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Production of synthetic lightweight aggregate using reservoir sediments for concrete and masonry

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ABSTRACT

The paper reports the investigation of rotary kiln manufactured lightweight aggregates (LWA) using fine sediment deposits dredged from the Shihmen Reservoir in Taiwan. The physical and mechanical properties of the sedimentary, synthetic LWA were assessed as well as the engineering properties of the lightweight aggregate concrete (LWAC) made from the LWA. The physical properties of the concrete masonry units (CMU) made from the LWA were then measured. The investigation revealed the sediments contain all the necessary elements to enable the bloating and calcining processes within the commercial kiln. When exposed to the high heat of the kiln, the extruded sedimentary material undergoes dramatic changes, developing a hard ceramic shell and a porous core comprised of non-interconnected capillaries. The particle densities of the synthetic LWA produced from the kilning process range from 1010 to 1380 kg/m^3. LWAC designs using the synthetic LWA produce compressive strengths comparable to normal density concretes and were 29%–35% lighter. The test strengths and densities of the LWAC satisfied the requirements of ACI 318 code for structural lightweight concrete. Additionally, sedimentary LWA could be incorporated in automated production facilities to produce high performance CMUs complying with the requirements of the Chinese National Standards (CNS).

1. Introduction

Based on specific gravity or bulk density, aggregates can be divided into three categories: lightweight, normal weight, and heavy-weight [1]. Lightweight coarse aggregates are predominately used in the production of lightweight aggregate concrete (LWAC) for structural concrete applications. Besides the manufacturing of lightweight structural concrete, lightweight aggregates (LWA) may be found in many applications including concrete masonry, asphalt pavement, geotechnical fill, horticultural and soil amendment, concrete wall board, roof tile, refractory products, filter media, and high-performance concrete [2–4].

LWA can be grouped into two distinct types: natural LWA and synthetic LWA. Natural LWA consists of particles derived from natural rocks, primarily those of volcanic origin, including pumice, scoria, and tuff [1]. Synthetic LWA is produced by expanding materials such as shale, clay and slate with high heat, and traditionally is manufactured in a rotary kiln. Thermal expansion of the material is the most significant condition in the production of LWA. There are two necessary requirements for the raw material to form and expand [5]. The first requirement is when the material is heated to the point of incipient fusion, gases must be formed. The second requirement is the glass formed as the material calcines must be of a sufficient viscosity as to entrap the gases as they are formed. Many researchers have advanced theories on the phenomenon of bloating [5–8]. A landmark study by Riley plotted the chemical compositions of a large number of clays on a triaxial diagram (Fig. 1) and found a limited area within which bloating clays fell [5].

The process of manufacturing a synthetic LWA in a rotary kiln was patented by Stephen J. Hayde in 1908. The resulting rotary kiln and sintering technologies represented tremendous achievements and the LWA industry in the United States and European countries showed steady progress until the 1950s. Afterward the development of LWA in these countries focused on the use of natural deposits and industrial wastes as raw materials to supplement irreplaceable natural resources and to satisfy the growing demand for quality aggregates [9–18]. An unsuitable natural deposit impacts many aspects of the environment. For instance, reservoir sediments reduce the storage capacity and impact the functions designed for reservoirs. As a result, reservoir sediments have become one of the most critical environmental issues facing many countries.

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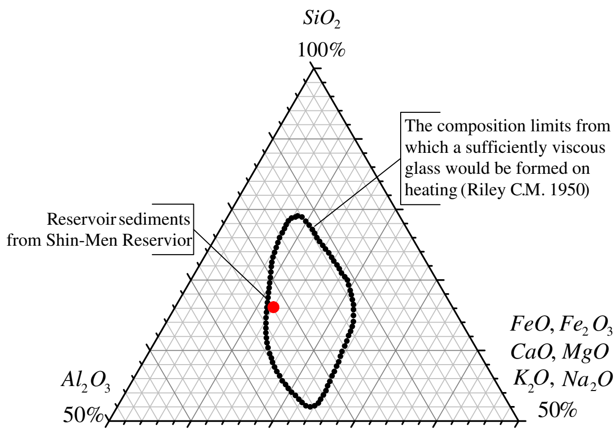


Fig. 1. Composition limits of bloating clays.

Without exception, Taiwan also experiences an undesirable shortage of quality natural aggregates of which most are excavated from riverbeds. Taiwan is an island nation dependent on water reservoirs for drinking water, irrigation, generating electric power, tourism and flood prevention. Currently, there are 69 primary reservoirs in Taiwan, some more than 60 years old. With their advanced age, most reservoirs face significant sediment problems seriously threatening their service life. For instance, Shihmen Reservoir in northern Taiwan is the country's third largest reservoir and was built in 1959. Originally, Shihmen Reservoir had an effective storage capacity approaching 309 million cubic meters [19]. Presently, the total sediment deposit is approximately 69-million cubic meters and is increasing at an estimated rate of 800-thousand cubic meters per year. The accumulating deposits affect the multiple functions of the reservoir and disposal severely impacts the surrounding ecological environment. In order to maintain the serviceability of the reservoir, the sediments have to be removed periodically. Historically, most of the sediments removed from the reservoir are disposed of in landfills, but suitable sites are becoming increasingly difficult to find. As landfill opportunities are disappearing, it has become an urgent task to research and find beneficial uses for the fine sediments.

This article explains how fine reservoir silt is being sintered into LWA suitable for structural and non-structural concrete applications. The overall process involves dredging of the reservoir sediment, followed by its hauling, air-drying, crushing, sieving, graining, and sintering. Properties of the manufactured aggregates are tested and compared with commercially available LWA. Additionally, the engineering properties of the LWAC and concrete masonry units (CMU) made from the sedimentary LWA are tested and examined.

2. Experimental work

2.1. Materials

Fine sediments dredged from the Shihmen Reservoir were used as the raw material for producing the synthetic lightweight aggregate. Table 1 shows the test results defining the physical properties of the sediments. The sample has a specific gravity of 2.74 and with D_{50} of 0.003 mm (i.e. more than 50% of the sample having a size greater than 0.003 mm). The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the sample is 40.4%, 25.6%, and 14.8%, respectively. According to the Unified Soil Classification System, the sediments are inorganic clays of low to medium plasticity (i.e. CL). In accordance with the present environmental laws in Taiwan [20], a toxicity characteristic leaching procedure (TCLP) standard was conducted to insure the sediments did not contain hazardous materials such as heavy metals that might be a concern when forming new products. In this study, leaching of five selected heavy metals (Zn, Pb, Cu, Cd and Cr) was investigated. In Table 2, the TCLP results in comparison with the limits for each regulated element show the sedimentary material complies with the Taiwan Environmental Regulatory requirements.

To study the feasibility of manufacturing LWAC and CMU using the synthetic sedimentary LWA, a total of six LWAC mixtures and 12 CMU mixtures were tested. Materials used for making specimens include cement, fine and coarse aggregates, and granulated blast furnace slag (only for CMU). The cement used was Type I Portland cement with a specific gravity of 3.15 and a specific surface of 344 m^2/kg. The fine aggregate used was natural river sand with its physical properties shown in Table 3. The coarse aggregate used in the study were synthetic LWA manufactured from the reservoir sediments. SA-600 and SA-800a were used in LWAC designs while SA-800b was used in the manufacturing of the CMU. The particle density and water absorption of the LWA used in the designs are listed in Table 4 and their details will be discussed later. Slag with a specific gravity of 2.86 and a specific surface of 386 m^2/kg was available locally from Chung Lien Factory.

2.2. Testing program of LWAC made from produced LWA

The LWAC was mixed in accordance with ACI 211.2-04 [21], and the experimental variables included LWA type and water/cement ratio. Table 5 gives the mix proportions for the LWAC, in which the coarse aggregates were composed of two sizes (i.e. 12.5–9.5 and 9.5–4.75 mm) and mixed together in a 1:1 ratio. Natural sand was cured in a room until the required saturated surface dry condition was reached, while LWA were dried in a 105 °C environment

Table 2
TCLP result of dredged silt.

Sample code	Heavy metals (mg/L)					Note
	Zn	Pb	Cu	Cd	Cr	
1	1.08	N.D.	0.08	N.D.	N.D.	Raw materials
2	1.38	N.D.	0.02	N.D.	N.D.	
3	0.95	0.06	0.01	N.D.	N.D.	
4	1.45	0.07	0.04	N.D.	N.D.	
5	0.91	0.09	0.02	N.D.	N.D.	
EPA regulation NIEA R201.13C	–	<5	<15	<1	<5	The standard for hazardous industrial wastes, EPA, Taiwan

Note: N.D. = non-detected.

Table 1
Physical test results of the fine sediments.

D_{50}[a] (mm)	Soil classification	Ingredients (%)				Specific gravity	LL (%)	PL (%)	PI (%)
		Gravels	Sands	Silts	Clays				
0.003	CL	0	1.4	38.5	60.1	2.74	40.4	25.6	14.8

[a] More than 50% of the sample having a size greater than 0.003 mm.

Table 3
Physical properties of natural fine aggregate.

Type of fine aggregate	Specific density (SSD[a])	Water absorption (SSD) (%)	F.M[b]
FA-1 (for LWAC)	2.64	0.60	2.67
FA-2 (for CMU)	2.61	1.13	2.05

[a] Saturated surface dry condition.
[b] Fineness modulus.

Table 4
Physical properties of sedimentary LWA used in LWAC and CMU.

Type of LWA	Aggregate size (mm)	Particle density (kg/m^3)	Water absorption (%)	
			30-min	24-h
SA-600 (for LWAC)	9.5–4.75	1000	6.8	10.7
	12.5–9.5	1010	5.5	12.3
SA-800a (for LWAC)	9.5–4.75	1230	9.5	11.3
	12.5–9.5	1380	6.6	10.4
SA-800b (for CMU)	7.0	1430	–	10.9

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 moisture changes.

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

The mixing procedure starts by blending cement, sand and coarse aggregates for 90–120 s and is followed by the slow and steady addition of water. The mixing process continues until a uniform mixture is reached, and continues for an additional 60–90 s. From each mix, six 100 mm diameter × 200 mm height cylindrical specimens were cast for compressive strength testing, and three 100 × 100 × 360 mm prismatic specimens were cast for flexural strength testing. Following casting, all the specimens were covered with wet burlap and removed from the molds 24 h after casting. All specimens were cured in a saturated calcium hydroxide solution bath at 23 ± 2 °C until the time of testing.

The slumps of the concrete mixes were measured according to ASTM C 143 [22]. As for the hardened properties of the concrete mixes; the compressive strength was measured according to ASTM C 39 [23], and the flexural strength was measured according to ASTM C 78 [24]. The electrical resistivity of the hardened concrete specimens were measured by a Surface Resistivity meter using a Wenner linear four-probe array consisting of four equally spaced electrodes connected to alternating current, and the inner electrodes connected to a voltmeter.

2.3. Testing program of CMU made from produced LWA

According to the relationship between the particle relative density and the bulk density of an aggregate sample, the fractional part of bulk volume occupied by aggregate particles, V_a, and the fractional part of bulk volume occupied by voids between particles, V_v, can be calculated as follows [2]:

$$PD_d = \frac{PD_{24}}{1+M} \tag{1}$$

$$V_a = \frac{D_b}{PD_d} \tag{2}$$

$$V_v = 1 - V_a \tag{3}$$

where PD_d = dry particle density; PD_{24} = particle density after 24-h saturation; M = 24-h water absorption by mass; D_b = measured dry loose bulk density.

Theoretically, the cement content only needs to provide enough cement paste to coat all of the lightweight coarse aggregate particles. To ensure the manufactured CMU have adequate strength, an excess amount of cement paste should be provided to fill the voids between particles. To reduce production cost, slag was used as a partial replacement for Portland cement by mass and a small amount of fine aggregate was incorporated into the matrix of the cement paste. A total of twelve mixtures were proportioned (Table 6). The main test variables and their ranges are listed as follows:

- Filling ratio of the mortar in V_v (F_v): 1.0, 0.85, and 0.70;
- Filling ratio of sand in the mortar (F_m): 0%, 15%, and 30%; and
- Cement replacement level by the slag (S_c): 0%, 15%, and 30%.

In order to reduce the production cost for manufacturing lightweight CMU, a commercially available apparatus with a minimum modification was used in the research. Raw materials were delivered to silos and bins and the various aggregates separated. Natural fine aggregates were prepared in a saturated surface dry condition before use, while lightweight aggregates were dried at 105 °C to a constant weight. Cement, slag, and aggregates were weighed automatically to predetermined quantities. If the raw materials changed in grading or moisture content, the mixture proportions were adjusted to compensate. In mixing, the cement, slag, sand and coarse aggregates were blended first followed by added water. Mixing continued until a uniform concrete was obtained.

From the mixer, concrete of correct proportions and workability was transported to a fully automatic, high-speed, block making machine. The concrete mixture was deposited and distributed in the mold and vibrated. The blocks were compacted on flat pallets composed of heavy steel plates designed to act as the mold bottom. Before each new cycle of the machine, a fresh machine pallet was placed under the mold. The blocks were then extruded downwards from the mold and remained on the pallet. The dimensions (width, height and length) of the blocks produced were 300 × 120 ×

Table 5
Mix proportions of LWAC.

Mix no.	W/C[a]	Cement (kg/m^3)	Water (kg/m^3)	Water 30-min[b] (kg/m^3)	FA (kg/m^3)	LWA (kg/m^3)	
						12.5–9.5 mm	9.5–4.75 mm
L600-40	0.40	489	207	25	640	154	223
L600-55	0.55	390	207	26	673	162	234
L600-75	0.70	300	207	27	702	170	245
L800-40	0.40	489	207	38	640	174	251
L800-55	0.55	390	207	40	673	183	263
L800-75	0.70	300	207	41	702	190	275

[a] Water-to-cement ratio.
[b] Water in quantity equal to half an hour's aggregate absorption; FA = natural fine aggregate.

Table 6
Mix proportions of CMU.

Mix no.	W/CM	F_v	S_c (%)	F_m (%)	V_a (m^3/m^3)	LWA (kg/m^3)	Cement (kg/m^3)	Slag (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)
CMU1	0.30	1.0	15	15	0.6604	878	473	84	158	167
CMU2	0.30	0.85	15	15	0.6517	878	402	71	135	142
CMU3	0.30	0.70	15	15	0.6427	878	331	59	111	117
CMU4	0.30	1.0	15	30	0.7200	878	390	69	317	138
CMU5	0.30	0.85	15	30	0.7020	878	331	59	269	117
CMU6	0.30	0.70	15	30	0.6844	878	273	48	222	96
CMU7	0.30	1.0	30	15	0.6604	878	390	167	158	167
CMU8	0.30	0.85	30	15	0.6517	878	331	142	135	142
CMU9	0.30	0.70	30	15	0.6427	878	273	117	111	117
CMU10	0.30	1.0	30	30	0.7200	878	321	138	317	138
CMU11	0.30	0.85	30	30	0.7020	878	273	117	269	117
CMU12	0.30	0.70	30	30	0.6844	878	225	96	222	96

Notes: W/CM = water-to-cementitious ratio; F_v = filling ratio of mortar; S_c = cement replacement level by slag; F_m = filling ratio of sand in mortar; V_a = aggregate content in the volume; LWA = lightweight coarse aggregate; FA = fine aggregate (sand).

300 mm. The newly made concrete blocks on the pallets were automatically transported to curing chambers.

After curing, the unit weight, compressive strength, and water absorption of the CMUs were measured in accordance with the regulations of CNS 7332 and CNS 8905 [25,26]. The water absorption of an individual unit is calculated as follow:

$$W_a = \frac{M_2 - M_3}{M_2 - M_1} \times D_w \tag{4}$$

where W_a = water absorption (g/cm^3); M_1 = mass of specimen in water after submerging for 24 h; M_2 = mass of specimen in saturated surface dry condition; M_3 = mass of specimen after drying in an electric furnace to a constant mass; and D_w = density of water.

3. Results and discussion

3.1. Characteristic of reservoir sediments

The appearance of the fine sediments gathered from the Shihmen Reservoir is shown in Fig. 2. The characterization of the sticky, fine sediments were analyzed and are shown below.

The X-ray diffractogram of the sediments indicates quartz peaks are dominantly and remarkably visible, followed by chlorite, illite and feldspar peaks (Fig. 3). These are the predominant minerals present.

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) curves of the fine sediments are shown in Fig. 4. The DTA 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. This is followed by an exothermic peak at 762 °C attributed to chlorite formation. Further, the feldspar liquefied at 1000 °C and another endothermic reaction at a relatively higher temperature around the 1100–1200 °C range. On the other hand, the TGA curve indicates the weight loss on ignition increased with increasing temperature. Once temperatures exceed 750 °C, the curve became horizontal. During the temperature change from 50 °C to 750 °C, a weight loss up to 7% was observed due to evaporation of the physically adsorbed water and the crystal water in the mineral. This implies the green pellet made from the sediments should be preheated in advance to avoid an explosion when fired in a kiln.

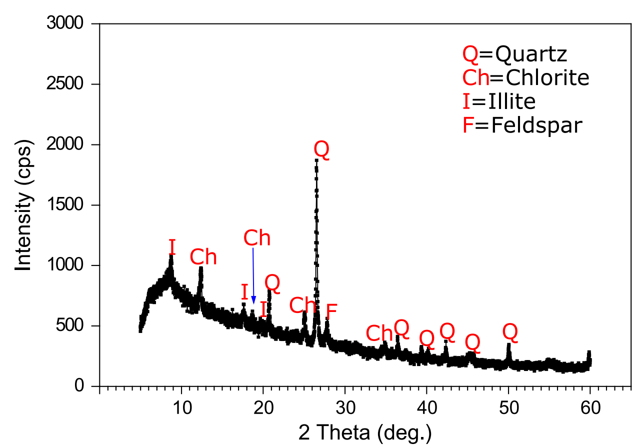


Fig. 3. X-ray diffraction pattern of the fine sediments.

Fig. 2. Appearance of the fine sediments gathered from the Shihmen Reservoir.

Chemical analysis of a representative sample of the sediments is presented in Table 7. The main ingredient is SiO_2 (59.31%), followed by Al_2O_3 (19.97%), Fe_2O_3 (6.53%), and other appreciable ingredients. Al_2O_3 content of the sample under investigation indicates it is clay of an acceptable quality (the approximate limit being 17%). The presence of CaO and MgO in the sample indicates it consists of materials that will liberate CO_2 at a temperature at which a vitreous phase forms. The presence of the fluxes Fe_2O_3, CaO, MgO, K_2O, and Na_2O in the sample would ensure the development of high temperature vitreous phases of sufficient viscosity. The analysis results were in the limits of the expandable region of the triaxial diagram produced by Riley (see Fig. 1), and the essential factors for bloating and expansion under high sintering temperatures were satisfied. Based on these observations and analysis, the fine sediments gathered from the bottom of the Shihmen Reservoir are feasible for sintering lightweight aggregates.

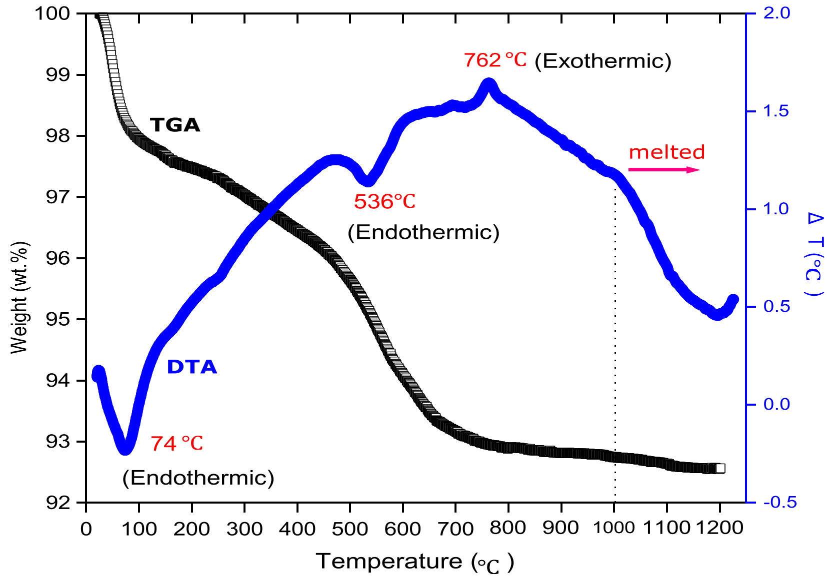


Fig. 4. TGA and DTA curves of the fine sediments.

Table 7
Chemical composition of the fine sediments.

Chemical compositions (wt.%)										
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI[a]	OS[b]	Total
59.31	19.97	6.53	1.41	2.02	0.08	0.01	0.07	7.70	2.90	99.97

[a] Loss on ignition.
[b] Organic substance content.

3.2. Production of LWA using reservoir sediments

The manufacturing processes for the synthetic LWA from reservoir sediments are described in detail below.

In the research, dredging was adopted in dealing with the reservoir sedimentation problem. The dredged material from the bottom of the Shihmen Reservoir was first deposited and dewatered in a sedimentary deposit tank. Then, the sticky sediment containing a high water content of approximately 40% was dried in the open air and sunshine until the desired moisture content of 20–25% was achieved. Next came the graining process, which controls the size and shape of the finished granules. The air-dried sediment was then crushed and sieved to accommodate a small amount of coarse-grained soils. After being screened into closely sized fractions, the raw material was blended with water to enable the mixture to be extruded and pelletized. The mixture was grained by an extrusion machine and chopped into cylinder-shaped pellets.

The main apparatus used in this research is a rotary kiln having an outer diameter of 2 m and a length of 39 m. The kiln is slightly inclined horizontal refractory-line cylinder rotating about its longitudinal axis. The device consists of a heat exchanger and uses heavy oil for fuel. In addition, it is equipped with a rotary cooler having an outer diameter of 1.5 m and a length of 14.3 m. The rotary cooler is used to recover some of the heat contained in the aggregates as they are discharged from the kiln. The heated air from the rotary cooler is re-introduced into the kiln as a source of secondary combustion air, and is much more thermally efficient than a traditional rotary kiln. The heating rate is gradual for about 2/3 the length of the kiln, then it increases rapidly until the maximum is reached. This is called the expansion zone, where the interior of the particles are heated so the liberated gases will be trapped by the glass formed matrix.

After graining, 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, the pellets traveling counter-current to the heat flow. During the material's journey through the kiln, a pellet undergoes a sequential process beginning with drying at temperatures of 100–105 °C, followed by preheating at temperatures of 500–700 °C, then expansion at temperatures of 1100–1200 °C. The material exiting the kiln is discharged into a rotary cooler where the synthetic lightweight aggregate pellets are cooled with ambient air.

As the pellets make their half-hour long journey through the slowly rotating kiln, they are fired at approximately 1200 °C. At these temperatures, the minerals soften and begin to melt. Meanwhile, reactions to the heat from organics and certain constituents produce internal gases generated naturally in the raw material, ultimately creating non-interconnected cells or bubbles in the vitrified material (Fig. 5). The process transforms the extruded reservoir sediment pellets into various sized lightweight ceramic granules which have a hard ceramic shell and a porous core. Fig. 6 demonstrates SEM micrographs of the reservoir sediment sintered at 1200 °C. It can be clearly observed that sintering at 1200 °C produced a significant vitreous phase which resulted in porous synthetic aggregates containing isolated, irregular pores.

3.3. Properties of produced LWA

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 heat exposure for the material. A variety of products were manufactured by establishing and regulating the relationships between the time scale of heat diffusion relative to that of material traverse,

Fig. 5. Appearance of sintered sedimentary LWA.

and the ratio of the time scales of material diffusion to the rate of particle expansion. By careful control of the variables, the weight, size and strength of the products can be controlled exactly. In the research, three types of LWA were manufactured by using different heat treatment processes such as drying, preheating, firing, and cooling. The three grades of synthetic LWA produced by controlling the variables were tested for comparison with a commercially available LWA.

All aggregates produced were tested in accordance with ASTM C 330 [27] and ASTM C 29 [28] for particle density and water absorption, respectively. The test results of the dry loose bulk density, particle density, and water absorption for the manufactured aggregates sizes; SA-600, SA-700, and SA-800 made from the reservoir sediments are shown in Table 8 where they are compared with CA-800, a commercially available LWA made in China. The names of the aggregates reflect their dry loose bulk densities (unit: kg/m^3). Table 8 shows the particle densities of the manufactured aggregates ranged from 1010 to 1380 kg/m^3, significantly lower than normal density aggregates. Additionally, the synthetic LWA grades meet the requirements of ASTM C 330 possessing bulk densities of less than 880 kg/m^3 required for coarse aggregate. Found in compliance with these specifications, the manufactured aggregates meet the criteria for LWA used for structural concrete. Table 8 shows the water absorption figures at 30 min did not follow the expected trend of a higher absorption corresponding to a low density. However, the water absorption figures at 24 h slightly decreased with the increasing bulk density. It was also noted; the SA-800 aggregate possessed relatively lower water absorption at 24 h when compared with the CA-800.

All aggregates produced were tested for crushing strength in accordance with GB2842-81 [29]. Oven-dried samples of the aggregates were placed in a steel cylinder with an internal diameter of 115 mm and a height of 145 mm. The strengths of the samples were then measured under compression by a steel plunger to a prescribed distance of 20 mm. The last column of Table 8 summarizes the aggregate crushing strength of the manufactured aggregates. The strengths of the SA-600, SA-700, and SA-800 aggregates were 7.2, 10.0, and 13.4 MPa, respectively. Comparing the bulk densities of the aggregates given in Table 8, the density of the SA-800 aggregate was the highest while the SA-600 aggregate was the lowest. The findings in Table 8 reveal the aggregate strength increases with the increasing bulk density. Additionally, it was found the SA-800 aggregate displays better strength than the CA-800 aggregate. The aggregates strength testing results indicate the fine sediment synthetic lightweight aggregate can serve as a structural aggregate.

Table 8
Physical and mechanical properties of LWA.

Type of LWA	Dry loose bulk density (kg/m^3)	Particle density (kg/m^3)	Water absorption (%)		Crushing strength (MPa)
			30-min	24-h	
SA-600[a]	622	1010	5.5	12.3	7.2
SA-700[b]	713	1160	6.3	11.1	10.0
SA-800[c]	859	1380	6.6	10.4	13.4
CA-800[d]	844	1410	7.1	11.5	7.5

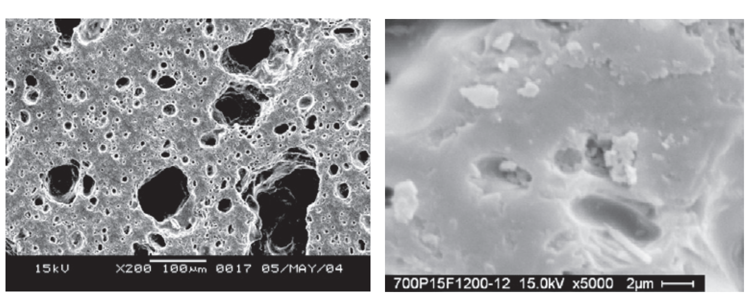
Notes: a, b and c were the sedimentary LWA; d was a commercially available LWA made in China.

3.4. Engineering properties of LWAC made from sedimentary LWA

Table 9 summarizes the fresh properties of the resulting concrete. Initial slumps varied between 130 and 230 mm indicating the concretes possessed good workability. From the mixer, the plastic lightweight concretes displayed lower densities than plastic normal density concrete. The densities ranged from 1659 to 1745 kg/m^3, which were a function of the variables of mixture proportions, air contents, water demand, and LWA particle density. After exposure to an environment with 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/m^3 (see Table 10). The densities of the LWAC changed less than 0.5%, and were approximately 29–35% lighter in comparison to normal density

Table 9
Fresh properties of concrete using sedimentary LWA.

Mix no.	Initial slump (mm)	Unit weight (kg/m^3)
L600-40	130	1685
L600-55	210	1676
L600-75	180	1659
L800-40	200	1745
L800-55	230	1724
L800-75	230	1718



(a) SEM×200 (b) SEM×5000

Fig. 6. SEM micrographs of sintered sedimentary LWA.

Table 10
Engineering properties of concrete using sedimentary LWA.

Mix no.	Compressive strength (MPa)		Flexural strength (MPa)	Density (kg/m^3)	Electrical resistivity (kΩ cm)
	7-day	28-day			
L600-40	27.6	32.0	6.1	1550	10.1
L600-55	21.8	26.2	5.9	1515	9.1
L600-75	15.8	19.8	5.1	1490	7.6
L800-40	30.7	34.7	7.2	1566	10.6
L800-55	22.8	30.4	6.5	1544	10.1
L800-75	16.3	21.3	5.3	1492	7.6

concrete. The results of the plastic and 28-day dry weight properties of the LWAC comply with the requirements for structural lightweight concrete.

The results of compressive strength testing are reported in Table 10, where each value is the average of three concrete cylinders for each mixture proportion at age of testing. In general, there is a strength-enhancing effect with higher aggregate density and lower *W/C* ratio (see Fig. 7). The 28-day compressive strength of the concrete ranged from 19.8 to 34.7 MPa, satisfying the strength requirement of ASTM C 330 and ACI 318 for structural lightweight concrete requiring a minimum 28-day compressive strength of 17 MPa [30]. On average, the 7-day strengths were 82% of the 28-day strengths which is typical for LWAC. The 28-day flexural strength of the concrete ranged from 5.3 to 7.2 MPa. Similar to the findings for compressive strengths, the flexural strengths of the concretes were affected by aggregate density and the *W/C* ratio of the concrete mix. Fig. 8 indicates the flexural strength of the concrete increased with both the increase of aggregate density and the decrease of the *W/C* ratio.

Fig. 9 presents the changes in electrical resistivity of the concrete mixes with varied *W/C* ratios. As anticipated, the resistivity decreased with the increase of the *W/C* ratio, confirming the lower the *W/C* ratio, the higher the electrical resistance. Furthermore for concrete mixes with the same *W/C* ratio, the concrete mix using SW-800 aggregate with a greater density possessed a higher resistivity.

3.5. Engineering properties of CMU made from sedimentary LWA

In accordance with CNS 8905, the overall dimensions of width, height, and length of the lightweight aggregate CMU, as shown in Fig. 10, were within dimensional tolerances of ±2 mm. The results of CMU measurements for various concrete mixtures at 28 days are

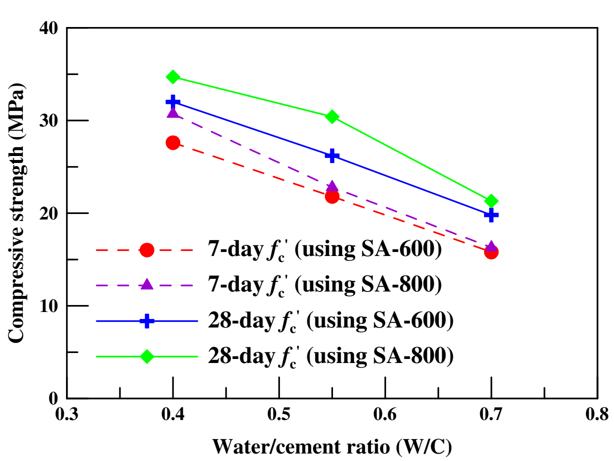


Fig. 7. Influence of aggregate density and water/cement ratio upon compressive strength.

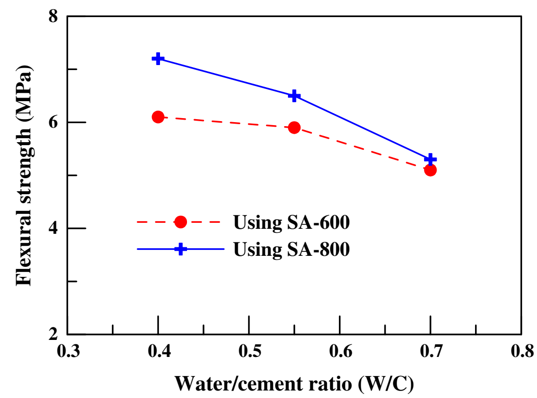


Fig. 8. Influence of aggregate density and water/cement ratio upon flexural strength.

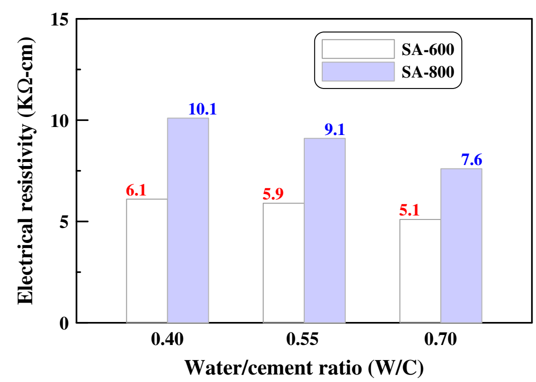


Fig. 9. Influence of aggregate density and water/cement ratio upon electrical resistivity.

Fig. 10. Appearance of manufactured concrete masonry units.

shown in Table 11, where each value is the average of measurements of three units. Influences of test variables upon the properties of the CMU produced are analyzed in the following subsections.

The unit weight (U_w) of CMU ranged from 1585 to 1743 kg/m^3, or 25–30% lower than that for a normal weight CMU at 2300 kg/m^3. Most of the CMU fall into the lightweight category meeting the requirements of CNS 8905 with a bulk density of less than 1680 kg/m^3, while a few CMU with bulk densities of greater than 1680 kg/m^3 fall into the medium weight category. In addition, Fig. 11 shows the influence of V_a upon U_w for CMU with

Table 11
Test results of CMU produced in the study.

Mix no.	U_w (kg/m^3)	σ (MPa)	W_a (g/cm^3)	k (W/m K)
CMU1	1743	15.1	0.05	0.37
CMU2	1660	12.6	0.07	0.34
CMU3	1608	9.1	0.09	0.30
CMU4	1716	13.3	0.06	0.35
CMU5	1679	9.3	0.08	0.33
CMU6	1657	8.5	0.10	0.30
CMU7	1699	14.5	0.06	0.35
CMU8	1687	12.9	0.10	0.34
CMU9	1585	8.4	0.13	0.28
CMU10	1697	13.1	0.06	0.33
CMU11	1641	11.0	0.08	0.31
CMU12	1612	10.3	0.09	0.27

Notes: U_w = unit weight; σ = compressive strength; W_a = water absorption; and k = thermal conductivity.

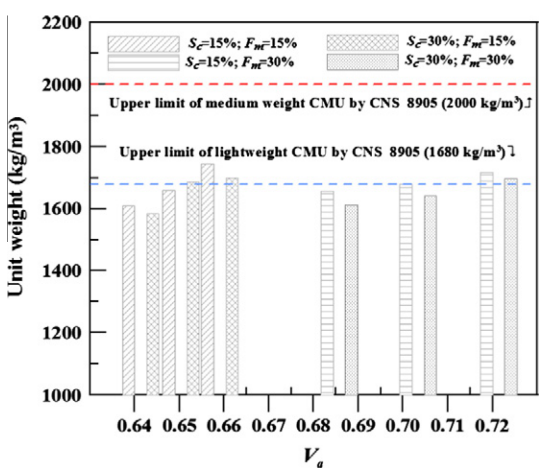


Fig. 11. Influence of V_a upon unit weight of CMU.

W/CM = 0.30. It can be clearly seen the lower the V_a, the lower the U_w. The lower weight of the CMU is primarily associated with more voids between lightweight aggregates in a low V_a mixture.

The compressive strength (σ) of CMU specimens was determined by using a servo-hydraulic material testing system. The compression load was applied onto the face of the specimen having a dimension of 300 × 120 mm^2. The compressive strength of CMU ranged from 8.4 to 15.1 MPa (Table 11), and was sufficient to meet the CNS 8905 minimum compressive strength requirement of 5.88 MPa for CMU with an air-dry bulk density of less than 1900 kg/m^3. The strengths of the CMU for various concrete mixtures are shown in Fig. 12. As expected, the values of σ generally

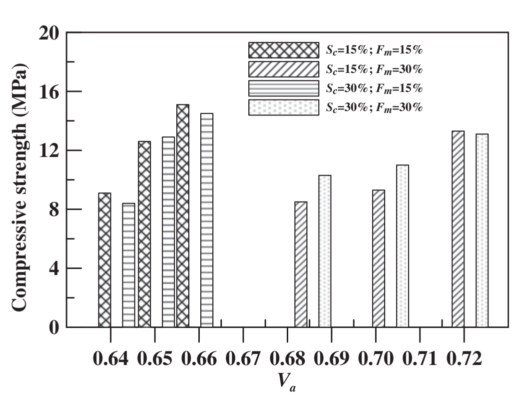


Fig. 12. Influence of V_a upon compressive strength of CMU.

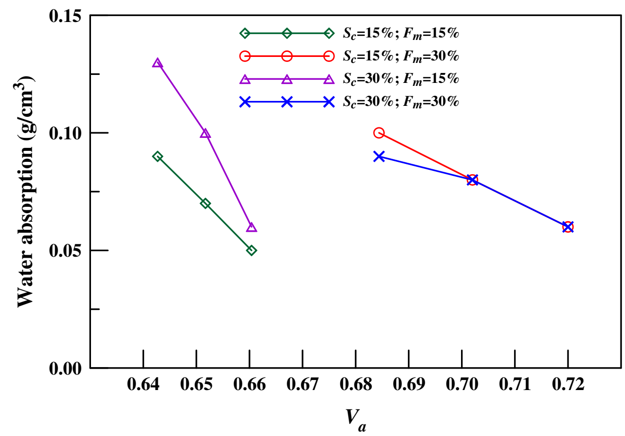


Fig. 13. Influence of V_a upon water absorption of CMU.

increased with increasing V_a. A high V_a mixture indicates a more dense structure which in turn leads to a greater compressive strength of the CMU. It can be observed in Table 11, there was an increasing trend in the data of σ with the increase of U_w.

Along with unit weight and strength, the water absorption of CMU is an important property, which can greatly affect the durability of the unit. Highly absorptive CMU can remove water from the mortar, affecting both the mortar's curing and bond strength. In the investigation, W_a of CMU was found to vary between 0.05 and 0.13 g/cm^3 depending on V_a, F_m, and S_c (Table 11), significantly lower than the 0.45 g/cm^3 maximum limit required by CNS 8905 for CMU with an air-dry bulk density less than 1900 kg/m^3. W_a of CMU specimens for various concrete mixtures is shown in Fig. 13, and generally, the value of W_a decreased with increasing V_a. This is attributed to the decreased porosity in a high V_a mixture, which in turn leads to a lower absorption of the CMU. There was also a decreasing trend in the data of W_a with increasing U_w.

It is well recognized the thermal conductivity of concrete depends on many factors such as aggregate volume fraction and moisture condition of the concrete. In the study, the thermal conductivity of CMU was measured by means of comparison with a standard plate of known conductivity [25]. Test results showed the thermal conductivity of CMU ranged from 0.27 to 0.37 W/m K, significantly lower than 1.16–1.74 W/m K for a normal weight CMU. It can be clearly observed from Table 11 the range of k was 0.27–0.30, 0.31–0.34 and 0.33–0.37 W/m K for specimens with F_v of 0.70, 0.85 and 1.0, respectively. In general, the findings show the lower the F_v, the lower the k. Moreover, the lower k of the CMU is primarily associated with more voids between lightweight aggregates in a low V_a mixture. As shown in Table 11, there was an increasing trend in the data of k with the increase of U_w.

4. Conclusions

In the study, the feasibility of manufacturing LWA by the use of reservoir sediments has been explored. X-ray diffraction and chemical analysis show the characteristic of the fine sediments dredged from the bottom of the Shihmen Reservoir meets the bloating demands for sintering LWA. As a result, the fine sediments can be used as a primary resource material for LWA. Utilizing the source of the material and methods of production achieves not only technical benefits, but also can result in good social and ecological benefits. Furthermore, it could promote the increased use and applications of LWA in Taiwan's building and construction industry. The results of the investigation can serve as a practical reference to the concrete community in other nations in dealing with reservoir sediments. A summary of the general conclusions from the data presented in this paper can be drawn:

(1) The particle densities of the sedimentary LWA range from 1010 to 1380 kg/m^3, significantly lower than normal density aggregates. This can be attributed to the fact the sedimentary LWA particles have a porous core. They also meet the requirements of ASTM C 330 with bulk densities of less than 880 kg/m^3 for coarse aggregate.
(2) The physical properties and crushing strength of the sedimentary LWA is better than that of the commercially available LWA. This may be due to the fact the sedimentary LWA particles have a hard ceramic shell. These results indicate the sedimentary LWA can serve as an aggregate source for structural concrete.
(3) The equilibrium density of the concrete made from the sedimentary LWA ranges from 1490 to 1566 kg/m^3, or about 29–35% lighter when compared to normal density concrete. This complies with most building code requirements for structural lightweight concrete.
(4) The 28-day compressive strength of the concrete made from the sedimentary LWA ranges from 19.8 to 34.7 MPa. This satisfies the 17 MPa minimum, 28-day strength requirement of ACI 318 for structural lightweight concrete.
(5) Unit weights of CMU ranged from 1585 to 1743 kg/m^3, and were 30–25% lower than the 2300 kg/m^3 required for a normal weight CMU. Most CMU fall into the lightweight category because they meet the requirements of CNS 8905 with a bulk density of less than 1680 kg/m^3.
(6) Compressive strengths of CMU ranged from 8.4 to 15.1 MPa, and were sufficient to meet the 5.88 MPa minimum compressive strength requirement of CNS 8905 for CMU with an air-dry bulk density of less than 1900 kg/m^3.
(7) Water absorption of CMU was found to vary between 0.05 and 0.13 g/cm^3 depending on the mix proportions. This is significantly lower than the 0.45 g/cm^3 maximum limit required by CNS 8905 for CMU with air-dry bulk density of less than 1900 kg/m^3. In addition, at a constant filling ratio of sand in mortar and a fixed cement replacement level by slag, the value of water absorption decreased with increasing aggregate content in the CMU. This is attributed to the decreased porosity in a high aggregate content mixture.

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References

[1] Somayaji S. Civil engineering materials. 2nd ed. Upper Siddle River, New Jersey: Prentice Hall; 2001.
[2] Holm TA, Ries JP. Reference manual for the properties and applications of expanded shale, clay and slate lightweight aggregate. Prepared by Expanded Shale Clay and Slate Institute; 2007.
[3] Doel A. Lightweight aggregates for use in concrete. Concrete (London) 2007;41(7):36–7.
[4] Henkensiefken R, Bentz D, Nantung T, Weiss J. Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions. Cement Concr Compos 2009;31(7):427–37.
[5] Riley CM. Relation of chemical properties to the bloating of clays. J Am Ceram Soc 1950;30(4):121–8.
[6] Holm TA, Bremner TW. 70 Year performance record for high strength structural lightweight concrete. In: Proc first materials engineering congress, August 1990, American Society of Civil Engineers, Denver, USA.
[7] Holm TA. Lightweight concrete and aggregates. American Society for Testing and Materials (ASTM), Standard Technical Publication STP 169C; 1995.
[8] Boateng AA, Thoen ER, Orthlieb FL. Modelling the pyroprocess kinetics of shale expansion in a rotary kiln. Trans IChemE 1997;75(Part A):278–83.
[9] Tay JH, Show KY. Resource recovery of sludge as a building and construction material – a future trend in sludge management. Water Sci Technol 1997;36(11):256–66.
[10] Wainwright PJ, Cresswell DJF. Synthetic aggregate from combustion ashes using an innovative rotary kiln. Waste Manage 2001;21:241–6.
[11] Wang KS, Sun CJ, Yeh CC. The thermo treatment of MSW incinerator fly ash for use as an aggregate: a study of the characteristics of size-fractioning. Resour Conserv Recycl 2002;35:177–90.
[12] Monzó J, Payá J, Borrachero MV, Girbés I. Reuse of sewage sludge ashes (SSA) in cement mixtures: the effect of SSA on the workability of cement mortars. Waste Manage 2003;23:373–81.
[13] Cheeseman CR, Virdi GS. Properties and microstructure of lightweight aggregate produced from sintered sewage sludge ash. Resour Conserv Recycl 2005;45:18–30.
[14] Chiou IJ, Wang KS, Chen CH, Lin YT. Lightweight aggregate made from sewage sludge and incinerated ash. Waste Manage 2006;26:1453–61.
[15] Andrade LB, Rocha JC, Cheriaf M. Evaluation of concrete incorporating bottom ash as a natural aggregates replacement. Waste Manage 2007;27:1190–9.
[16] Kayali O. Fly ash lightweight aggregates in high performance concrete. Constr Build Mater 2008;22(12):2393–9.
[17] Qiao XC, Ng BR, Tyrer M, Poon CS, Cheeseman CR. Production of lightweight concrete using incinerator bottom ash. Constr Build Mater 2008;22(4):473–80.
[18] Mun KJ. Development and tests of lightweight aggregate using sewage sludge for nonstructural concrete. Constr Build Mater 2007;21:1583–8.
[19] Hsu RL, Hsu MC. Dredging program for Shihmen reservoir. In: Sixth congress, Asian and pacific regional division of the international association for hydraulic research, Kyoto, Japan; 20–22 July 1988. p. 229–35.
[20] Waste/Waste Disposal. Methods and facilities standards for the storage, clearance and disposal of industrial waste. Environmental Protection Administration order on December 14; 2006.
[21] ACI 211.2. Standard practice for selecting proportions for structural lightweight concrete. American Concrete Institute; 2004.
[22] ASTM C143/C143M–08. Standard test method for slump of hydraulic-cement concrete. ASTM International; 2008.
[23] ASTM C39/C39M-05e2. Standard test method for compressive strength of cylindrical concrete specimens. ASTM International; 2005.
[24] ASTM C78-08. Standard test method for flexural strength of concrete (using simple beam with third-point loading). ASTM International; 2008.
[25] CNS 7332. Method of determination for thermal conductivity of heat insulating materials by means of comparison with a standard plate of known conductivity. Bureau of Standards, Metrology & Inspection, MOEA, ROC; 2007.
[26] CNS 8905. Hollow concrete blocks, Bureau of Standards. Metrology & Inspection, MOEA, ROC; 2007.
[27] ASTM C 330. Standard specification for lightweight aggregates for structural concrete. ASTM International; 2005.
[28] ASTM C 29. Standard test method for unit weight and voids in aggregate. ASTM International; 2007.
[29] GB/T2842-81. China National Standard. Test method for lightweight aggregates; 1981.
[30] ACI 318-08. Building code requirements for structural concrete and commentary. American Concrete Institute, Farmington Hills, Mich.; 2008.