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# Ceramsite obtained from water and wastewater sludge and its characteristics affected by $(Fe_2O_3 + CaO + MgO)/(SiO_2 + Al_2O_3)$

G.R. Xu[a,*], J.L. Zou[a,b], G.B. Li[a]

[a]State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China
[b]School of Chemistry and Materials Science, Heilongjiang University, Harbin 150080, China

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ABSTRACT

To control and optimize the process for making ceramsite from wastewater treatment sludge (WWTS) and drinking-water treatment one (DWTS), the effect of mass ratios of $(Fe_2O_3 + CaO + MgO)/(SiO_2 + Al_2O_3)$ (defined as F/SA ratios); $SiO_2$:$Al_2O_3$ and $Fe_2O_3$:CaO:MgO (under the condition of fixed F/SA ratio) on the characteristics of ceramsite were investigated. It was found that the optimal F/SA ratios for making ceramsite range 0.175–0.45. Na–Ca feldspars and amorphous phases increase in ceramsite as F/SA ratios increase. Ceramsite with porous surfaces, expanded structures, and complex crystalline phases can be obtained at $0.275 \leq F/SA \leq 0.45$, which accordingly cause the decrease in compressive strength. Higher strength of ceramsite with lower porosity can be obtained at $0.175 \leq F/SA < 0.275$, and under the condition of F/SA ratio $= 0.275$, the raw materials can produce ceramsite with desired physical properties at $18.2{:}35 \leq SiO_2{:}Al_2O_3 \leq 45{:}10.2$ and $10{:}2.7{:}1.4 \leq Fe_2O_3{:}CaO{:}MgO \leq 5.3{:}6{:}1.6$. Ceramsite with higher compressive strength and lower porosity can be obtained at $SiO_2{:}Al_2O_3 > 27.2{:}15.8$ and $Fe_2O_3{:}CaO{:}MgO > 6{:}3.5{:}1.8$. Results indicate that F/SA ratios could be used as an important parameter to control the production process of ceramsite with desired physicochemical properties and resolve the disposal problems of residual sludges.



## 1. Introduction

Concern has been increasing about the environment and has resulted in the development of new environmentally friendly technologies, new materials, and new ways to reduce and minimize wastes such as wastewater treatment sludge (WWTS) (Nakasaki et al., 1999; Rubli et al., 2000; Liu, 2003; Ahlberg et al., 2006; Garcia-Valles et al., 2007; Seredych and Bandosz, 2007; Kante and Bandosz, 2008; Kante et al., 2008a; Xu et al., 2008a,b) and drinking-water treatment sludge (DWTS) (Bourgeois et al., 2004; Makris et al., 2004; Makris et al., 2006; Muruganandham et al., 2007; Sotero-Santos et al., 2007). WWTS is a mixture of biosolid generated in the aerobic and anaerobic digestion of the organic constituents of municipal sewage along with inorganic materials (Liu, 2003; Ahlberg et al., 2006). DWTS is discharged from drinking water treatment plants and the conventional treatment processes usually include coagulation, flocculation and sedimentation followed by filtration and disinfection. DWTS are mainly organic and inorganic compounds in solid, liquid and gaseous forms, and they can have a variable composition regarding physical, chemical, and biological characteristics (Bourgeois

* Corresponding author. Tel.: +86 451 86282559; fax: +86 451 86282559.
E-mail address: xgr@hit.edu.cn (G.R. Xu).
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et al., 2004; Makris et al., 2006; Muruganandham et al., 2007; Sotero-Santos et al., 2007).

Various methods have been used to dispose WWTS, such as landfill, composting, combustion/incineration, pyrolysis, etc. (Bagreev and Bandosz, 2004; Fuliana et al., 2004; Folgueras et al., 2007). Typical practices of DWTS disposal are landfill, recycling, regeneration, reuse, and mechanical sludge treatment (Makris et al., 2006; Muruganandham et al., 2007; Sotero-Santos et al., 2007). Continuous increases in the quantity of WWTS and DWTS produce call for efficient and environmentally friendly approaches to solve their disposal problems. Re-utilization of wastes and their environmental "neutralization" is one of the current energy-efficient directions related to the environmental protection and cost-reductive advantages (Kante et al., 2008b). So, the conversion of WWTS and DWTS into useful resources or materials is of great interest and needs to be intensely investigated.

One of the feasible methods for utilization of WWTS and DWTS is their conversion into ceramsite (ceramsite, which contains inorganic components, such as $A_2O_3$, $SiO_2$, $Fe_2O_3$, FeO, CaO, MgO, $Na_2O$ and $K_2O$, has been used as construction materials, for example cement mortars, concrete mixtures, bricks, or as fine aggregate in mortars and ceramic materials (Xu et al., 2008a)). In our previous investigations, DWTS and WWTS have successfully been tested as components for producing ceramsite (Xu et al., 2008c). Converting WWTS and DWTS into ceramsite can be prompted to achieve the sustainable disposal options in saving the natural resources of raw materials as well as the protection of environment. The findings of this conversion can revolutionize handling of such kinds of sludge in the future for their reuse as low-cost raw materials, rather than as waste requiring costly disposal, in accordance with the concept of sustainable development.

Properties of ceramsite were highly influenced by the inorganic components such as acidic oxides ($SiO_2$ and $Al_2O_3$) and basic oxides ($Fe_2O_3$, CaO, and MgO), since their contents strongly affect the microstructures and crystalline phases, which in turn determine the compressive strength of ceramsite. However, it is impossible to properly control every inorganic component in the optimal contents ranges during the making process for production of ceramsite.

Objective of this paper is to examine the feasibility of the mass ratio of $(CaO + Fe_2O_3 + MgO)/(SiO_2 + Al_2O_3)$ (F/SA ratios) as a simple controlling parameter to optimize the components for production of ceramsite and to investigate the effect of $SiO_2$:$Al_2O_3$ and $Fe_2O_3$:CaO:MgO on the characteristics of ceramsite under the condition of fixed F/SA ratios, as well as to establish effective parameters for evaluation.

## 2. Materials and methods

### 2.1. Materials

The WWTS used in this study was obtained from the Wenchang Wastewater Treatment Plant, Harbin, China. The wastewater treatment plant has a design capacity of $1.0 \times 10^6\ m^3\ d^{-1}$. The dewatering of WWTS was conducted using a belt filter press and cationic polymeric flocculants were used for sludge conditioning. The sludge cake generated from the activated sludge process is approximately $1.6 \times 10^5\ kg\ d^{-1}$ in wet weight with 24% solids, which is directly landfilled. The DWTS were collected from the chemical coagulation/flocculation unit of the third drinking-water treatment plant, Harbin, China. The coagulant was aluminum sulfate ($Al_2(SO_4)_3$).

The WWTS and DWTS were treated by air-dry method and were ground at sizes below 100 μm that are sufficiently fine to be mixed homogeneously. Components of DWTS and WWTS are shown in Tables S1 and S2 (Supplementary material). The ceramsite was made of DWTS, WWTS, and water glass (sodium silicate-$Na_2O{\cdot}(SiO_2)_x{\cdot}(H_2O)_y$). The modulus of water glass used in the study was 3.2. All used oxides ($SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, and MgO) with particle sizes below 10 μm were of the highest purity and of the analytical grade.

### 2.2. Methods

The raw materials were mixed and pelletized to particle sizes of 5–8 mm and left in a room at a temperature of about 20 °C for a few days and then the samples were dried at 110 °C in a blast roaster for 24 h. The heating of samples started at 20 °C, heated at a rate of 8 °C/min in a muffle furnace, and the samples were soaked at 200 °C, 600 °C, and 800 °C for duration of 10 min and at 1000 °C for duration of 35 min, and then these samples were naturally cooled until they reached room-temperature.

Bulk density, including all voids and spaces in the volume, particle density which is also the apparent specific gravity of the aggregates including all intraparticle voids, water absorption determined from the weight difference between the sintered and water saturated samples (immersed in water for 1 h), and porosity ((1-bulk density/particle density) × 100%) were analyzed (Xu et al., 2006). To achieve statistical soundness, at least three replicates were carried out for each sample. Thermal behaviors of samples were examined by thermodifferential and thermogravimetric analyses (DTA–TGA) with ZRY-2P simultaneous DT–TG analyzer (China). The samples were heated in dry air atmosphere at a rate of 8 °C $min^{-1}$ from 20 °C to about 1080 °C. About 5–10 mg raw materials sample was used in every investigation. Powder XRD patterns of ceramsite were recorded on a D/max-γ β X-ray diffractometer with 50 mA and 40 kV, Cu Kα radiation (Japan). SEM analyses were conducted with S-570 scanning electron microscope (Japan) at an accelerating voltage of 20 kV. Major components of materials were analyzed with Philips PW 4400 XR spectrometer (X-ray fluorescence-XRF, Netherlands). Compressive strength of ceramsite was analyzed with INSTRON 5569 automatic material testing machine (USA). The ceramsite with diameter of 6–8 mm was placed vertically on the platform of the press (INSTRON 5569 automatic material testing machine) and was pressed at a crosshead speed of 0.5 mm $min^{-1}$ until it was crushed. The compressive strength (N $mm^{-2}$) of the sintered ceramsite was the compressing force (N) divided by the pressed area ($mm^2$). The compressive strength results were the average values of three tests for each composition.