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Technical Note

Lightweight aggregates from water reservoir sediment with added sodium hydroxide

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ABSTRACT

Lightweight aggregates were produced from a mixture of water reservoir sediment and sodium hydroxide at a temperature of 1045–1085 °C. The mixtures were also pre-cured at 120 °C to observe the effect of geopolymerization. The physical properties of dry and wet sediment samples were observed at a given NaOH concentration. The results showed that the obtained LWAs meet the European Union regulation UNIEN 13055-1, which requires the LWA bulk density to be lower than 2000 kg/m^3. The performance of most of the obtained LWAs reached that of commercial products. When calcined at 1110 °C, the LWAs lost the properties of a geopolymer cement and bloated, which lowered their bulk density. The addition of NaOH promoted the formation of a glassy phase that vitrified the LWA surface, making the level of water adsorption below 5%. The mineral phases of LWAs were quartz, hematite, albite, and hercynite.

1. Introduction

Water reservoir sediment is a kind of weathering product that precipitates at the bottom of reservoirs. It reduces the capacity of reservoirs and shortens their usage life. In order to extend the usage life of reservoirs, a dredging process is employed. The excavated sediment is usually buried or disposed of downriver, damaging the ecology. According to a government report, the total amount of swept sediment in Taiwan from 2002 to 2009 was 32.98 million metric tons; the amount in 2009 was 4.33 million metric tons. This huge amount of swept sediment causes landfill problems.

Lightweight aggregates (LWAs) are a building material that is applied to the construction of high-rise buildings due to its low weight. European Union regulation UNIEN 13055-1 [1] requires LWAs to have a unit weight of particles of lower than 2000 kg/m^3 and a loose weight of lower than 1200 kg/m^3. Cheeseman et al. [2] suggested that LWAs should have high strength, low density, low water adsorption, and a near-spheroid shape. Recently, many wastes have been recycled into LWAs, such as mined residue [3–7], sludge, and ash. The sludge can be washing aggregate sludge [8], industrial sludge [9–11], or sewage sludge [12,13]. Ash includes fly ash [14] and bottom ash [2,15,16]. Some studies reported that LWAs can be manufactured from a mixture of ash and sludge [17,18]. Water reservoir sediment is also a kind of waste. Chen et al. [14] mixed ash and reservoir sediment to manufacture LWAs and concluded that reservoir sediment is feasible for use due to its high content of glass-forming oxides and low level of flux oxides. Tang et al. [19] manufactured LWAs from reservoir sediment for lightweight aggregate concrete (LWAC). The results showed that the physical performance of LWAs made from reservoir sediment was better than that of commercial LWA (CA-800), owning the compressive strength of 7.5 MPa and the particle density of 1.41 g/cm^3, and that the 28-day strength of LWAC met the requirements for structural LWAC. Wei et al. [20] mixed reservoir sediment with various percentages of harbor sediment by end-to-end mixing. The mixtures were pressed and heated to produce LWAs with a bulk density of particles of lower than 2.0 g/cm^3 and water adsorption in the range of 2–20%. Wei and Lin [21] used reservoir sediment to produce LWAs with an apparent particle density of 2.08 and 1.18 g/cm^3 at 1050 °C and 1150 °C, respectively, and investigated the role of Fe compound in bloating behavior. They concluded that the reduction of Fe_2O_3, releasing O_2 gas, did not occur in the heating process. Recently, Chen et al. [22] has used a commercial rotary kiln to produce lightweight aggregate from reservoir sediment with a relative density ranging from 1.01 g/cm^3 to 1.38 g/cm^3. These LWAs meet the requirements of ASTM C330 [23] with bulk density less than 880 kg/m^3 for light coarse aggregate, and were verified as qualified LWA for structural concrete.

LWAs can be applied to high-rise buildings due to their highly porous structure, which gives them properties of acoustic and thermal insulation. The formation of porous structures was studied by Riley [24], who found two causes: raw materials contain chemical compositions which can form a glassy phase during the heating

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process, and gas is generated as the glassy phase forms. When the glassy phase wraps the gas, bloating occurs, causing a porous structure to form. The glassy phase is mainly formed by flux oxides reacting with alumino-silicate compounds at high temperature. Calcium oxide, a kind of flux oxide, was found to decrease water adsorption of LWAs in a previous study [25]. Since water adsorption of LWAs affects the setting time and hydration reaction of concrete [26], LWAs with low water adsorption are commonly used for concrete production.

Another common flux ion is sodium; however, few studies have discussed the effect of the addition of sodium ions for the manufacture of LWAs. NaOH can be easily obtained as a source of sodium ions and used in an activated solution for geopolymerization. Geopolymers are an environmentally friendly concrete due to the low CO_2 emission during their production process [27,28]. Geopolymers, which have high strength, fire resistance, and chemical stability [29–31], are formed by the condensation reaction between $Si(OH)_4$ and $Al(OH)_4^-$ after thermal curing. The curing temperature determines the strength development of geopolymers because temperature affects the condensation rate in the geopolymerization reaction [32]. NaOH has a high alkalinity and is mostly used in an activated solution to dissolve silica and alumina to $Si(OH)_4$ and $Al(OH)_4^-$, respectively.

In the present study, NaOH solution was used as the source of sodium ions to react with alumino-silicate compounds in sediment to form a glassy phase to reduce water adsorption. In order to observe how the state of raw materials affects the physical properties of LWAs, various concentrations of NaOH were mixed with wet and dry sediment, respectively. The weight percentages of NaOH were controlled to be the same for wet and dry sediment. These mixtures were then calcined into LWAs. The effects of NaOH addition on the physical properties of bulk density, water adsorption, and compressive strength, and the geopolymerization are discussed.

2. Materials and methods

The water reservoir sediment was obtained from Shihmen Reservoir in Taiwan. The sediment had a D50 particle size of 8.49 μm, a water content of 30%, and an ignition loss of 5.57%. The sediment was dried at 120 °C and then milled to pass a 100-mesh sieve. The chemical composition of the raw sediment was determined using an X-ray fluorescence spectrometer (XRF, Rigaku) and the mineral phases were measured by X-ray diffraction (XRD, Siemens D5000). NaOH pellets were obtained from Merck and dissolved to make solutions with various concentrations.

In this study, wet mud and dry powders of sediment were used and respectively mixed with various concentrations of NaOH solution. In order to control NaOH addition at 7.6 wt%, 6.8 wt%, and 6 wt% in the wet and dry sediment, 26 M, 23 M, and 20 M NaOH solutions were added into the wet sediment with a solid–liquid ratio of 18: 1 and 9.25 M, 8.2 M, and 7.2 M NaOH solutions were added into the dry sediment with a solid–liquid ratio of 18:4. The mixtures were manually palletized into 10–20 mm spheres and dried at room temperature. The samples were denoted by the state of sediment and their NaOH concentrations as WN26, WN23, WN20, DN9.52, DN8.2, and DN7.2, respectively. Table 1 shows the definition of these sample codes. In order to observe the geopolymerization reaction, all samples were cured at 120 °C for 1 h. The samples were denoted as WCN26, WCN23, WCN20, DCN9.52, DCN8.2, and DCN7.2. After curing, these samples were stored at room temperature without any controlled condition.

The spheres were put into a laboratory-scale furnace and calcined for 30 min at a heating rate of 15 °C/min at 1085 °C, 1100 °C, 1115 °C, 1130 °C, and 1145 °C, respectively. When the air inside the furnace cooled to room temperature, the calcined LWAs were characterized using the following procedures. The calcined LWAs were crushed and milled into powders to measure their mineral phases by XRD. After the LWAs were placed in boiling water for 24 h, the Archimedes method was employed to measure the bulk density and water adsorption. The bulk density and water adsorption were calculated as follows [33]:

$$\text{Bulk density} = W_D/(W_S - W_I)$$

$$\text{Water adsorption } (\%) = 100(W_S - W_D)/W_D$$

where W_D is the dry weight of the calcined LWA, W_S is the 24-h saturated surface-dry weight, and W_I is the immersed weight in water. The compressive strength was measured using a material test system (MTS) with a cross-head speed of 0.1 mm/s. The compressive strength of the calcined LWAs was calculated using [34,35]:

$$\text{Compressive strength} = 2.8P_c/\pi X^2$$

where P_c is the fracture load and X is the diameter of the LWAs. The physical properties of LWAs in this study were compared to those of commercial LWA, Leca Strutturale [7] and CA-800 [19], which have been applied to the production of structural concrete. Finally, an optical microscope was used to observe the appearance and microstructure of samples WN23 and DN8.2.

3. Results and discussion

Table 2 shows the chemical compositions of Shihmen Reservoir sediment. The sediment is mainly SiO_2 (61.4%), followed by Al_2O_3 (22.5%), and Fe_2O_3 (8.6%). The total amount of flux was 15.9%. The mineral phases of the raw sediment are shown in Fig. 1. The sediment included quartz (SiO_2), albite ($NaAlSi_3O_8$), clinochlore ($(Mg, Fe)_6(Si, Al)_4O_{10}(OH)_8$), and muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$). Although no ferrite compound was detected, the amount of Fe_2O_3 was 8.6% due to Fe^{2+} ions replacing the sites of Mg^{2+} ions in the clinochlore structure. In a previous study [25], this raw sediment was manufactured into LWAs with a water adsorption of larger than 9.14%.

The relationship between the bulk density and water adsorption at various calcining temperatures is shown in Fig. 2. All bulk densities of LWAs of each series slightly decreased with increasing calcining temperature and were in the range of 1.0–1.6 g/cm^3, which meets European Union regulation, UNIEN 13055-1, which states that LWAs should have a unit weight of particles of lower than 2000 kg/m^3. The bulk densities of LWAs made from the dry sediment, DN-series (Fig. 2c) and DCN-series (Fig. 2d), were slightly lower than those of LWAs made from the wet sediment, WN-series (Fig. 2a) and WCN-series (Fig. 2b). The bulk densities of samples DN9.25, DN8.2, and DN7.2 were as low as 1.0 g/cm^3. Dry sediment thus seems to be better for producing LWAs. These results also show that a higher concentration of NaOH solution

Table 1
Definitions of sample code.

Sample code	Sediment state	Curing condition	Concentration of NaOH (M)
WN26	Wet	–	26
WN23	Wet	–	23
WN20	Wet	–	20
DN9.52	Dry	–	9.52
DN8.2	Dry	–	8.2
DN7.2	Dry	–	7.2
WCN26	Wet	Cured	26
WCN23	Wet	Cured	23
WCN20	Wet	Cured	20
DCN9.52	Dry	Cured	9.52
DCN8.2	Dry	Cured	8.2
DCN7.2	Dry	Cured	7.2