The Utilization of Recycled Sewage Sludge Ash as a Supplementary Cementitious Material in Mortar: A Review

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Abstract: The output of sewage sludge has been increasing in recent years in China. Traditional treatment methods, such as incineration and landfiling, cannot meet the requirement of sustainability in various industries. As one of the efficient recycling methods for sewage sludge, previous studies have proven that sewage sludge ash (SSA) can be used as a supplementary cementitious material to partly replace cement in mortar or concrete. To understand the performance of SSA comprehensively, which contributes to its better utilization, this study reviews the basic properties of SSA and the effect of SSA on the performance of mortar. Firstly, the basic properties of SSA, such as chemical composition, heavy metal content, activity, and microstructure, are investigated. Then, the effects of SSA on the workability, setting time, and mechanical properties of mortar are reviewed. The results show that the particle size distribution of SSA is in the range of 2.5–250 µm. SSA contains active oxides such as SiO2, Al2O3, Fe2O3, and CaO, which are similar to fly ash, indicating that SSA has potential pozzolanic properties. The leaching concentration of SSA is much lower than the required values in the relevant specifications, leading to an allowable environment influence. The incorporation of SSA has a negative impact on the workability, setting time, water absorption, compressive strength, and flexural strength of the mortar. The 90-day compressive strength of the SSA mortar is 71.72–98.6% of the cement mortar, when the replacement ratio of SSA is in the range of 10–30%. However, performance can be improved by increasing the grinding time or adding an admixture. The drying shrinkage and capillary water absorption of SSA mortar are higher than those of normal mortar, which is mainly related to an increase of porosity. In conclusion, it is proven that SSA can be used to partly replace cement in mortar with appropriate properties. Source and production process have a great influence on the basic properties of SSA, leading to varied, even opposite, effects on the mechanical properties and durability of mortar. In the future, the selected raw materials and a standard preparation method should be proposed for promoting the application of SSA.

Keywords: sewage sludge ash (SSA); mortar; compressive strength; durability; porosity

1. Introduction

Sewage sludge, an inevitable byproduct of the sewage treatment process of sewage treatment plants, is a complex heterogeneous mixture. Its composition and properties depend on the source of the sewage and the chemical substances added in the process of sewage purification and storage [1]. With the acceleration of urbanization and the improvement of people’s living standards, the number of sewage treatment plants in urban and rural areas in China increased from 1445 to 4326 during 2008–2020, according to the statistics of the Ministry of Housing and Urban-Rural Development of China [2]. At the same time, annual sewage discharge increased from 42.729 billion m³ to 64.76 billion m³ (as shown in Figure 1). These phenomena bring new challenges to the reduction, neutralization, and recycling of sewage sludge.
Figure 1. Number of sewage treatment plants and annual sewage discharge from 2008 to 2020 [2].

The traditional treatments for sewage sludge include landfilling and incineration [3,4], which can solve the problems of increasing sewage sludge but lead to an environmental burden. In terms of landfilling, the pH values of sewage sludge produced from most sewage treatment plants in China are within the range of 6–9 [4], which meets the pH limit of 5.5–8.5 in Chinese standard GB 4284–2018, “Agricultural Sludge Pollutant Control Standard”. However, the wastewater from a sewage treatment plant is acid- or alkali-producing industrial wastewater, which results in lower or higher pH values of sewage sludge compared to the limited pH values above. In addition, heavy metals, pathogens and parasite eggs in sewage sludge easily threaten human health through the food chain after landfills. On the other hand, a shortage of land resources has become a serious problem around the world. The proportion of sanitary landfills in the UK changed from 27% in 1980 to 6% in 2005 [5]. France has banned landfilling as a sewage sludge treatment [3]. In China, only dewatered sludge can be confined to a landfill [6]. As for the incineration process, the water content of sewage sludge is reduced to 25–30% with incineration temperatures of 800–900°C [7,8]. Incineration is a relatively mature technology for the harmless disposal of municipal sewage sludge, and organic matter is carbonized and bacterial and viral microorganisms are mostly killed during the incineration process [9]. However, it faces problems of significant CO$_2$ emissions and high costs. In addition to disposal, sewage sludge can be used to produce sewage sludge derived biochar, due to its excellent adsorptive characteristics, contributing to the removal of various pollutants from industrial wastewater, such as phenolic compounds and pharmaceuticals [10,11]. However, the utilization of sewage sludge with this method is not common at present. Therefore, it is necessary to seek new resource utilization methods for sewage sludge.

On the other hand, concrete is the most widely used building material in the world. As the cementitious material in concrete, cement has been widely used in civil construction, national defense and water conservancy projects, which have made a great contribution to the development of the construction industry. However, CO$_2$ emissions during the production and utilization of cement account for approximately 5–8% of the global total CO$_2$ emissions [12]. According to the Research Report on the Analysis and Investment Prospect of China Cement Products Market in 2019–2025, China’s cement output in the first half of 2019 reached 1044.691 million tons, with a cumulative increase of 6.8%, which causes a prominent problem for the mining resource consumption and ecological destruction of cement enterprises. Within this context, supplementary cementitious materials (SCM), such as fly ash and granulated blast furnace slag, are studied and used to partly replace cement [13]. However, the traditional SCMs are facing the problem of a resource shortage in China, nowadays.
Previous studies [14–18] found that sewage sludge ash (SSA) from sewage sludge has certain activity, in that it can be applied in mortar to partly replace cement. SSA can be used as a filler or SCM to partly replace cement, which can resolve the problem of increasing number of sewage sludge. On the other hand, the production process of cement results in a large CO$_2$ emission, which causes global warming. The utilization of SSA can reduce the demand for cement, contributing to sustainable production of mortar. In addition, the use of SSA has potential for immobilizing heavy metals in the matrix of hydrated phases, thereby reducing the emission of heavy metals to the environment [19]. The authors searched the literatures from 2008 to 2020 using the keywords “SSA”, “cementitious materials” and “mineral admixtures” in Web of Science. The result is shown in Figure 2, in which the red region represents the hot content. The values in Figure 2 represent the occurrence probability for different keywords in the literatures, and the higher the value is, the higher the occurrence probability is. It can be determined that the application of SSA in cement-based materials is the focus of the researchers’ attention. Smol et al. [20] studied the possible use of SSA in the construction industry from the aspect of a circular economy. They reviewed the potential application of SSA in cement, brick, ceramic and glass production. Świerczek et al. [21] reviewed the potential application of SSA in cement-based materials as a binder or aggregate. However, the effects of SSA on the properties of cement-based materials have no common regular due to the different sources and production process of SSA. There have been few literatures reviewing the comprehensive basic properties of SSA and its effect on the properties of mortar at the same time. Therefore, in this study, the basic characteristics of SSA after drying, incineration, grinding and other treatments are studied in details. Then, the influences of SSA as a SCM on the performance of mortar are investigated, aiming to provide reference for the resource utilization of SSA in mortar.

Figure 2. Visual analysis of the literature on SSA.

2. Basic Characteristics of SSA
2.1. Specific Gravity and Density

The specific gravity of SSA ranges from 2.33 to 3.51 [14,15,22], with an average of 2.76, which is lower than Portland cement (3.16) [22]. The density of SSA increases with the increase of incineration temperature and reaches its maximum at about 1000 °C. The grinding process can increase SSA density in a certain range. Nevertheless, the SSA density after incineration and grinding is still lower than that of Portland cement [16].
2.2. Particle Size Distribution

The particle size of SSA is mainly between silt (2.5–62.5 µm) and fine sand (62.5–250 µm) [8] (as shown in Figure 3), with a similar particle size distribution of cement and fly ash [15–18,23–27]. The particle size of cement is mainly concentrated between 10 and 70 µm, while SSA with an average diameter of about 26 µm has larger particles in the range of 70–100 µm [7]. The finer particles with good gradation can lead to the micro filling effect of SSA, which contributes to a denser microstructure.

Figure 3. Particle size distribution of SSA [15–18,23–28].

2.3. Chemical Composition

The mineral compositions of SSA are quartz, hematite, magnetite, albite, anorthite, mullite, calcite, and feldspar [14,17,19,23,29–32]. In terms of oxides, the main contents in SSA are SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, and CaO. In addition, SSA contains Na$_2$O, MgO, P$_2$O$_5$, K$_2$O, SO$_3$, and P$_2$O$_5$ [16,18,33–38]. Compared the oxide composition (mass ratio) of SSA with fly ash and cement, it is found that the oxide composition of SSA is similar to that of fly ash. However, the proportion of oxides in SSA has great discreteness. The content of CaO in SSA is much lower than cement, which is the main reason for the low activity of SSA. However, SSA has more SiO$_2$ and Al$_2$O$_3$ in content than cement (as shown in Figure 4). The amorphous SiO$_2$ and Al$_2$O$_3$ in SSA can react with calcium hydroxide and form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), respectively, which can improve the strength of mortar. The incorporation of SSA increases the number of nucleation sites of C-S-H in mortar [39], which can fix the heavy metals in the hydration matrix [19,40]. In addition, the presence of Al$_2$O$_3$ contributes to the formation of calcium sulfoaluminate hydrate in cement-based materials, such as monosulphide calcium sulfoaluminate hydrate, which possesses obvious adsorption capacity of aboriginal chloride [41] and thus improves the chloride resistance of cement-based materials [8].
The content ternary diagrams of SiO$_2$, Al$_2$O$_3$, and CaO for SSA are plotted in Figure 5 to further explore the feasibility of SSA as a SCM [14,16,18,29,33]. According to the reference, the latent hydraulic activity and pozzolanic activity can be evaluated by the contents of SiO$_2$, Al$_2$O$_3$ and CaO [8]. Figure 5 shows the contents of SiO$_2$, Al$_2$O$_3$, and CaO in traditional SCMs and cement. The results show that the average contents of SiO$_2$, Al$_2$O$_3$ and CaO in SSA (with 10 samples) are 29.57%, 13.58% and 17.53%, in reference with the standard deviations of 11.47%, 2.43%, and 13.06%, respectively. The values of SSA samples are basically within the range of latent hydraulic activity and pozzolanic activity, such as fly ash, indicating the potential pozzolanic activity of SSA.

Figure 4. Comparison of chemical composition for SSA, fly ash, and cement [17,23,33–38].

Figure 5. Triplex diagram of the SiO$_2$, Al$_2$O$_3$, and CaO content for SSA [14,16,18,29,33].

2.4. Heavy Metal Content

The total content of heavy metals in SSA is shown in Table 1. The Länder-Arbeitsgemeinschaft Abfall (LAGA) limits and Swiss regulations are used to evaluate the content of heavy metals. The results show that the average contents of heavy metals in SSA are lower than LAGA limits. The average contents of Zn and Cu are higher than Swiss regulations and the average contents of Cr, Pb and Cd are slightly higher than Swiss regulations. The total content of heavy metals in SSA has a high coefficient of variation of 51.54–227.17%, indicating that the total content of heavy metals in different SSA samples varies greatly,
which is related to the source, treatment, and storage conditions of sewage sludge and preparation process of SSA.

Table 1. Total heavy metal content of SSA samples (mg/kg) [14,16,17,27,42–65].

<table>
<thead>
<tr>
<th>Elements</th>
<th>Sample Number</th>
<th>Range</th>
<th>Average Value</th>
<th>Standard Deviations</th>
<th>Coefficient of Variation</th>
<th>LAGA Limits</th>
<th>Swiss Regulation Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba</td>
<td>5</td>
<td>245–1663</td>
<td>1159.20</td>
<td>597.40</td>
<td>51.54</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zn</td>
<td>58</td>
<td>19.08–7103</td>
<td>1724.96</td>
<td>1384.81</td>
<td>80.28</td>
<td>10,000</td>
<td>500</td>
</tr>
<tr>
<td>Cu</td>
<td>54</td>
<td>33.32–8325</td>
<td>841.38</td>
<td>1327.20</td>
<td>157.74</td>
<td>7000</td>
<td>250</td>
</tr>
<tr>
<td>Cr</td>
<td>57</td>
<td>1.2–2636</td>
<td>302.46</td>
<td>466.88</td>
<td>154.36</td>
<td>2000</td>
<td>250</td>
</tr>
<tr>
<td>Pb</td>
<td>58</td>
<td>0.28–4254</td>
<td>284.88</td>
<td>559.27</td>
<td>196.32</td>
<td>6000</td>
<td>250</td>
</tr>
<tr>
<td>Hg</td>
<td>30</td>
<td>0.05–11</td>
<td>1.45</td>
<td>2.49</td>
<td>171.85</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>As</td>
<td>31</td>
<td>0.27–270</td>
<td>35.57</td>
<td>60.58</td>
<td>170.30</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Cd</td>
<td>50</td>
<td>0.1–130</td>
<td>8.63</td>
<td>19.60</td>
<td>227.17</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Ni</td>
<td>49</td>
<td>4–720</td>
<td>137.44</td>
<td>180.78</td>
<td>131.54</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Sb</td>
<td>17</td>
<td>3.9–183</td>
<td>41.42</td>
<td>48.19</td>
<td>116.35</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Se</td>
<td>16</td>
<td>0.5–57</td>
<td>6.49</td>
<td>13.60</td>
<td>209.62</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Furthermore, the heavy metal elements, including Ba, Zn, Cu, Cr, Pb, Hg, As, Cd, and Ni, are selected for statistic analysis of the leaching concentration (Table 2) to investigate the influence of SSA on the environment, according to the Toxicity Characteristic Leaching Procedure (TCLP) limit from the United States Environmental Protection Agency and Chinese standard GB 5085.3-2007 “Identification standards for hazardous wastes-Identification for extraction toxicity”. The results show that the leaching concentration of heavy metals in SSA has a high coefficient of variation (96.19–278.37%). However, the leaching concentrations of SSAs are all lower than the corresponding limits in TCLP and GB 5085.3-2007.

Table 2. Heavy metal leaching concentrations of SSA samples (mg/L) [17,27,29,32,52,58,60,66–84].

<table>
<thead>
<tr>
<th>Elements</th>
<th>Sample Number</th>
<th>Range</th>
<th>Average Value</th>
<th>Standard Deviations</th>
<th>Coefficient of Variation</th>
<th>TCLP Limits (Us EPA)</th>
<th>GB 5085.3-2007 Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba</td>
<td>9</td>
<td>0.004–0.75</td>
<td>0.221</td>
<td>0.28</td>
<td>125.66</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Zn</td>
<td>22</td>
<td>0.019–17.66</td>
<td>5.64</td>
<td>5.51</td>
<td>97.66</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>Cu</td>
<td>24</td>
<td>0.008–11.9</td>
<td>4.028</td>
<td>3.87</td>
<td>96.19</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>Cr</td>
<td>24</td>
<td>0.009–15.2</td>
<td>1.523</td>
<td>4.24</td>
<td>278.37</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Pb</td>
<td>27</td>
<td>0.012–2.43</td>
<td>0.262</td>
<td>0.46</td>
<td>176.86</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Hg</td>
<td>5</td>
<td>0.0002–0.2</td>
<td>0.041</td>
<td>0.09</td>
<td>216.96</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>As</td>
<td>12</td>
<td>0.01–0.77</td>
<td>0.265</td>
<td>0.26</td>
<td>98.15</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Cd</td>
<td>25</td>
<td>0.009–1.05</td>
<td>0.145</td>
<td>0.29</td>
<td>197.09</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ni</td>
<td>14</td>
<td>0.033–6.52</td>
<td>0.986</td>
<td>1.73</td>
<td>175.40</td>
<td>25</td>
<td>5</td>
</tr>
</tbody>
</table>

The statistic results in Tables 1 and 2 show that the leaching concentration of heavy metals in SSA is far lower than the relevant specifications although the content of some heavy metals in SSA is relatively high (Zn, Cu, Cr, Pb, Cd), which illustrates the potential for the safe application of SSA.

2.5. Appearance Morphology and Microstructure

Highly dehydrated sewage sludge heated at 200 °C for six hours contains many smooth crystals, which are considered as siliceous particles (Figure 6a) [85]. SSA has porous structure and irregular shape with rough surface (Figure 6b,c) [86]. The particles of SSA will be smoother and smaller with reduced pores after grinding [15], as shown in Figure 6d–f. However, the extension of grinding time has a limited effect on the reduction of SSA particles. When the grinding time is 360 min, SSA particles are compacted and agglomerated in ball mill [14] as shown in Figure 6g–i.
In addition, Wang et al. [87] found that SSA, obtained by drying at 105 °C and grinding with organic matter for 4 min in a ball mill, is black-brown in color and cannot be directly used as an admixture [26]. The existence of organic matter increases the water requirement of SSA, affects the formation of structure when mixing SSA with cement, and then reduces the strength of mortar. With the increase of incineration temperature, the color of SSA gradually changed from dark brown to light yellow, and this is due to the fact that the organic matter and carbon-containing particles in SSA were gradually removed under high temperature.

2.6. Pozzolanic Activity

Generally speaking, SCMs can be classified into self-gel material and pozzolanic material [88]. The reaction of self-gel material is similar to cement, which can be hardened with water. The pozzolanic material is defined in American Society of Testing Materials (ASTM) C125 as “a silicon and aluminum material that has little coagulation value, but in the presence of water, it can undergo chemical reaction with calcium hydroxide at room temperature to form a compound with coagulation properties” [89,90]. The Bureau of Indian Standards 1344 [91] and ASTM C618-17a [90] have the requirement on the total content of SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$ in the range of 50–70% for pozzolanic materials. By the summary of the chemical compositions for SSA, it is found that most SSA from different literatures meet the requirement.

It is found that the fine ground SSA can be used as pozzolanic material in mortar due to its pozzolanic activity similar to fly ash [92]. The strength activity index value of SSA was between 53.6% and 74.3% due to the existence of amorphous silicon oxide [93]. The activity characteristic of pozzolanic material relies on its ability to react with Ca(OH)$_2$ and generate hydration products [94]. It is found that SSA can react with Ca(OH)$_2$ to produce a large number of hydration products, which can be defined as a pozzolanic material, showing the utilization potential as a SCM in mortar [95].

Donatello et al. [96] found that grinding SSA can improve the pozzolanic activity based on different test methods, including the strength activity index and Frattini tests. Pan et al. [14] found that there is an increasement ratio of 5% for strength activity index value when the specific surface area of SSA increases per 100 m$^2$/kg. Besides, the calcination temperature has a significant effect on the pozzolanic activity of SSA. Basto et al. [97] found that the optimal calcination temperature for sewage sludge is 600 °C, after which the SSA has a higher loss in conductivity up to 88.3%, indicating the higher pozzolanic activity. The higher the calcination temperature is, the lower the pozzolanic activity will be.

3. Effect of SSA on the Performance of Mortar

3.1. Workability

The replacement ratio of SSA is a major factor influencing the workability of mortar [15,84,98,99]. Figure 7 shows the relative fluidity of mortar with the SSA replacement rate of 0–30% from different literatures. The results show that the fluidity of mortar decreases with the increase of SSA content. For every 5% increase on average in SSA content, the fluidity of mortar decreases by 4.07%. This is due to the porous properties and irregular morphology of SSA [34]. The porous microstructure increases the water absorption, and the irregular morphology can rearrange SSA particles in mortar and form a large number of gaps [66]. Besides, the particle size distribution of SSA has a significant influence on the workability of mortar [87]. The grinding makes the surface of SSA particles smoother [14,25,81,100,101], reduces the interlocking and friction between particles, and then improves the workability of mortar [26,102]. When the water to binder ratio of mortar is constant, the fluidity of mortar with SSA can be adjusted by adding an appropriate amount of superplasticizer.
Figure 6. Appearance and microscopic morphology of the SSA [14,15,17,85,86]. Reprinted with permission from Ref. [14]. Copyright 2003 Elsevier Ltd. Reprinted with permission from Ref. [15]. Copyright 2017 Elsevier Ltd. Reprinted with permission from Ref. [17]. Copyright 2017 Taylor & Francis. Reprinted with permission from Ref. [85]. Copyright 2020 Elsevier Ltd. Reprinted with permission from Ref. [86]. Copyright 2019 Elsevier Ltd.

Figure 7. Effect of SSA on the relative fluidity for mortar [15,18,19,25,84,99,103].

3.2. Setting Time

The setting time of mortar increases with the addition of SSA [84,98,104,105]. With the increase of SSA, the content of phosphate in mortar rises. Then, the phosphate reacts with Ca(OH)₂ and generates the insoluble calcium phosphate on the surface of cement particles, hindering the hydration of cement [104,105]. The Al₂O₃ in SSA hinders the formation of C-S-H gel and delays the hydration of cement [66]. Furthermore, the grinding process for SSA leads to the adsorption of more calcium ions on its surface, which affects the
accumulation and nucleation of calcium concentration in mortar, resulting in a prolonged
setting time [14].

3.3. Water Absorption and Water Requirement

The water absorption and water demand of mortar increase when SSA is applied.
Firstly, the adsorption of water molecules on the surface of SSA particles reduces the content
of free water in mortar due to the porous microstructure and irregular shape of SSA [18].
Secondly, the rough surface of SSA leads to the large relative sliding resistance between
particles, which reduces the fluidity of mortar. Besides, the density of SSA is smaller than
that of cement. Therefore, when cement is replaced with SSA by mass, the volume of
binders increases and then the water requirement of mortar further increases [8].

3.4. Compressive Strength

Many researchers found that the compressive strength of mortar with SSA is lower
than that of cement mortar [19,25,66,84,87,106,107], which can be explained by the low
reactivity of SSA [108,109], high porosity, and irregular shape [110]. The low reactivity
of SSA is caused by the low content of CaO and amorphous silica [14]. In addition, SO$_3$
and carbohydrates contained in SSA, which decompose when the temperature exceeds
390 °C [19], delay the hydration of cement [16], thereby affecting the formation of hydration
products of mortar.

The increase of incineration temperature has a dual effect on the pozzolanic activity of
SSA. On the one hand, the raise of temperature increases the content of amorphous SiO$_2$
in SSA, which promotes the formation of C-S-H gel in mortar, resulting in a positive effect
on the performance of mortar. On the other hand, the sintering bonding phenomenon
appears with the raise of temperature [87], which has a negative effect on the performance
of mortar. The grinding process can improve the pozzolanic activity of SSA to some
extent [14,15,17,32,111]. The compressive strength of mortar prepared by SSA with fine
particles is higher than that of mortar prepared by coarse SSA at the same curing age. when
the replacement ratio is 20%, the 7-day and 28-day compressive strengths of recycled mortar
increase by 1.4 MPa and 1.9 MPa for every 100 m$^2$/kg increase in SSA, respectively [14].

The 90-day compressive strength of recycled mortar is 71.72–98.6% of the 90-d com-
pressive strength of cement mortar when the replacement ratio of SSA is 10–30% [17,84],
which is higher than that of SSA mortar at 28-day age (63.24–95.45% of cement mortar),
reflecting the long-term pozzolanic activity of SSA. The porous structure and high-water
absorption contribute to the enhancement of long-term compressive strength, which can be
explained by the internal curing of porous structure.

The replacement ratio of SSA is an important factor affecting the compressive strength
of mortar. The higher the replacement ratio is, the lower the compressive strength of mortar
is [16,19,66,84,106,112]. This is due to the fact that the active Ca$^{2+}$ and Si$^{2+}$ is reduced with
the increasing replacement of SSA, leading to the decrease in the total content of active
binder [15,19,98]. When CaO is added in the form of lime or cement to mortar with a water
to binder ratio of 0.5, the compressive strength of SSA mortar is similar to that of the control
group [99,100]. The use of mineral additives such as metakaolin, nano-silica and multi-
component cement [113,114] can also reduce the adverse effect of SSA on the compressive
strength of mortar. For example, the use of nano-silica accelerates the hydration reaction
of cement, promotes the nucleation and crystal growth of hydration products [66], and
then improves the compressive strength of mortar. This also shows that CaO and the other
oxides in SSA have an important impact on the compressive strength of mortar without the
addition of other substances.

The compressive strength of mortar is related to the ratio of CaO/SiO$_2$ and the ratio
of SiO$_2$/Al$_2$O$_3$. The increasing ratio of CaO/SiO$_2$ is beneficial to the improvement
of compressive strength of mortar, while the increasing ratio of SiO$_2$/Al$_2$O$_3$ has an adverse
effect on the compressive strength of mortar. Figure 8 shows the content of cement and
SSA in mortar (by weight) and the 28-day compressive strength of mortar in different
The main oxide content of SSA is summarized in Table 3. When SSA with low CaO content (1.93%) and high SiO$_2$/Al$_2$O$_3$ ratio (3.95) is used, the recycled mortar has the lowest 28-day compressive strength [14]. When SSA with higher CaO content (23.8–32.9%) and higher CaO/SiO$_2$ (1.39–2.03) is used, the compressive strength of mortar is higher [18,25]. However, when SSA with low CaO content (1.863%) and high SiO$_2$/Al$_2$O$_3$ (2.61) is used, the 28-day compressive strength of mortar is the highest among the samples, which mainly attributes to the lowest replacement ratio of SSA (5%) [16]. In addition, the 28-day compressive strength of mortar ranks second of all samples when SSA with SiO$_2$/Al$_2$O$_3$ of 3.35 is used at the replacement rate of 20%. This can be explained by the use of CEM II/B-M (V-LL) 42.5R cement, which is considered as an ideal material for preparing SSA mortar in reference [114]. The compound use of SSA and CEM II/B-M (V-LL) 42.5R cement can promote the bonding of mortar. In addition, a limited reduction for the compressive strength appears when the SiO$_2$/Al$_2$O$_3$ ratio in SSA is similar to that of fly ash (about 2.4) [21,115–117].

![Graph](image)

**Figure 8.** The binders’ content and the corresponding 28d compressive strength of mortars [14–19,25,66,112].

**Table 3.** Main oxide content within the SSA of the sample (%) [14–19,25,66,112].

<table>
<thead>
<tr>
<th>References</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>CaO/SiO$_2$</th>
<th>SiO$_2$/Al$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[14]</td>
<td>50.6</td>
<td>12.8</td>
<td>7.21</td>
<td>1.93</td>
<td>0.04</td>
<td>3.95</td>
</tr>
<tr>
<td>[15]</td>
<td>28.3</td>
<td>12.5</td>
<td>18.6</td>
<td>10.6</td>
<td>0.37</td>
<td>2.26</td>
</tr>
<tr>
<td>[16]</td>
<td>37.895</td>
<td>14.503</td>
<td>22.646</td>
<td>1.863</td>
<td>0.05</td>
<td>2.61</td>
</tr>
<tr>
<td>[17]</td>
<td>27.78</td>
<td>12.2</td>
<td>18.23</td>
<td>10.42</td>
<td>0.38</td>
<td>2.28</td>
</tr>
<tr>
<td>[17]</td>
<td>27.91</td>
<td>12.26</td>
<td>18.32</td>
<td>10.47</td>
<td>0.38</td>
<td>2.28</td>
</tr>
<tr>
<td>[18]</td>
<td>20.8</td>
<td>14.9</td>
<td>7.4</td>
<td>31.3</td>
<td>1.50</td>
<td>1.40</td>
</tr>
<tr>
<td>[18]</td>
<td>30.1</td>
<td>11.9</td>
<td>7.1</td>
<td>25.9</td>
<td>0.86</td>
<td>2.53</td>
</tr>
<tr>
<td>[18]</td>
<td>16.2</td>
<td>14.7</td>
<td>8.2</td>
<td>32.9</td>
<td>2.03</td>
<td>1.10</td>
</tr>
<tr>
<td>[19]</td>
<td>27.24</td>
<td>14.44</td>
<td>27.35</td>
<td>6.34</td>
<td>0.23</td>
<td>1.89</td>
</tr>
<tr>
<td>[25]</td>
<td>17.1</td>
<td>5.1</td>
<td>15.7</td>
<td>23.8</td>
<td>1.39</td>
<td>3.35</td>
</tr>
<tr>
<td>[66]</td>
<td>64.6</td>
<td>23.1</td>
<td>1.31</td>
<td>8.6</td>
<td>0.13</td>
<td>2.80</td>
</tr>
<tr>
<td>[112]</td>
<td>28.8</td>
<td>7.8</td>
<td>3.9</td>
<td>21.9</td>
<td>0.76</td>
<td>3.69</td>
</tr>
</tbody>
</table>
3.5. Flexural Strength

The 28-day flexural strength of mortar containing SSA is generally lower than that of cement mortar. In consistence with the trend of compressive strength, the higher the replacement ratio is, the lower the flexural strength is, as shown in Figure 9 [15,19,99,114,118–122]. However, a few researchers found that the 28-day flexural strength of SSA mortar is higher than that of cement mortar at low replacement ratio, which results from the high-water absorption and filling effect of SSA. The effective water to cement ratio of the mortar is reduced due to the high-water absorption [92], and the cement dilution effect is offset [15]. However, a great reduction in flexural strength can be obtained when the replacement rate of SSA is higher than 30%, due to the low reactivity of SSA [19].

![Figure 9. Effect of SSA incorporation on flexural strength of mortar [15,19,99,114,118–122]. Note: The points represent the increase or decrease ratio of 28d flexural strength of different SSA mortar compared with that of cement mortar. The different replacement ratio of SSA, different SCMs and different calcined temperature of SSA mortar are also shown next to the point, which are shown as the terms of “a + b(c)”, where “a” represents the replacement ratio of SSA (unit: %), “b” represents the replacement ratio and type of SCM, “c” represents the calcined temperature (unit: × 100 °C). For example, 20+10Metakaolin from reference [99] means 20% replacement ratio of SSA and 10% replacement ratio of Metakaolin. If there is no other SCM and calcined temperature, only the replacement ratio will be shown, such as “10” in reference [19], which represents the replacement ratio of SSA is 10%.

The addition of mineral admixtures, such as silica fume and metakaolin, can improve the flexural strength of mortar. The flexural strength of mortar mixed with 10% silica fume and 20% SSA was slightly higher than that of cement mortar. The optimum dosage is 10% metakaolin with the SSA replacement rate of 20%, in which case, the flexural strength is 28.32% higher than cement mortar [99]. The source and treatment process of SSA have an important influence on the flexural strength of mortar. For example, the 28-day flexural strength of mortar prepared by SSA calcined at 700 °C is higher than mortar prepared by SSA calcined at 600 °C when keeping the same source of SSA and the replacement ratio of 10% [118]. Avlîk et al. [123] found that the pozzolanic activity of SSA was low due to the coarse particles (even though it has 41% amorphous substances).
3.6. Durability

Most studies show that the drying shrinkage of mortar is increased as the incorporation of SSA [15,19,124,125], as shown in Figure 10. This is related to the large porosity of mortar with SSA, which increases the loss of free water in the evaporation process [19,126–128]. The grinding process on SSA increases the drying shrinkage when the replacement ratio keeps the same [15]. The higher the calcined temperature is, the larger the drying shrinkage is. Liu et al. [124] found that the drying shrinkage of mortar with SSA at 900 °C was the largest when compared with mortar containing 30% SSA calcined at 500–900 °C. This phenomenon was related to the maximum porosity and average pore size of SSA mortar at 900 °C, which confirmed that the drying shrinkage of mortar was closely related to its porosity [129].

The incorporation of SSA can increase the capillary water absorption of mortar. The grinding process on SSA can enhance the capillary water absorption coefficient of mortar [130], which may be due to the higher specific surface area of SSA after grinding [14,131], resulting in the increase of the number of pores in mortar. The study by Krejcirikova et al. [132] indicated that the water permeability of mortar is enhanced as SSA is incorporated. Further, the water permeability of mortar is improved with the increase of SSA replacement ratio.

The freeze-thaw resistance of mortar is related to its pore structure. Water in the pores of mortar starts to freeze when temperature drops to a specific level, and then results in the volume expansion [133]. The expansion further damages the microstructure of mortar and induces the unfrozen water in the pores of the mortar to migrate outwards. Liu et al. [124] found that the average pore size is 4.9% for recycled mortar with 30% SSA, which is lower than that of cement mortar. The mass loss of recycled mortar with SSA after 100 freeze-thaw cycles was 2.5% lower than cement mortar. Similar results are obtained in references [103,134,135], showing that mortar with SSA has higher freeze-thaw resistance.

In addition, the carbonation of mortar with 20% SSA meet the requirement of the quality index of T-IV according to the Chinese code JGJ/T 193-2009 [136]. It can be determined that the application of SSA from different references has different influence on the performance of mortar, which is caused by their various sources and production process. Besides, there is little research on thermal performance of mortar with SSA at present, which should be studied in the future [137].

3.7. The Influence Mechanism of SSA on the Properties of Mortar

The influence mechanism of SSA on the properties of mortar can be summarized into two main points. On the one hand, the utilization of SSA has a dilutive effect on the cement
paste, resulting in low content of active composition. Thus, the strength and durability is reduced due to the loose microstructure. On the other hand, the pozzolanic activity, filling effect, and self-curing effect of SSA have positive effect on the properties of mortar. Firstly, the pozzolanic activity of SSA contributes to the mechanical properties of mortar. SSA can react with the hydration products Ca(OH)$_2$ and produce C-S-H gel. Besides, the finer SSA particles provides the nucleation site for cement, contributing to the hydration of cement and dense structure of mortar [39]. Secondly, SSA contributes to the strength of cement mortar through a variety of interactions, including reducing the effective water to cement ratio, releasing water required for cement hydration by porous structure, forming dicalcium phosphate crystals, as well as the irregular shape of SSA [15]. Thirdly, the finer particles of SSA after grinding have the filling effect in mortar. These reasons can be proven by the investigation on the microstructure of mortar with SSA, such as the SEM images and pore properties.

The microcracks and un-hydrated SSA particles trapped between the hydration products can be found in Figure 11a–c, which contributes to the reduction of mechanical properties and durability [85,95]. The smaller the SSA particle size is, the denser the mortar structure is [32], see Figure 11d–f. The incorporation of SSA can produce more ettringite and sulfate, which is negative to the mechanical properties of mortar. However, it is found that the addition of nano-$\text{Al}_2\text{O}_3$ and nano-$\text{SiO}_2$ can fill in the pores between C-S-H and C-A-H gels to densify the microstructure and improve compressive strength (Figure 11g–i) [138].

Figure 11. Microstructure of pastes and mortars mixed with SSA [33,85,95,138]. Reprinted with permission from Ref. [32]. Copyright 2008 Elsevier Ltd. Reprinted with permission from Ref. [85]. Copyright 2020 Elsevier Ltd. Reprinted with permission from Ref. [95]. Copyright 2018 Elsevier Ltd. Reprinted with permission from Ref. [138]. Copyright 2015 Taylor & Francis.

In addition, Wang found the calcined temperature has great influence on the microstructure of mortar. The interfacial bonding effect of mortar doped with 700 °C SSA is better than that of mortar doped with SSA at other temperatures, but the compactness has limited change, which is related to the irregular morphology of SSA [87].

Porosity is an important parameter affecting the mechanical properties and durability of mortar. When mortar is exposed to humid environment, the pores in mortar provide
channels for water, chloride ion penetration and carbonation. The strength is affected by
the addition of mineral admixtures (such as fly ash, slag and limestone), which can be
explained by the optimized pore size and pore structure [139–145]. Figure 12 shows the
porosity of mortar containing SSA with the replacement ratio of 0–60%. It can be deter-
dined that the porosity of mortar increases by 0.2–14.53% with the increase of SSA content. On
average, the porosity of mortar increases by 3.73% for every 20% increase of SSA, which
leads to the decrease of mechanical properties and durability for mortar.

Figure 12. Effect of the cement substitution rate of SSA on the mortars porosity [106,124,146].

4. Conclusions

The SSA can be used in mortar to partly replace cement after a production process of
drying, incineration and grinding, which can promote the resource utilization of sewage
sludge and reduce the consumption of cement. This study investigated the basic properties
of SSA and its effect on the properties of mortar. The results can be concluded as follows.

(1) The specific gravity of SSA is lower than cement. Most studies show that the
particle size distribution of SSA is 2.5–250 µm. SSA contains active oxides such as SiO₂,
Al₂O₃, Fe₂O₃ and CaO, which are similar to the active oxides in fly ash, indicating that SSA
has the potential to be used as a pozzolanic material.

(2) The leaching concentration is much lower than the required values in relevant
specifications, leading to an allowable environment influence. The physical properties of
SSA, such as density and particle size, are closely related to the source and production
process. The proportion of oxides in SSA has a great discreteness.

(3) The addition of SSA has a negative impact on the workability, setting time, water
absorption and compressive strength of most mortars, which is mainly related to the porous
properties and irregular particle morphology of SSA. The performance of mortar can be
improved by grinding and using admixtures, but the improvement effect is limited. The
raise of incineration temperature can increase the content of amorphous SiO₂, which has a
positive effect on the pozollanic reactivity of SSA.

(4) Most studies show that the addition of SSA can increase the porosity, drying
shrinkage and capillary water absorption of mortar. Few studies show that the micro-
aggregate filling effect of SSA can refine the pore size of mortar matrix and improve
the freeze-thaw resistance of mortar. The microstructure and durability of SSA mortar
can be improved by incorporating nano materials or selecting 700 °C SSA incineration
temperature.

In conclusion, SSA can be used in mortar with a certain replacement ratio. However,
due to the different sources and production process, the basic properties of SSA are different,
leading to various or even opposite influences on the mechanical properties and durability.
Therefore, the optimal replacement ratios of SSA in different literatures are various. In the future, the sources of SSA should be selected before its utilization to control its chemical properties. In addition, standards for the preparation methods, test methods and utilization of SSA should be proposed for its application promotion.

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