, and 30% sludge ash replacement was 13.7 cm, 13.2 cm, 11.6 cm, and 8.9 cm, respectively. When the design 28-day compressive strength was 34.3 MPa, the slump of freshly mixed concrete at 0, 10, 20, and 30% sludge ash replacement was 11.9 cm, 10.4 cm, 9.1 cm, and 6.9 cm, respectively. This is because the higher water absorption on SSA particle surfaces and the irregular morphology of SSA particles when SSA was reused to take the place of cement (Monzo *et al.* 2003). Increasing replacement of cement by SSA produces a decrease of concrete workability. Moreover, because the cement was less and the mixed water was more, the slump of design 20.6 MPa concrete was higher than design 34.3 MPa concrete.

Figure 4 shows the test results of compressive strength of hardened sludge ash concrete and the design 28-day compressive strength. When the design 28-day compressive strength was 34.3 MPa, the compressive strength of hardened concrete was 10% sludge ash concrete > control concrete > 20% sludge ash concrete > 30% sludge ash concrete at 3 days curing age. In the other curing age, the compressive strength of hardened concrete was control concrete > 10% sludge ash concrete > 20% sludge ash concrete > 30% sludge ash concrete regardless of the design 28-day compressive strength. The compressive strength of

Table 3 | Physical and chemical properties of the coarse and fine aggregate

Item	Coarse aggregate	Fine aggregate
Specific gravity	2.61	2.63
Water absorption (%)	1.19	1.59
Fineness modulus	–	2.81
Soundness (%)	2.46	2.70
Finer than 75 μm sieve (%)	0.09	0.96
Unit weight (kg/m^3)	1,584	1,711
Voids (%)	38.6	33.5
Resistance to degradation		
Arasion and impact	20.3	–
Uniform	0.2	–
Clay lumps and friable particles (%)	0.27	0.31
Lightweight particles (%)	0.00	0.00
Organic Impurities	–	Colorless
Plastic fines	–	89.6
Water-soluble Cl^{-1} (%)	–	0.00067

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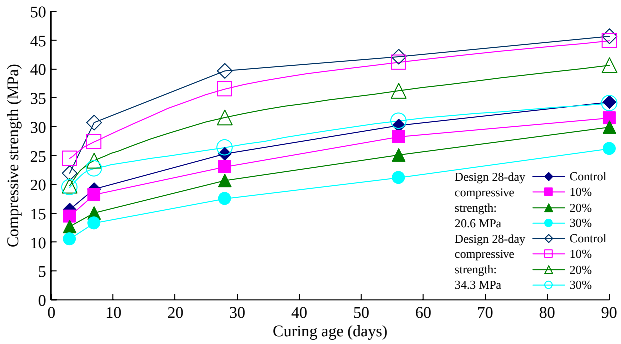

Figure 4 | Compressive strength of sewage sludge ash concrete.

10% sludge ash concrete was similar to the design 28-day compressive strength at different cured days. This was primarily due to the content of pozzolanic active matter. Moreover, the tendency of compressive strength of sludge ash concrete is also similar to that of sludge ash mortar at the replacement range.

The compressive strength of 20 and 30% sludge ash concrete was lower than the design 28-day compressive strength when cured at 28 days. But the compressive strength of 20% sludge ash concrete was higher than the design 28-day compressive strength. This is because the sludge ash had potential pozzolanic activity and decreases the compressive strength of concrete at early ages and increases it later. Therefore, the 10% sludge ash concrete could be applied to unreinforced concrete. And the 20% sludge ash concrete could be applied to non-structure concrete. The replacement for cement by 30% sludge ash is not appropriate for compressive strength and workability.

CONCLUSIONS

This study investigates the effect of different amounts of sewage sludge ash replacements on the physical properties and micro-structures cement mortar and concrete. Results based on the experimental data can be summarized as follows.

1. When a portion of the cement was replaced by sewage sludge ash in mortar, the sludge ash has potential pozzolanic activity, it can have a chemical reaction with $Ca(OH)_2$ crystal in the mortar.
2. When the sludge ash was used to replace mortar or concrete cement, its water-adsorption capability will result in the reduction of workability and compressive strength for mortar and concrete. The compressive strength of 10% sludge ash mortar or concrete conformed to the design 28-day compressive strength when cured more 28 than days. Therefore, the 10% sludge ash concrete could be applied to unreinforced concrete to reduce the use of cement.

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