Producing synthetic lightweight aggregates from reservoir sediments

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ABSTRACT

This paper proposes a procedure to produce lightweight aggregate (LWA) made of fine sediments, which were dredged from the Shihmen Reservoir in the northern Taiwan. The synthetic aggregates were manufactured in a newly developed rotary kiln. Physical and mechanical properties of the synthesized aggregates were subsequently assessed. In addition, engineering properties of the concrete made of the produced aggregates were experimentally measured. The test results show that the sediments containing all necessary materials are expansive as passing through the heated zone in the commercial rotary kiln. The produced aggregates possessed a hard ceramic shell, and a porous core, and a relative density ranging from 1.01 g/cm³ to 1.38 g/cm³, which is significantly lower than normal density of aggregates. The produced aggregates also meet the requirements of ASTM C330 with bulk density less than 880 kg/m³ for light coarse aggregate, and were verified as qualified LWA for structural concrete. Further, the engineering properties of the concrete made from the produced aggregates comply with the requirements of structural lightweight concrete.

1. Introduction

Based on specific gravity or density measured in bulk, aggregate is divided into three types: light-, normal-, and heavy-weight aggregates [1]. Among them, lightweight aggregates (LWA) are used as ingredients in the manufacture of lightweight aggregate concrete for structural use.

LWA can be used in the production of concretes or as raw materials for the manufacture of concretes and concrete bricks. Compared to the dense aggregates, such as sand, gravel and ground rock, LWA is lighter and more porous [1,2]. The unit weight of LWA is about 2/3 or 1/3 of the dense aggregates that decreases the bulk density and increases the convenience of work and transport. Besides LWA may be found in a multitude of applications, such as asphalt pavement, geotechnical fills, horticulture, cement wallboard, roofing tiles, refractory products, and filter media [3,4].

Generally, there are two types of lightweight aggregates (LWA), i.e. natural LWA and synthetic LWA. Natural LWA consists of particles derived from natural rocks, such as pumice, scoria, and tuff. Synthetic LWA is usually produced by expanding raw materials such as shale, clay, and slate under heating surroundings. Thermal expansion of the material is the most significant process in the production of LWA. Two characteristic of the raw material is necessary during forming LWA [5], such as gas formation while being heated to the point of incipient fusion and liquid glass formation on heating the material of such a viscosity as to entrap the gases formed. Many researchers developed advanced theories of the phenomenon of bloating [5–7]. A landmark study was made by Riley who plotted the chemical compositions of a large number of clays on a triaxial diagram (Fig. 1) and found a limited area within bloating clays fell [5].

Synthetic LWA is formed by rapid heating at high temperature of materials which is able to bloom. Two requirements have to be met to be a suitable expanded material [5,8–10]:

(1) containing substances that develop gases at high temperature,
(2) producing a highly viscous liquid phase at the temperature that could entrap the gases.

To examine its highly viscous liquid phase at the temperature, the materials should be experimented on chemical properties that can be illustrated on Riley's Ternary diagram of bloating materials [5]. The gases causing expansion come from the thermally instable materials, such as [11–13]

(1) water vapor from the volatilization of interlayer water molecules or crystallization water of clay minerals or other silicates, 
(2) CO and CO₂ from the combustion of organic matter,  
(3) CO₂ from the dissociation of carbonates,  
(4) O₂ and CO₂ formed from the reduction of ferric iron,  
(5) SO₄ from sulfide oxidation,  
(6) F and Cl from clay minerals,
up about 76,000,000 m³ at an increasing rate of 1430,000 m³/yr that causes a significant impact on the reservoir’s multiple functions and the ecological environment around. To remain the regular utility of the reservoir, these sediments have to be removed periodically that potentially provide a sufficient source of producing synthetic LWA. At first, the physical, mineralogical, and chemical characteristics of the sticky mud were analyzed and reported below.

2.1. Physical characteristic

Table 1 presents the results of physical tests of the sediments. The sample has a specific gravity of 2.74. The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the sample are 40.4%, 25.6%, and 14.8%, respectively. According to the Unified Soil Classification System, the sediments are classified as inorganic clays of low to medium plasticity (i.e. CL).

2.2. Mineralogical characteristic

The X-ray diffractogram of the sediments indicates that quartz peaks are dominant and remarkably visible, followed by chlorite, feldspar and illite peaks (Fig. 2). Thermo gravimetric analysis (TGA) and differential thermal analysis (DTA) curves of the fine sediments are shown in Fig. 3. The TGA curve is characterized by a strong endothermic peak at 74 °C attributed to physically adsorbed water and another endothermic peak at 536 °C corresponding to the evaporation of the crystal water in the chlorite and illite mineral, which is followed by an exothermic peak at 762 °C attributed to mullite formation. Further, the feldspar liquefied at 1000 °C and another endothermic reaction at a relatively high temperature ranging from 1100 to 1200 °C. On the other hand, the DTA curve indicates that the weight loss on ignition increased with temperature. During a temperature change from 50 °C to 750 °C, weight loss was up to 7% due to the evaporation

### Table 1

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Gravels</th>
<th>Sands</th>
<th>Silts</th>
<th>Clays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dₐ₀ (mm)</td>
<td>0.003</td>
<td>CL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil classification</td>
<td>2.74</td>
<td>40.4</td>
<td>25.6</td>
<td>14.8</td>
</tr>
</tbody>
</table>

2. Characteristic analysis of fine sediments from Shihmen Reservoir

Shihmen Reservoir, the third largest reservoir in Taiwan, was constructed in 1956 and had an effective storage up to 309,000,000 m³ originally [29]. Currently, Shihmen Reservoir has silted...
of the physically adsorbed water and the crystal water in the mineral. This implies that the green pellet made from the sediments should be preheated in advance to avoid explosion while being fired in a kiln.

### 2.3. Chemical characteristic

Chemical analysis of the sediment samples is presented in Table 2. The main ingredient is SiO$_2$ (59.31%), followed by Al$_2$O$_3$ (19.97%), and Fe$_2$O$_3$ (6.53%). The presence of CaO and MgO makes sure to liberate CO$_2$ at a temperature which a glassy phase forms. The presence of fluxes (Fe$_2$O$_3$, FeO, CaO, MgO, K$_2$O, and Na$_2$O) would ensure the development of high temperature glassy phases of sufficient viscosity. The analysis results were within the limits of the expandable region on the Riley’s triaxial diagram (see Fig. 1) that assured the fine sediments from the Shihmen Reservoir feasible for generating lightweight aggregates.

### 3. Production of LWA using fine sediments

The flow chart of the manufacturing process for the synthetic LWA from reservoir sediments is described in detail as follows and in Fig. 4.

#### 3.1. Preparation of raw material

The dredged sludge from the bottom layer of the Shihmen Reservoir was deposited and dewatered in a sedimentary deposit tank. Thereafter the sticky sediment with high water content (about 40%) was dehydrated in the sunshine until the desired moisture content (about 20–25%) was achieved. The graining process involves controlling the size and shape of the finished granules. Accordingly, the air-dried sediment was crushed and sieved since it contained a few coarse-grained soils. After being screened into fractions with fairly similar sizes, the raw material was blended

### Table 2

Chemical compositions of the fine sediments.

<table>
<thead>
<tr>
<th>Chemical compositions (wt.%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>Al$_2$O$_3$</td>
<td>Fe$_2$O$_3$</td>
<td>CaO</td>
<td>MgO</td>
<td>K$_2$O</td>
<td>Na$_2$O</td>
</tr>
<tr>
<td>59.31</td>
<td>19.97</td>
<td>6.53</td>
<td>1.41</td>
<td>2.02</td>
<td>0.08</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Note: LOS = Loss on ignition; OS = Organic substance content.*

Fig. 3. TGA and DTA curves of the fine sediments.
with water, and was grained by an extrusion machine and was chopped into cylinder-shaped pellets as raw pellets (see Fig. 4).

3.2. Sintering

The main apparatus used in this research is a rotary kiln with an outer diameter of 2 m and a length of 39 m (see Fig. 5). The kiln is a refractory cylinder with a slight incline (3° in this experiment) rotating about its longitudinal axis. This device has a heat exchanger using heavy oil as a fuel. In addition, it has a rotary cooler with an outer diameter of 1.5 m and a length of 14.3 m to recover the heat contained in the aggregate discharged from the kiln. The heated air from the cooler is re-introduced into the kiln as secondary combustion air, with much more thermally efficient than a traditional one. The bottom of the rotary kiln is heated by a burner. The bottom section of the kiln (about 1/5 of the kiln length and so-called the expansion zone) has a higher temperature to heat the interior of the particles so to liberate gases, which is trapped by glass-formed matrix, and finally to expand the raw pellets.

Subsequently, the formed pellets were transferred by a conveyor belt directly into the kiln. The green pellets were fed into the upper end and the heat was applied at the lower end, so the pellets traveling counter-current to the heat flow. In fact, during the journey through the kiln, a pellet went through a sequential process beginning with drying at temperatures of 100–105 ºC, followed by preheating at temperatures of 500–700 ºC, then expanding at temperatures of 1100–1150 ºC. The pellet was then discharged into a rotary cooler for cool-down by cold air and became lightweight aggregate.

At the last 30-min journey down through the slowly rotating kiln, the pellets are fired at temperatures of approximately 1200 ºC. Meanwhile, the minerals of the raw pellets soften and start melting and releasing gases. Eventually, the reservoir sediment was transformed into various sized lightweight ceramic granules with a hard ceramic shell and a porous core.

Fig. 6 demonstrates SEM (scanning electron microscope) micrographs and shows that the reservoir sediment sintered at 1200 ºC turned into a material containing significant glassy phase with isolated and irregularly pores.

3.3. The effect of operation conditions on LWA product properties

The relationship between the Particle density of LWA and operation conditions, such as the temperature and soaking time during preheating and sintering processes, was observed during the following laboratory process:

1. Dewatering sediment in an oven and powdering it by a ball-mill,
2. Generating a volume of green pellets with 0.54 g/cm³ through dry pressing, and
3. Putting green pellets in alumina basement into an oven to produce LWA.

To reveal the effect of operation conditions on LWA product properties, several conditions were set as: (1) the preheating temperature of 500 ºC with two soaking times of 7.5 min and 15 min and (2) the sintering temperatures of 1175 ºC and 1200 ºC at three soaking times of 4, 8, and 12 min. The experimental results were listed in Table 3. At both sintering temperatures of 1200 ºC shown in Fig. 7 (sample no. 1–6) and 1175 ºC shown in Fig. 8 (sample no. 7–12), the particle density of LWA produced by the preheating

<table>
<thead>
<tr>
<th>No.</th>
<th>Preheating condition</th>
<th>Sintering condition</th>
<th>Particle density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature (ºC)</td>
<td>Soaking time (min)</td>
<td>Temperature (ºC)</td>
</tr>
<tr>
<td>1</td>
<td>500</td>
<td>7.5</td>
<td>1200</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7.5</td>
<td>1175</td>
<td></td>
</tr>
<tr>
<td>8</td>
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<tr>
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<tr>
<td>11</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6. SEM micrographs of sintered sediment LWA.
soaking time of 7.5 min is lower than one by 15 min. The shorter the preheating soaking time is, the smaller the particle density of LWA is. Under the same condition of preheating soaking time and sintering temperature, the sintering soaking time has an inverse relationship with the particle density as shown in Figs. 7 and 8. No matter how long the preheating soaking time is (7.5 min or 15 min), the particle density of LWA produced at the temperature of 1200 °C is smaller than one produced at 1175 °C as shown in Figs. 9 and 10.

Overall, a short preheating soaking time and a high sintering temperature result in a low particle density of LWA. Also, a long sintering soaking time decrease the particle density of LWA. In a practical application, through controlling the rotating rate of rotary kiln the particle density of LWA can be adjusted. To produce a low particle density of LWA, a high rotating rate of rotary kiln during preheating and a low rotating rate and a high temperature of rotary kiln during sintering are necessary.

4. Properties of LWA from reservoir sediments

The properties of the sintered sediment LWA made from reservoir sediments significantly depends on the operating conditions set by temperature profiles within the kiln and the residence time of the feed material. A variety of products were manufactured by establishing and regulating the relationships between the ratio of the time scale of heat diffusion relative to the time of material traverse and the ratio of the time scales of material diffusion to the rate of particle expansion. That is to say, the weight, size and strength of the products can be controlled exactly. In this research, three types of LWA manufactured through processes with different heat treatments (such as drying, preheating, firing, and cooling) and a commercially available LWA were tested for comparison.

4.1. Physical properties

All aggregates were tested for relative density and water absorption in accordance with BS 812, ASTM C330, and ASTM C29. The dry loose bulk density, relative density, and water absorption at different times for the produced aggregates (i.e. SA-600, SA-700, and SA-800 made from the reservoir sediments) are compared with CA-800 as Table 4. The aggregates were named after their bulk densities (kg/m³). The relative densities of the produced aggregates ranging from 1.01 g/cm³ to 1.38 g/cm³ are significantly lower than normal density aggregates, and meet the requirements of ASTM C330 with bulk density less than 880 kg/m³ for coarse aggregate. Therefore, the produced aggregates can be used as LWA for structural concrete. On the other hand, Table 4 shows that the water absorption rate at 30 min did not follow the expected trend of high absorption corresponding to low density. By contrast, the water absorption figures at 24 h decreased with the bulk density. Compared with CA-800 aggregate, SA-800 aggregate possesses a relatively low water absorption figure at 24 h.
Table 4 Physical and mechanical properties of LWA.

<table>
<thead>
<tr>
<th>Type of LWA</th>
<th>Aggregate size (mm)</th>
<th>Dry loose bulk density (kg/m²)</th>
<th>Relative density (SSD)</th>
<th>Water absorption (%)</th>
<th>Crushing strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-600 (for LWAC)</td>
<td>9.5–4.75</td>
<td>622</td>
<td>1.00</td>
<td>6.8</td>
<td>10.7</td>
</tr>
<tr>
<td>SA-700</td>
<td>12.5–9.5</td>
<td>713</td>
<td>1.16</td>
<td>6.3</td>
<td>11.1</td>
</tr>
<tr>
<td>SA-800 (for LWAC)</td>
<td>9.5–4.75</td>
<td>859</td>
<td>1.23</td>
<td>9.5</td>
<td>11.3</td>
</tr>
<tr>
<td>CA-800</td>
<td>12.5–9.5</td>
<td>844</td>
<td>1.41</td>
<td>7.1</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Note: SA-600 = The sedimentary LWA; CA-800 = A commercially available LWA made in China; SSD = Saturated surface dry condition.

Table 6 Mix proportions of concrete using sedimentary LWA (kg/m³).

<table>
<thead>
<tr>
<th>Batch no.</th>
<th>W/C</th>
<th>Cement Water 30-min</th>
<th>Water 24-h</th>
<th>Natural fine aggregate</th>
<th>Lightweight coarse aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6-40</td>
<td>0.40</td>
<td>489</td>
<td>207</td>
<td>25</td>
<td>640</td>
</tr>
<tr>
<td>M6-55</td>
<td>0.55</td>
<td>390</td>
<td>207</td>
<td>26</td>
<td>673</td>
</tr>
<tr>
<td>M6-70</td>
<td>0.70</td>
<td>300</td>
<td>207</td>
<td>27</td>
<td>702</td>
</tr>
<tr>
<td>M8-40</td>
<td>0.40</td>
<td>489</td>
<td>207</td>
<td>38</td>
<td>640</td>
</tr>
<tr>
<td>M8-55</td>
<td>0.55</td>
<td>390</td>
<td>207</td>
<td>40</td>
<td>673</td>
</tr>
<tr>
<td>M8-70</td>
<td>0.70</td>
<td>300</td>
<td>207</td>
<td>41</td>
<td>702</td>
</tr>
</tbody>
</table>

Note: W/C = Water-to-cement ratio; Water 30-min = Water in quantity equal to half an hour’s aggregate absorption.

4.2. Mechanical properties

All aggregates were tested for crushing strength in accordance with GB2842-81 (GB/T2842-81, China National Standard Test method for lightweight aggregates). Oven-dried samples of the aggregate were placed in a steel cylinder with an internal diameter of 115 mm and a height of 145 mm. The strength of the samples was then measured under a specific compression when a steel plunger reached a prescribed distance of 20 mm. Table 4 summarizes the crushing strength of SA-600, SA-700, and SA-800 aggregates as 7.2 MPa, 10.0 MPa, and 13.4 MPa, respectively. Among the bulk densities of the aggregates in Table 4, the density of SA-800 aggregate is the highest whereas SA-600 aggregate is the lowest that indicates the aggregate strength increasing with the bulk density. In addition, SA-800 aggregate was found to have better strength than CA-800 aggregate that verifies fine sediment lightweight aggregate able to serve as structural aggregate.

5. Application of sintered LWA in concrete

To reveal the feasibility of manufactured concrete using the produced aggregates, a total of six concrete mixtures were tested as followings.

5.1. Materials

Ingredient of specimens includes cement, fine aggregate, and coarse aggregate. In this experiment, Type I Portland cement and natural river sand were adopted. The physical properties of the river sand are shown in Table 5. The coarse aggregate were composed of two different sizes (i.e. 12.5–9.5 mm and 9.5–4.75 mm). The relative density and water absorption of the lightweight aggregates are listed in Table 4.

5.2. Mixture proportions and fabrication of specimens

The experimental variables include the type of lightweight aggregate and the water/cement ratio. The lightweight aggregate concrete (LWAC) was mixed according to the specifications of ACI 211.2-04. Table 6 lists the mixture proportions of the LWAC, in which the coarse aggregates were composed of two different aggregate sizes (i.e. 12.5–9.5 mm and 9.5–4.75 mm) and mixed together at a 1:1 ratio. River sand was cured in a room until the required saturated surface dry condition was reached, while lightweight aggregates were dried in a 105 °C environment until no further weight loss was observed. The treated aggregates were then stored in a room in which the ambient temperature and relative humidity (RH) were controlled at 25 ± 3 °C and 50 ± 5% to avoid possible moisture changes.

In preparing LWAC mixtures, a careful observation on the amount of water absorbed by the aggregate during mixing and placement was exercised. In the mixing process the pre-assessed amount of water was slowly added to LWA without presoaking. The amount of added water was computed based on the 30-min absorption of same aggregate tested previously.

The mixing started by blending cement, sand, and coarse aggregates for 90–120 s, poured water, and terminated until a uniform mixture for approximately 60–90 s. For each mixture, six cylindrical specimens with an 100 mm diameter and 200 mm height were cast for compressive strength test, and three 100 × 100 × 360 mm prismatic specimens were cast for flexural strength test. Following casting, all specimens were covered with wet burlap and then were removed from the molds 24 h later. All specimens were cured in a saturated calcium hydroxide solution bath at 23 ± 2 °C until being tested.

5.3. Test measurements

The slumps of the concrete mixes were measured according to ASTM C143. As for the hardened properties of the concrete mixes, compressive strength was measured according to ASTM C39 and flexural strength was measured according to ASTM C78. The electrical resistivity of the hardened concrete specimens was measured by Surface Resistivity meter with a Wenner linear four-probe array that consists of four electrodes with an equal distance in between.

5.4. Test results

Table 7 summarizes the fresh properties of the concrete mixes. The initial slumps of the fresh concrete mixes varied between 130 and 230 mm which indicates these concretes with good workability. The fresh concrete had lower fresh densities, which was a function of mixture proportions, air contents, water demand, particle density, and moisture content of the lightweight aggregate, ranging from 1659 to 1745 kg/m³ than normal weight concrete. After exposure to a relative humidity of 50 ± 5% and a temperature of 23 ± 2 °C for 28 days, the densities of the concrete mixes ranged from 1490 to 1566 kg/m³ (see Table 7) with a slight change less than 0.5%. This result complies with the requirement of structural lightweight concrete.

The results of compressive strength are reported in Table 7, in which each value is the average of three concrete cylinders for each mixture at testing age. In general, except for M6-40 mix, a
strength-enhancing effect occurred with a higher aggregate density and a lower W/C ratio (see Fig. 11). In addition, the 7-day strength was 82% of the 28-day strength on average, which is a typical value for LWAC. The 28-day flexural strength of the concrete ranged from 5.3 MPa to 7.2 MPa. Similar to the compressive strength, the flexural strength of the concrete was affected by the aggregate density and W/C ratio of the concrete mix. Fig. 12 indicates that the flexural strength of the concrete increased with the aggregate density, but decreased with the W/C ratio. Moreover, Fig. 13 shows the data pairs of 28-day flexural and compressive strength along with the best-fit curve of exponential function and the corresponding coefficient ($R^2$). This regression equation can predicate the flexural strength of the concrete made from the produced aggregate. Fig. 14 presents the change in the electrical resistivity of the concrete mixes with different W/C ratios. As expected, the resistivity decreased with the W/C ratio. Moreover, with the same W/C ratio, the concrete mix using aggregate with a greater density (i.e. SW-800) possessed higher resistivity so to improve its durability.

### 6. Conclusion

Based on the carried out tests, the following conclusions can be drawn:

1. The reservoir sediments can be used as primary resource materials for lightweight aggregates that can achieve not only technical benefits, but also can result in good social and ecological benefits.

2. The relative densities of the produced aggregates ranged from 1.01 g/cm³ to 1.38 g/cm³, which are significantly lower than the normal density of aggregates, and also meet the requirements of ASTM C330 with bulk density less than 880 kg/m³ for coarse aggregate.
3. The density of the fresh concrete made from the produced aggregate ranged from 1659 to 1745 kg/m³. After exposure to a relative humidity of 50 ± 5% and a temperature of 23 ± 2 °C for 28 days, the densities of the concrete mixes ranged from 1490 to 1566 kg/m³ with a light change less than 0.5% that complies with the requirement of structural lightweight concrete.

4. The engineering properties of the concrete made from the produced aggregate comply with the requirements of structural lightweight concrete. On average, the 7-day strength is 82% of the 28-day strength, which is a typical value for LWAC. The flexural strength of the concrete increased with the aggregate density, but decreased with the W/C ratio.

References