Is ceramsite the last straw for sewage sludge disposal: a review of sewage sludge disposal by producing ceramsite in China

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ABSTRACT

With the rapid development of urbanization, the amount of urban sewage treatment is increasing. Waste activated sludge (WAS) is a by-product of sewage treatment, and its output is increasing year by year. How to properly handle WAS is related to the sustainable development of the sewage treatment industry. The production of ceramsite from WAS is an effective way to realize the utilization of sludge. This paper comprehensively describes the use of WAS as raw material, adding clay, cement, glass powder, shale, coal gangue, river sediment, pulverized fly ash and other auxiliary materials (AM) to produce sintered sewage sludge ceramsite and non-sintered sludge ceramsite. This paper analyzes the advantages and disadvantages of the process of making ceramsite from WAS. The research points out the development prospect of ceramsite from WAS.

Key words | ceramsite, disposal, review, sludge

INTRODUCTION

With the acceleration of global urbanization, urban sewage treatment rates are increasing. Sewage sludge is the main by-product of urban domestic sewage treatment, and its production is increasing. The term ‘sludge’ as used herein refers to the waste activated sludge (WAS) produced by the municipal sewage treatment plant. Studies have shown that WAS has long-term toxicity and non-degradability; if not handled properly, it will threaten human health through contamination of air, groundwater, surface water and soil, and by entering the food chain (Camargo et al. 2016; Iglesias et al. 2018).

In China, the main methods of sludge disposal include landfill, incineration, marine dumping and land use. Although these methods can accommodate a large amount of sludge, which is an effective way to dispose of WAS, there are also many problems needing to be solved (He et al. 2003). The moisture content of WAS after conventional mechanical dewatering is still more than 80%, and the relevant laws in China stipulate that the sludge entering the landfill must have a moisture content of less than 60%, which increases the sludge dewatering difficulty (Yao et al. 2014). Landfills occupy a large amount of land, shorten the service life of landfills and cost a lot of transportation fees, and landfill leachate and odor are also important constraints (Wu et al. 2001). The residual sludge contains heavy metals, furans and other harmful substances. If WAS is applied to the land for a long time, people’s health may be affected by the accumulation of harmful substances (Chen & Xiong 2003). Although long-term studies have reported no accumulation of heavy metals in plants, there have also been reports of tree death after sludge was used in woodlands (Campbell 2000; Yao 2000). Therefore, developed countries such as Europe and the United States have used the remaining sludge land as a strict standard. Consequently, the environmental economics of sludge landfill is worth evaluating.

Incineration is always used to deal with solid wastes. The high moisture content of sewage sludge will affect the incineration process. Therefore, the dewatering treatment before the WAS incineration treatment will inevitably lead to an increase in the treatment cost. In addition, the incineration process may generate SO₂, TCDD (tetrachlorodibenzo-p-dioxin) and other gases to cause air pollution (Yang 2001). The potential environmental risks of sludge incineration are objective facts that
cannot be avoided. The dumping of WAS in the ocean is simple and the treatment cost is low. However, the negative impact of the WAS marine dumping on the ocean ecological environment must be critically assessed (Wang 2005). Sludge compost can effectively utilize trace elements such as nitrogen, phosphorus and potassium in the sludge and organic matter (Wang & Zhou 2005). However, the long-term food chain safety of sludge composting soil use needs further research.

At present, the production of ceramsite from WAS as a matrix material has aroused the attention of scholars. Sludge ceramsite was first produced by Nakouzi and colleagues (Nakouzi et al. 1998). Sludge ceramsite is a new type of building material which is made from sludge as base material. According to the different commercial uses of ceramsite, sludge ceramsite is mainly divided into sintered ceramsite and non-sintered ceramsite. Among them, sintered ceramsite is mainly used as light aggregate and building insulation material for commercial concrete (Cheeseman & Virdi 2005); non-sintered ceramsite is mainly used in commercial fields such as water treatment filter material and garden cultivation (Wang et al. 2018). It is true that the use of sewage sludge as a base material and the addition of auxiliary materials (AM) to produce commercial ceramsites has caused great concerns among scholars (Yan et al. 2015). The scheme of manufacturing ceramsites from WAS as a raw material (RM) realizes the resource disposal of WAS, which is of great significance (Franus et al. 2016). However, the manufacturing of ceramsite from WAS also faces some complications, such as high energy consumption of sintering ceramsite (Chiou et al. 2014) and air pollution during the sintering process (Białowiec et al. 2014). These technical bottlenecks need to be properly handled. This paper deeply analyzes the research status of ceramsite from WAS, and aims to promote the further development of WAS utilization disposal technology.

**RESEARCH REVIEW**

**Basic characteristics of WAS**

The color of WAS is often gray or dark gray, and the relative density is slightly larger than water. Table 1 shows the physical and chemical characteristics of the WAS and the AM commonly used in the manufacture of sludge ceramsite.

It can be seen from Table 1 that the physical and chemical characteristics of WAS from different sources are different, but the overall characteristic is that SiO₂ and Al₂O₃ are the main components of WAS. The loss on ignition (LOI) of WAS is mainly due to the thermal reaction weight loss of organic matter. The heating vaporization of a small amount of surface-adsorbed water and capillary-bound water is also a factor that causes thermal weight loss (He et al. 2010). Some scholars have pointed out that the chemical composition of RM suitable for sintering high-quality ceramsite should have a SiO₂ content between 40% and 79%, Al₂O₃ content between 10% and 25%, and flux concentration between 13% and 26% (Yang 1997). According to Table 1, it can be seen that the SiO₂ content of commonly used AM can compensate for the low SiO₂ content of the WAS. The Al₂O₃ content of the AM also increases the Al₂O₃ content of the ceramsite raw material mixture. Obviously, WAS is used as a base material and the auxiliary material such as pulverized fly ash (PFA) or clay is added to have a chemical substance for sintering ceramsite.

**Sintered sewage sludge ceramsite**

**Process flow**

The production of sintered ceramsite is a process in which the RM is crushed and mixed, and then an auxiliary agent such as a binder is added, which is granulated, preheated,
and calcined. The process flow for preparing sintered ceramsite from WAS is shown in Figure 1.

According to the process flow, the main energy consumption processes in the production of sintered sewage sludge ceramsite (SSSC) include: RM grinding and mixing, granulation molding, drying and dewatering, and sintering. At present, scholars pay attention to the study of sintering ceramsite by mixing WAS with clay (Latosinska & Zygodlo 2011), shale (Lau et al. 2017), and coal gangue (Pei et al. 2015). Due to the large difference in particle size of RM, it is necessary to crush and grind the RM to achieve uniform mixing (Huang et al. 2010). Currently, there is a lack of quantitative research on the energy consumption of crushing and grinding of RM. The granulation of sludge ceramsite usually uses a disc granulator and drum granulation equipment (Luo et al. 2018). The working efficiency and energy consumption level of such equipment have not been reported. The drying of raw pellets is mostly through baking in a laboratory oven at 105 °C for about 2 hours (Liu et al. 2008). It aims to reduce the breakage rate of the sintering process by reducing the water content. There is also a lack of research on the energy consumption of raw pellets dewatering. Calcination is the key factor of the entire process. The calcination temperature is usually between 1,000 °C and 1,200 °C (Cheeseman & Virdi 2005). The residence time of the raw pellets in the calcining equipment exceeds 20 minutes, which means that SSSC needs a great energy consumption (Wierczek et al. 2018). The quantitative study of energy consumption in the whole process of producing SSSC has not been reported, and a great number of research studies remain in the scope of laboratory process feasibility. Under the premise of scientifically proven process feasibility, quantitative research on the energy consumption of producing sintered sludge ceramsite is of great significance for the industrialization of SSSC.

The environmental problems that making SSSC may cause are mainly the noise effects and harmful gases of equipment operation. Mechanical noise mainly comes from grinding and crushing, mixing and granulation, and measures such as vibration isolation, energy absorption and sound barriers can effectively reduce the impact of noise on the environment (Nassiri et al. 2014). Combustion is a deep thermal reaction process. The combustion process involves complex thermodynamic processes such as pyrolysis, vaporization, cracking, oxidation, and reduction, etc., and will also produce a variety of thermochemical products (Feng et al. 2001). In the process of producing SSSC, the harmful gases that may be produced are mainly SOx, COx, NH3, TCDD, etc. (Xu et al. 2013a; Qu et al. 2016). Further research is needed on the generation rules and prevention measures for harmful gases in the calcining process. In particular, the use of fossil fuels in the process of firing ceramsite, producing greenhouse gases such as carbon monoxide, carbon dioxide and nitrogen oxides, is also a focus of attention.

Research status

In recent years, many scholars have paid attention to the resource utilization of WAS and carried out experimental research on SSSC. The research results are summarized in Table 2.

Among the WAS disposal methods, scientists chose the SSSC process to conduct research, mainly considering that the sludge can spontaneously ignite during the calcining process, thereby providing an auxiliary heat source to reduce fuel consumption (Bui Le Anh et al. 2014). According to Table 2, it can be seen that in the process of sintering ceramsite, the amount of sludge added is high or low, depending on the functional requirements of the ceramsite. For example, it is not advisable to add excess WAS to the high-strength building structure ceramsite lightweight aggregate for two reasons: first, WAS has a big LOI, and adding too much WAS will result in the strength of the ceramsite declining (Liu et al. 2017) – it is difficult to meet the strength requirements of structural concrete aggregates; second, excessive WAS reduces the bulk density of ceramsite, and ceramsite floats during the process of making concrete, which in turn leads to a decrease in the shear strength of concrete (Yan et al. 2018). How to reduce the aggregate floating phenomenon of ceramsite concrete will be an important topic worthy of further study.

Figure 1 | Process flow for preparing sintered ceramsite (WAS, waste activated sludge; AM, auxiliary materials).
At present, many scholars have carried out a lot of experimental research on the SSSC, and achieved some valuable research results (Latosinska & Zygadlo 2001; Chen et al. 2015; Lau et al. 2018). However, we should also be aware that the ultimate goal of scientific research is not only to verify the laboratory reliability of the process, but to translate scientific research into real productivity and serve the sustainable development of society. The scientific research on SSSC should be for commercial applications. Therefore, we need to consider the following factors. First, the source of RM should be stable, reliable, and accessible. Second, the manufacturing process should be in line with national industrial policies, and have low energy consumption, low pollution, and resource conservation. Finally, ceramsite should have a commercial application market. Based on the above factors, the research indicates that the research scheme of using WAS to incorporate sewage sludge ash in sintered ceramsite has more commercial potential (Chiou et al. 2006). The characteristics of sewage sludge ash and its use in ceramic applications pertaining to bricks, tiles and glass ceramics have been assessed using globally published literature in the English language (Lynn et al. 2016).

The non-sintered sludge ceramsite

Process flow

The non-sintered ceramsite is an artificial light aggregate which is granulated and then cured by using various active solid wastes, cavity knot materials, admixtures and AM (Wang et al. 2018). The process flow of non-sintered sludge ceramsite (NSSC) is shown in Figure 2.

The main energy consumption processes of the NSSC production include: grinding and mixing of RM, granulation and maintenance. According to the physical and chemical characteristics of RM, the crushing and grinding process is

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**Table 2 | Overview of study on SSSC**

<table>
<thead>
<tr>
<th>RM/wt.%</th>
<th>AM/wt.%</th>
<th>Process parameters</th>
<th>Ceramsite properties</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAS 20</td>
<td>Kaolin 40, clay 40</td>
<td>Preheated at 500°C for 25 min, sintered at 1,150°C for 8 min.</td>
<td>Stacking density 1.0–1.2 g/cm³, water absorption 12–16%.</td>
<td>Lu et al. (2013)</td>
</tr>
<tr>
<td>WAS 20–50</td>
<td>Coal gangue 80–50</td>
<td>Sintered at 1,120°C, heat preservation for 1 h.</td>
<td>Stacking density 1.03–1.20 g/cm³, porosity 26–50%, water absorption 23–35%.</td>
<td>Pei et al. (2015)</td>
</tr>
<tr>
<td>WAS 50–70</td>
<td>Glass powder 30–50</td>
<td>Pellets consisting of 30% and 50% waste glass could be expanded at above 950°C and 930°C. No expansion was recorded with 10% waste glass, even up to 1,100°C.</td>
<td>Stacking density 2 g/cm³, water absorption lower than 10%, and workable lightweight concrete with the 28-day compressive strength of 49 MPa was obtained.</td>
<td>Tuan et al. (2013)</td>
</tr>
<tr>
<td>WAS 10–30</td>
<td>Sewage sludge ash 70–90</td>
<td>Sintered at 1,050, 1,100 and 1,150°C for 10 and 20 min.</td>
<td>Bulk density 0.76–2.12 g/cm³, water absorption 1.65–32.54%.</td>
<td>Chiou et al. (2006)</td>
</tr>
<tr>
<td>WAS 28.5</td>
<td>Quartz tailings 28.5, binder 21.5 and RS 21.5</td>
<td>Preheated at 400°C for 20 min, sintered at 1,080°C.</td>
<td>Bulk density 0.871 g/cm³, water absorption 11.6%.</td>
<td>Guo et al. (2015)</td>
</tr>
<tr>
<td>WAS 45</td>
<td>PFA 45, clay &amp; coal powder 10</td>
<td>Preheated at 400°C for 10 min, sintered at 1,050°C for 25 min.</td>
<td>Specific area 0.4–2.5 m²/g, water absorption 15–20%.</td>
<td>Shao et al. (2015)</td>
</tr>
</tbody>
</table>

Notes: WAS, waste activated sludge; PFA, pulverized fly ash; RS, river sediment; AM, auxiliary materials; RM, raw material; SSSC, sintered sewage sludge ceramsite.
the key to ensuring uniform mixing of the mixture. PFA was used as the base material, WAS and cement were used as additives, and steam curing was applied to make biological aerated filter ceramsite (Liu et al. 2012). These authors pointed out that the use of water vapor diffusion promotes the hydration reaction of the particles layer by layer, thereby increasing the strength of the ceramsite; the steam curing time is positively correlated with the strength of the ceramsite. The granulation and shaping of the NSSC is mostly carried out by disc granulation and extrusion molding (Luo et al. 2018). The research on the operation efficiency and energy consumption of the granulation equipment has not been reported. The maintenance methods of the NSSC mainly include natural curing, solar curing and steam curing. The above three curing methods have their own advantages and disadvantages. (i) The advantages of natural curing are simple operation and low energy consumption (Ma 2005). The significant disadvantage is that the maintenance site occupies a large space. (ii) The advantages of solar curing are simple operation and low energy consumption (Feng 1998). The disadvantages include low land-use efficiency and high cost of maintenance facilities. (iii) The advantages of steam maintenance are short maintenance period and high efficiency (Tang et al. 2014). The disadvantage is the high level of energy consumption and the environmental hazards of greenhouse gases from the steam curing process.

The environmental problems that may occur in the production of NSSC are mainly the noise from the operation of the equipment and the mixed use of various additives. Mechanical noise mainly comes from grinding and crushing, mixing and granulation, and measures such as vibration isolation, energy absorption and sound barriers can effectively reduce the impact of noise on the environment (Nassiri et al. 2014). To make non-sintered ceramsite based on WAS, it is necessary to add various AM such as adhesive, foaming agent and curing agent (Zhou et al. 2016). The addition of AM causes two effects: on the one hand, it improves the performance quality of the non-sintered ceramsite; on the other hand, it adds new substances to the environment, and after the ceramsite loses its use value, it produces more solid waste. Therefore, the research value of making non-sintered ceramics with WAS as the base material remains to be discussed.

### Research status

The non-sintered ceramsite has the characteristics of relatively large density, high strength, and continuous increase in strength over time. The non-sintered ceramsite has a low manufacturing cost and a relatively simple production process. At present, some scholars have carried out experimental researches on NSSC, and a research summary is shown in Table 3.

#### Table 3 | Overview of study on NSSC

<table>
<thead>
<tr>
<th>RM/wt.%</th>
<th>AM/wt.%</th>
<th>Process parameters</th>
<th>Ceramsite properties</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAS 6</td>
<td>PFA 79, CaO 5 and cement 10</td>
<td>Natural curing or low heat steam curing at 80°C.</td>
<td>Fragmentation rate is 1.9%, apparent density is 1.67 g/cm³, and specific surface area is 7.84 m²/g.</td>
<td>Liu et al. (2012)</td>
</tr>
<tr>
<td>PFA 85</td>
<td>Ca(OH)₂ 10 and WAS 5</td>
<td>Low heat steam curing at 50°C and 75°C, the curing time is 12 hours.</td>
<td>Tube pressure strength 4.53–5.95 MPa, packing density 808–898 g/cm³, water absorption 17.0–22.5%, softening coefficient 0.81–0.91.</td>
<td>Zhu et al. (2002)</td>
</tr>
<tr>
<td>WAS 7</td>
<td>PFA 70.9, CaO 7.1, NaHCO₃ 1, cement 9, sodium silicate 5</td>
<td>Natural curing.</td>
<td>Specific surface area 17.038 m²/g, the sum of fragmentation rate and wear rate is 2.2%, bulk density 0.729 g/cm³, apparent density 1.140 g/cm³.</td>
<td>Zhou et al. (2016)</td>
</tr>
</tbody>
</table>

Notes: WAS, waste activated sludge; PFA, pulverized fly ash; AM, auxiliary materials; RM, raw material; NSSC, non-sintered sludge ceramsite.
As can be seen from Table 3, WAS plays a secondary role in the production of NSSC, which means that the amount of sludge added is low. Some scholars, in the process of making NSSC, found that the weight percentage of WAS (dry basis) only accounts for 6% of all RM (Zhou et al. 2016). Zhou et al. 2016 confirmed the possibility that the NSSC has agricultural use, which is a positive side. However, an important question arises: Is it worthwhile to use more than 90% of additives in order to deal with 6% of WAS? When these ceramsites lose their usefulness, the additives used to make ceramsites become more waste. Therefore, it is meaningful to carry out the life cycle environmental benefit assessment of the NSSC. Under the premise of ensuring the performance quality of ceramsite, improving the use of WAS is also a topic worthy of further study.

REVIEW ON THE APPLICATION OF SLUDGE CERAMSITE

Sludge ceramsite is an important method to realize the utilization of sludge resources. In recent years, the practical exploration of sludge ceramsite in the fields of water treatment materials, building materials and soilless cultivation has attracted the attention of scholars. Table 4 shows the results of small-scale commercial applications of sludge ceramsite.

In general, the main characteristics of calcined ceramsite include: light weight, high strength, low water absorption, low heat transfer coefficient and high porosity. The SSSC is used as a building material to replace light natural aggregates for the manufacture of lightweight aggregate concrete (Tay et al. 1991). This is to reduce the weight of the building, mainly used in the construction of skyscrapers and long-span bridges (Yang et al. 2018). The SSSC has a low heat transfer coefficient and is often used as insulation material for building facades (Yang et al. 2016). The slag produced in the process of manufacturing the SSSC can be used for water treatment filter materials for purifying wastewater owing to more pores and larger specific surface area than natural stone (Lin et al. 2018). The NSSC can have good durability under the action of additives such as cement and glass water (Wang et al. 2018). As time goes on, the hydration reaction inside the ceramsite continues, and the ceramsite strength continues to increase until the hydration reaction inside the ceramsite ends. According to this feature of the non-sintered ceramsite, the NSSC can theoretically produce ultra-high strength ceramsite (Yang 2011). Sludge ceramsite can also be used in the fields of sound insulation and sound absorbing materials and landscaping soilless cultivation (Lv 2004).

Although the potential application fields of sludge ceramsite are relatively wide, they also face the following complications: (i) whether the objective demand for sludge ceramsite is strong in the market; (ii) the high energy consumption of producing sintered sludge ceramsite, environmental problems such as dioxin need to be solved; (iii) subsequent problems such as heavy metal leaching toxicity of sludge ceramsite, uplifting of ceramsite aggregate in concrete, and biotoxicological effects of garden cultivation. After solving the above problems, the next step is to explore the economic and social benefits of sludge ceramsite.

BENEFIT ANALYSIS OF SLUDGE CERAMSITE

In China, Xu et al. (2013b) conducted pilot experiments using a combination of WAS, river sediment (RS) and...
PFA to produce sintered sludge ceramsite. The percentage of RM was 55% for WAS, 5% for PFA, and 40% for RS. Through practical operation, the RM usage per ton of sludge ceramsite produced was: WAS (water content 80%) 4.33 tons, RS 0.77 tons, PFA 0.1 tons. Table 5 shows the direct production cost of the sludge ceramsite sintering demonstration project (1 ton of sludge ceramsite).

According to Table 5, the direct economic cost of producing 1 ton of SSSC is RMB 425; the most important cost comes from the dewatering and drying of RM, accounting for 51.55% of the total cost; followed by the calcining process, accounting for 27.88% of the total cost. The SSSC can be divided into building aggregates and filter materials according to the use of commodities. In China, the market price of light aggregate for construction is about RMB 300–600/t, and the market price of ceramsite as water treatment filter is RMB 1,000–2,400/t (Xu et al. 2013b). The sales of SSSC theoretically exceed the direct production cost of ceramsite, and it is possible to achieve profitability. In China, the treatment of 1 ton of WAS will be subsidized by the government by RMB 80, and the production of 1 ton of SSSC will receive a subsidy of RMB 346 (Xu et al. 2013b). If the amount of WAS (dry basis) exceeds 30%, the company can enjoy the national tax incentives for exempting product value-added tax and corporate income tax within 5 years, and its economic benefits are considerable (Xu et al. 2013b).

### CONCLUSION

Through the previous review analysis and discussion, the study draws the following main conclusions.

1. At present, scholars have conducted a large number of experimental studies on the preparation of ceramsite from WAS. However, most of the research results only provide a theoretical basis for the use of WAS to produce ceramsite, and most of the research results have insufficient commercial application value.

2. Through a comprehensive analysis, the research findings on the sludge ceramsite production schemes with potential commercial application value include the following. (i) It takes WAS and sewage sludge ash as raw materials to sinter ceramsite, the water absorption rate of which is 1.65%, and the bulk density is less than 0.8 g/m³. These ceramsites can be applied to buildings’ exterior insulation or lightweight sound insulation walls. This method does not add other resource-based AM, and realizes the resource utilization of waste. (ii) The use of WAS, PFA and RS as raw materials for producing ceramsite has objective economic benefits, and AM are low value, easy to obtain, and stable in source.

3. Energy saving and consumption-reducing measures for sintered sludge ceramsite technology, and harmful gas and smoke pollution prevention measures are the next research focus. The whole life cycle assessment of NSSC is also a subject worthy of study.

### Table 5 | Direct production costs for 1 ton of SSSC in China (Xu et al. 2013b)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Objects</th>
<th>Handling capacity (ton)</th>
<th>Energy type</th>
<th>Power consumption (kWh)</th>
<th>Equivalent standard coal (kg)</th>
<th>Cost of manufacture (RMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying system 1 t/h</td>
<td>WAS</td>
<td>4.33</td>
<td>Electricity</td>
<td>35 kw 50 kg</td>
<td>–</td>
<td>100.2</td>
</tr>
<tr>
<td>Gridding system 1 t/h</td>
<td>WAS, PFA and RS</td>
<td>1.87</td>
<td>Electricity</td>
<td>30 kw</td>
<td>56.1</td>
<td>–</td>
</tr>
<tr>
<td>Mixed feeding 0.6 t/h</td>
<td>WAS, PFA and RS</td>
<td>1.87</td>
<td>Electricity</td>
<td>10 kw</td>
<td>31.3</td>
<td>20.7</td>
</tr>
<tr>
<td>Pelletization 50 kg/h</td>
<td>WAS, PFA and RS</td>
<td>1.87</td>
<td>Electricity</td>
<td>7.5 kw</td>
<td>37.4</td>
<td>27.6</td>
</tr>
<tr>
<td>Sintering system 1 t/h</td>
<td>WAS, PFA and RS</td>
<td>1.87</td>
<td>Electricity</td>
<td>305 kw</td>
<td>46.8</td>
<td>118.5</td>
</tr>
<tr>
<td>Gas cleaning</td>
<td>Waste gas</td>
<td>–</td>
<td>Electricity</td>
<td>3 kw</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>326.2</td>
<td>425.0</td>
</tr>
</tbody>
</table>

Notes: WAS, waste activated sludge; PFA, pulverized fly ash; RS, river sediment; SSSC, sintered sewage sludge ceramsite.
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