Sewage sludge ash characteristics and its potential applications

S.C. Pan and D.H. Tseng
Graduate Institute of Environmental Engineering, National Central University, Chungli 32054, Taiwan

Abstract This study investigated the characteristics of SSA in Taiwan area. The potential applications of SSA reuse were also evaluated. Four major characteristics of SSA, including chemical compositions, pozzolanic properties, physical properties, and surface properties were analyzed. Experimental results found that SSA was a complex mixture of burnt residues of sludge biomass and minerals. The major chemical compositions of SSA were silicon oxide, aluminium oxide, and iron oxide. The most predominant silicon oxide occupied 41.3 to 56.1% of overall SSA weight and approximately 60% weight of silicon oxide in SSA was amorphous type. Due to the effect of amorphous silicon oxide, the SSA exerted pozzolanic activity. The strength activity index (SAI) value of SSA was between 53.6 and 74.3%. The SSA particles were also the agglomeration of finer grains between 0.1 and 1µm of size. Therefore the SSA was porous with irregular particles with significant pore surface area. Additionally, the SSA exerted negative surface charge and cation-exchange capacity in neutral aqueous phase. Based on the SSA characteristics found in this study, four potential applications of SSA reuse were evaluated. These technologies included reusing as fine aggregate, reusing as pozzolanic material, melting or vitrification treatment, and reusing as adsorbent. In addition, the advantages and disadvantages of the above potential applications of SSA were discussed.

Keywords Chemical compositions; pozzolanic activity; reuse; sewage sludge ash; sludge disposal

Introduction
To year 2009, the waste sludge cake produced from sewage treatment plants in Taiwan is estimated as 40,000 MT/d (metric tons per day). Due to limited landfill site availability, the incineration of sewage sludge has become the most feasible alternative for sludge disposal. It is also estimated that about 2,800 MT/d of residual sewage sludge ash (SSA) will come out as a waste if all sewage sludge is incinerated. In order to minimize the environmental impact, the SSA must be reused instead of disposal. However, as no sludge incineration facility has been built, the SSA characteristics in Taiwan are still unknown. In addition, the current available technologies for reusing SSA have not been evaluated based on characteristics of SSA. For these reasons, this study investigated the characteristics of SSA in Taiwan area. In this study, the samples of sludge cake were collected from typical primary and secondary sewage treatment plants in northern Taiwan. The SSA samples were then prepared and analyzed in the laboratory. The major characteristics of SSA, including chemical compositions, pozzolanic properties, physical properties, and surface properties were tested and analyzed. According to the characteristics of SSA, the potential applications of SSA reuse were also evaluated.

Materials and methods
The sewage sludge samples used in this study were collected from Ming-Shen Community Wastewater Treatment Plant (MSCWWTP) and Pa-Li Wastewater Treatment Plant (PLWWTP). The MSCWWTP is a typical sewage treatment plant with secondary biological processes. On the other hand, the PLWWTP is a typical sewage treatment plant with only primary treatment. Five sludge cake samples were collected: three samples from...
MSCWWTP and two samples from PLWWTP. The sampled sludge cake was incinerated at 700°C for three hours in a modular incinerator. The produced SSA samples were then finely ground in a ball mill. The three prepared SSA samples of MSCWWTP were designated as MS1, MS2, and MS3 respectively. The two prepared SSA samples of PLWWTP were designated as PL1 and PL2 respectively. The test methods of SSA samples in this study were classified into four categories: chemical properties, pozzolanic properties, physical properties, and surface properties. The test methods and instruments used in this study are shown in Table 1. The corresponding tested samples of each test are also given.

### Results and discussion

#### Chemical compositions of SSA

As shown in Table 2, the most predominant constituent of four SSA samples was silicon oxide. The ratio of silicon oxide in SSA was 41.3–56.1%. The aluminium oxide and iron oxide were also dominant constituents of SSA. The overall ratio of silicon oxide, aluminium oxide, and iron oxide in SSA was between 66.3 to 79.0%. In addition, the SSA samples of this study did not contain a significant amount of heavy metals. The heavy metal contents of SSA shown in Table 2 were mostly less than those reported in the literature (Khanbilvardi and Afahari, 1994; Tay and Yip, 1989; Alleman and Berman, 1984). The XRD spectra of two SSA samples are shown in Figure 1. They show that quartz and moganite are the predominant crystalline constituents of SSA. Both quartz and moganite are crystalline minerals primarily composed by silicon dioxide (SiO₂). This result revealed that certain natural minerals including fine sands and clays entered the sewerage system and precipitated into sewage sludge.

#### Pozzolanic properties of SSA

Pozzolanic reaction is defined as the hydration of amorphous silicon oxide or aluminium oxide with calcium hydroxide (Mindess and Young, 1981). The pozzolanic reaction produces gels of calcium silicate hydrate (C-S-H) or calcium aluminate hydrate (C-A-H), which are similar to the hydration product of Portland cement. In this study, the pozzolanic
activity of SSA was represented by strength activity index (SAI). As indicated in Table 3, the SAI value of SSA samples was between 53.6 and 74.3%. The SAI value of fly ash, which was one of the most common pozzolanic materials, was between 96 and 134% (Bhatty and Reid, 1989; Pan et al., 2000). The pozzolanic activity of SSA was lower than that of fly ash. This phenomenon could be explained by the lower amount of amorphous silicon oxide in SSA. In this study, the content of amorphous silicon oxide was represented by the maximum weight loss of SSA after digestion with sodium hydroxide solution and filtration. As shown in Figure 2, the maximum weight loss of SSA after digestion and filtration was 24.6%. This result implied that the content of amorphous silicon oxide was approximately 60% of the overall silicon oxide in SSA. The remaining 40% of silicon oxide was primarily crystalline, as mentioned above, predominantly quartz and moganite minerals. Because the portion of non-reactive crystalline silicon oxide was still significant, the pozzolanic activity of SSA was lower than that of fly ash.

In this study, the $^{29}$Si NMR was used to investigate the characteristics of amorphous silicon oxide of SSA. As shown in Figure 3, three characteristic signals are present in the $^{29}$Si NMR spectra of SSA. The Q$^4$ signal represented that the silicon atom in a SiO$_4$ tetrahedron shared oxygen atoms with four other silicon atoms. In $^{29}$Si NMR spectra, the Q$^4$ signal represented the presence of quartz and moganite minerals in SSA. On the other hand, the Q$^2$ and Q$^3$ signals represented that the silicon atom in tetrahedron shared oxygen atoms with two and three silicon atoms respectively. In $^{29}$Si NMR spectra, the Q$^2$ and Q$^3$ signal represented the presence of chain-type and plate-type silicon oxide minerals in SSA respectively. Since the Q$^4$ signal already represented the crystalline silicon oxide, the chain-type and plate-type silicon oxide essentially represented the amorphous silicon oxide in SSA. The source of chain-type and plate-type amorphous silicon oxide in SSA was not exactly determined yet. However, there were two possible mechanisms to explain this phenomenon. First, the chain-type and plate-type silicon oxide were originally some clay minerals. During the calcination of sewage sludge, these minerals were dehydrated and formed

<table>
<thead>
<tr>
<th>Sample</th>
<th>Primary Constituents, % by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO$_2$</td>
</tr>
<tr>
<td>MS1</td>
<td>56.1</td>
</tr>
<tr>
<td>MS2</td>
<td>41.3</td>
</tr>
<tr>
<td>PL1</td>
<td>50.2</td>
</tr>
<tr>
<td>PL2</td>
<td>50.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Heavy Metals, g/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ag</td>
</tr>
<tr>
<td>MS1</td>
<td>0.047</td>
</tr>
<tr>
<td>MS2</td>
<td>0.059</td>
</tr>
<tr>
<td>PL1</td>
<td>0.049</td>
</tr>
<tr>
<td>PL2</td>
<td>0.049</td>
</tr>
</tbody>
</table>

"N.D." Not detected.
amorphous silicon oxides. Certain clay mineral, such as kaolinite (Al$_2$O$_3$-2SiO$_2$-2H$_2$O), could transfer into amorphous and pozzolanic active metakaolin (Al$_2$O$_3$-2SiO$_2$) under 650–925°C calcination (He et al., 1995; Salvador, 1995; Pera and Amrouz, 1998). Second, the amorphous silicon oxide was possibly a burnt residue of sewage sludge biomass. When the sewage sludge was incinerated, the carbon and nitrogen portion of biomass was oxidized and evaporated. However, the heavier atoms in the biomass including silicon, iron, aluminium, calcium etc., were oxidized and formed SSA. In this case, small pieces of chain-type and plate-type silicon oxide formed in the beginning. Then the small pieces of silicon oxide randomly precipitated with aluminium oxide, iron oxide, and other burnt residues. Therefore the amorphous silicon oxide was present in the SSA.

**Physical and surface properties of SSA**

The primary physical and surface properties of SSA are presented in Table 4. The specific gravity of SSA was between 2.47 and 2.61, which was very similar to that of silica sand. The specific surface area of SSA was between 10.9 and 19.9 m$^2$/g. As shown in Figure 4, the pore size of SSA was primarily between 20 and 1,000 Å. According to that, the pores smaller than 100 Å (0.01 µm) of SSA exerted approximately 20% of overall pore volume. However, these small pores of SSA significantly exerted 70% of overall pore area. The SEM images of SSA also revealed the porous nature of SSA. As shown in Figure 5a and 5b, the surface morphology of SSA particles is porous and irregular. Figure 5c is a higher magnification SEM image of Figure 5b. This image shows that the larger SSA particle is essen-

---

![Figure 1](https://iwaponline.com/wst/article-pdf/44/10/261/424071/261.pdf)  
**Figure 1** The XRD spectra of SSA

![Figure 2](https://iwaponline.com/wst/article-pdf/44/10/261/424071/261.pdf)  
**Figure 2** Weight loss of SSA during digestion

![Figure 3](https://iwaponline.com/wst/article-pdf/44/10/261/424071/261.pdf)  
**Figure 3** The NMR spectra of SSA

![Figure 4](https://iwaponline.com/wst/article-pdf/44/10/261/424071/261.pdf)  
**Figure 4** The pore volume and pore area distribution of SSA
Initially an agglomeration of many finer grains. The finer grains are possibly burnt residues of sludge biomass and natural minerals. In addition, pores among those finer grains are observed. As shown in Figure 5c, the size of finer grains is approximately between 0.1 and 1 µm. Additionally, the size of observed pore among finer grains is about 0.1 µm (1,000 ≈ 1 µm). This phenomenon confirmed the test results of pore volume and pore area distribution of SSA. However, further investigation is necessary to discover the exact nature of those finer grains.

In this study, some chemical properties of SSA particle surface were also investigated. As given in Table 4, the pH of zero point of charge (pH\textsubscript{ZPC}) of SSA sample is between 3.3 and 4.4. These values are close to some natural minerals, for example, 4.6 of kaolinite and 2.0 of silicon oxide (Stumm and Morgan, 1981). Also as shown in Table 4, the zeta potential of SSA is between –11.5 and –12.5 mV. These results revealed that the SSA particle surface carried negative charge when immerged in neutral aqueous solution. However, the surface potential of SSA was lower than that some natural minerals, for example, –120 mV of kaolinite (Stumm and Morgan, 1981). In addition, the cation-exchange capacity of SSA sample was between 2.26 and 2.30 meq/100 g. These values are lower than those of some natural minerals, for example, 23 meq/100 g for kaolinite (Stumm and Morgan, 1981).

### Preliminary evaluation of reusing SSA

According to above results, this study preliminarily concluded that the SSA was a complex mixture of burnt residues of sludge biomass and natural minerals. Based on the major characteristics of SSA found in this study, current possible technologies of reusing SSA were evaluated as follows:

**Reusing SSA as fine aggregate.** Since SSA was fine particles, it could be reused as fine aggregate or filler in cement concrete or road construction. However, due to its porous nature, the SSA seemed not to exert high mechanical strength. In addition, the pore volume and pore surface might adsorb moisture and water. This disadvantage could affect the workability of concrete if SSA is applied.
Reusing SSA as pozzolanic material. The finely ground SSA exerted significant pozzolanic activity although lower than that of fly ash. The SSA could potentially be reused as pozzolanic material to replace partial Portland cement in concrete. However, the workability of concrete could be affected due to the porous and irregular nature of SSA particles. This disadvantage might be adjusted by adding water-reducing agent in concrete mixture. In addition, since the SSA particle was an agglomeration of finer grains, advanced grinding of SSA to size of 1 µm might help to eliminate the internal pores.

Melting or vitrification of SSA. Since SSA contained primarily silicon oxide and aluminium oxide, it could be melted to manufacture glass-like product. Through pelletizing and sintering, the SSA could also be reused to manufacture artificial and lightweight aggregate. In addition, the SSA could potentially be applied in brick-manufacturing process to replace part of the raw material. When melting or sintering of SSA is undertaken, energy consumption and economic issues could become important concerns.

Reusing SSA as adsorbent. The SSA was confirmed as a porous material with significant pore surface area. In addition, the SSA provided negative surface charge and cation-exchange capacity. Although the surface charge and cation-exchange capacity of SSA was lower than that of some natural minerals, the SSA could still be reused as adsorbent for removing heavy metals from aqueous phase. In this case, the SSA could also be used as a liner material for landfill sites. This would help to eliminate heavy metal pollution of groundwater caused by leakage of landfill leachate.

Conclusions
The SSA was a complex mixture of burnt residues of sludge biomass and natural minerals. In this study, the chemical compositions of SSA were predominantly silicon oxide, aluminium oxide, and iron oxide. The amount of heavy metals in SSA was insignificant when compared to literature data. Due to the presence of amorphous silicon oxide, the SSA exerted certain pozzolanic activity. The SAI value of SSA was between 53.6 and 74.3%. In addition, the SSA particles were the agglomeration of finer grains. For this reason, the SSA particles were porous, irregular, and exerting significant pore surface area. The surface of SSA also possessed minor negative charge and cation-exchange capacity in neutral aqueous solution.

According to the properties of SSA, this study evaluated current technologies for reusing SSA. These potential technologies included reusing as fine aggregate, reusing as pozzolanic material, melting or vitrification treatment, and reusing as adsorbent. Each reusing technology has its own advantages and disadvantages. Due to less treatment needed, reusing SSA as pozzolanic material and adsorbent seemed to have higher feasibility. However, further investigations are necessary to verify the feasibility and performance of reusing SSA.

Acknowledgements
This research was funded by National Science Council, Republic of China (project number: NSC89-2211-E-008-067). The authors would like to thank Mr. C. C. Lin, who was a graduate student of National Central University. Mr. Lin helped to analyze the physical and surface properties of SSA samples in this study.

References


