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Manufacture and performance of lightweight aggregate from municipal solid waste incinerator fly ash and reservoir sediment for self-consolidating lightweight concrete

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ABSTRACT

Reservoir sediment, as the main material, was blended with municipal solid waste incinerator (MSWI) fly ash (including cyclone ash and scrubber ash) to manufacture lightweight aggregates (LWAs) using a pelletizing disk, and then sintering in a rotary kiln. The selected LWA was used as coarse aggregate for producing self-consolidating lightweight concrete (SCLWC). The results show that the maximum content of MSWI fly ash should be less than 30%. LWA with specific gravity in the range of 0.88–1.69 g/cm^3 and crushing strength as high as 13.43 MPa can be produced. SCLWCs showed excellent flow-ability without bleeding or segregation. The 28-day compressive strengths of the SCLWCs ranged between 25 and 55 MPa. The electrical resistivity and ultrasonic pulse velocity of the SCLWCs satisfied the required values of 8.5 kΩ cm and 3600 m/s, respectively. Therefore, the SCLWCs produced in this study have good corrosion resistance and can be classified as good quality.

1. Introduction

The generation of large amounts of municipal solid waste (MSW) is one of the main environmental problems in many industrialized countries. Although the original volume of MSW can be reduced by up to 80–95% by incineration, a large amount of solid residues is still produced by the incineration process [1,2]. Municipal solid waste incineration (MSWI) fly ash is one by-product of the combustion of MSW. The reuse of MSWI fly ash has been studied [1,3–11]. For example, MSWI fly ash can be used in cement production, concrete, road pavement, embankment, solid stabilization, ceramics, glass and glass–ceramics [2,4].

Sedimentary rock consists of argillite, slate and shale. This kind of rock, which has been disturbed by ground shifts and weathered by heavy rain, is often washed into water reservoirs by precipitation where it accumulates as fine sediment or sludge [12]. Generation of a large amount of the reservoir sediment seriously impacts reservoir use, so that dredging becomes necessary. Due to its high water content, such reservoir sediment cannot be simply dumped into final repository yards, but rather needs to be stored temporarily in downstream sink basins. In some regions, however, all potential sink basins are fully utilized and unable to accept additional sediments. Therefore, it is necessary to investigate alternative, environmentally sustainable applications for this type of waste. The use of reservoir sediment in construction applications has been a common practice and has grown worldwide [13–16].

To counter the declining availability of natural resources to use as raw and construction materials, many kinds of manufactured products (e.g., artificial lightweight aggregates (LWAs) and geopolymer binders) have been investigated, produced from different waste streams. MSWI fly ash and reservoir sediment have been widely used to manufacture LWA. Hung and Hwang [17], Liao and Huang [13] and Tang et al. [15] have reported the possible application of sediment from the Shihmen Reservoir in Taiwan for manufacturing LWA. They have concluded that the sediment of Shihmen Reservoir corresponds to the bloating area in Riley's diagram [18] and can be applied as a good material for making LWA. The sediment-based LWA meets the relevant standards of bulk density, strength and water absorption. The particle densities of the LWA range from 1010 to 1380 kg/m^3 [15]. The 28-day compressive strength of the concrete made from the sedimentary LWA ranges from 19.8 to 34.7 MPa [15]. On the other hand, there are numerous studies on the production of LWA using MSWI fly ash. For example, Huang et al. [8] has manufactured LWA by combining mining residues, heavy metal sludge, and incinerator fly ash. The properties of the produced LWA were specific gravity of 0.6, a water adsorption rate of less than 5%, and cylindrical compressive strength of 4.3 MPa. Chiou et al. [9] have used sewage sludge ash as the principal material and sewage sludge as an admixture to sinter LWA. They concluded that a mixture using 20–30% of sewage sludge was adequate to make aggregate in an energy-efficient

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manner. Chen et al. [1] have investigated manufacturing LWA by incorporating MSW incineration fly ashes and reaction ashes with reservoir sediments from the Wushe Reservoir located in central Taiwan. The investigation showed that MSW incineration fly ashes and reaction ashes can only be used as additives due to the positioning of their chemical compositions in comparison with the expandable region of Riley's ternary diagram. The particle density of the manufactured aggregate was 0.99 g/cm^3 and its dry loose density was 593 kg/m^3. From the above-cited studies, it can be seen that most studies have not provided in-depth analyses of the properties of concrete made from LWA produced or the feasibility of large-scale production of LWA, especially application of LWA in self-consolidating concrete.

In this study, LWA is produced by adding 10–50% MSWI fly ash (containing cyclone ash and scrubber ash) to reservoir sediment. A pelletizing disk is used for manufacturing the raw LWA on a pilot scale. The raw LWA is sintered in a commercial rotary kiln. The properties of raw materials and the manufactured LWA are tested. Afterward, the manufactured LWA is used as coarse aggregate within self-consolidating lightweight concrete (SCLWC). Additionally, compressive strength, ultrasonic pulse velocity (UPV) and electrical resistivity of the SCLWC are tested and examined against relevant standards.

2. Experimental methods

2.1. Raw materials used in lightweight aggregate production

The MSWI fly ash used in this study was collected from the cyclone of a mass-burning incinerator located in northern Taiwan. The incinerator, capable of processing 1350 metric tons of local municipal solid waste per day, is equipped with air pollution control devices (APCDs) consisting of a cyclone, a semidry scrubber system and a fabric bag house filter. The ash types used in this paper were cyclone ash and scrubber ash. Reservoir sediment was collected from the Shihmen Reservoir in Taiwan. The chemical composition of raw materials was determined by XRF. The toxicity characteristic leaching procedure (TCLP) and total concentrations of heavy metals were also measured. Six heavy metals, including Pb, Cd, Cr, Cu, Zn and Ni, were selected for analysis. The extraction procedure requires the preliminary evaluation of the pH characteristic of the sample to determine the proper extraction fluid necessary for the experiment. After testing, extraction fluid #B (pH 2.88 ± 0.05) was selected for the TCLP analysis. This fluid was prepared by adding 5.7 mL of acid to 500 mL of double distilled water, diluted to a volume of 1 L. A 25 g sample was placed in a 1 L Erlenmeyer flask, and 500 mL of extraction fluid was added to each Erlenmeyer flask. The samples were then agitated for 18 h with an electric vibrator. The slurry was filtered using 6–8 μm pore size Millipore filter paper. The leachates were preserved in 2% HNO_3. The heavy metal concentrations in the MSWI fly ash and samples were confirmed by ICP-AES. The samples were crushed, and the heavy metals were extracted by acid ($HF:HClO_4:HNO_3 = 2:1:1$).

The chemical composition of cyclone ash, scrubber ash and reservoir sediment are shown in Table 1. The chemical composition of the reservoir sediment is as follows: SiO_2 60.92%; Al_2O_3 25.21% and Flux (Fe_2O_3, CaO, MgO, Na_2O and K_2O) 9.96%. The compositions meet the requirements of expansive clay (SiO_2: 48–70%, Al_2O_3: 8–25% and Flux: 4.5–31%) according to Riley [18]. The SiO_2 and Al_2O_3 in cyclone ash and scrubber ash are low (i.e. SiO_2 8.01–11.51%, Al_2O_3 4.38–7.95%), while the flux in the ashes is in the range of 47.91–59.05%. Therefore, the sediment from the Shihmen Reservoir should be used as suitable raw material for the production of expanded LWAs. Since the chemical compositions of the cyclone ash and scrubber ash are not in the limit of the requirements of expansive clay due to the low content of SiO_2 and Al_2O_3 and the high content of the Flux, the cyclone ash and scrubber ash should not to be used as primary material for making expanded LWAs. The melting points of Fe_2O_3, CaO, MgO, Na_2O and K_2O are all very well low when compared with those of SiO_2 and Al_2O_3 [19]. Therefore, the ashes can be used as additives in order to improve sintering temperature of LWA.

TCLP results and total concentrations of heavy metals in raw materials are shown in Table 2. In terms of cyclone ash and scrubber ash, the total concentrations of Pb, Cu, and Zn are extremely high in comparison to those of other metals. The total concentrations of Cd, Cr and Ni in the ashes are relatively low. The total concentrations of heavy metals in the reservoir sediment are significantly low in comparison to those of the ashes. Moreover, the TCLP leaching concentrations of the raw materials all met the Environmental Protection Agency (EPA) regulatory requirements as shown in Table 2.

2.2. Manufacture of lightweight aggregate

A pelletizing disk was designed, 80 cm in diameter and 30 cm in depth as shown in Fig. 1. The revolution speed of the pelletizing disk and the angle of the disk plane were controlled by the designed systems. In the granulation process for this study, the disk was operated at the angle of 53° and the speed of 11 rpm.

The cyclone ash and scrubber ash were mixed at ratio of cyclone ash:scrubber ash = 1:3, which is referred to as MSWI fly ash. Three different weight ratios of MSWI fly ash to reservoir sediment were prepared for use in producing LWA (i.e. 10%, 30%, and 50%). A total of three proportions of the MSWI fly ash and the reservoir sediment used in this study are shown in Table 3. For each granulation process, 5 kg of MSWI fly ash-reservoir sediment mixture was used. To ensure the homogeneity of the mixture, after having fed the mixture into the pan, the disk was run at constant speed for 2 min. Water was sprayed on the mixture by an electric spray

Table 2
TCLP results and heavy metal concentrations of raw materials.

Element	Pb	Cd	Cr	Cu	Zn	Ni
TCLP (mg/L)						
Cyclone ash	0.18	0.09	4.45	0.25	0.29	0.11
Scrubber ash	4.16	ND	ND	0.19	0.74	1.1
Reservoir sediment	ND	ND	ND	ND	0.65	ND
Regulatory threshold (mg/L)	5	1	5	15	–	–
Heavy metals in material (mg/kg)						
Cyclone ash	2000	135	539	1380	9071	221
Scrubber ash	3500	206	35	1310	2257	143
Reservoir sediment	60	ND	55	43	286	81

ND: below detection limit.

Table 1
Chemical composition of raw materials (unit: %).

Type	SiO_2	Al_2O_3	Fe_2O_3	CaO + MgO	K_2O	Na_2O	S_2O	P_2O_5	Cl
Cyclone ash	11.51	7.95	4.03	34.78	4.24	4.86	11.59	3.31	16.25
Scrubber ash	8.01	4.38	2.35	51.72	2.21	2.77	11.08	1.79	12.99
Reservoir sediment	60.92	25.21	5.55	0.92	3.49	0	0.34	0	0

Fig. 1. A pelletizing disk.

gun. The sprayed water was used as the wetting agent and as a coagulant such that the wet mixture would be pelletized through the rolling motion and the effects of capillary attraction by a tilted rotary pan. The optimum sprayed water content was controlled in the range of 16–24% by weight of the mixture.

The freshly manufactured pellets were dried at 105 °C in an oven for 24 h prior to firing in a commercial electric rotary kiln 5 m in length. Only those passing through a 1/2″ sieve (12.5 mm) and retained by a #4 sieve (4.75 mm) were selected as coarse aggregates. The collected aggregates were sintered in the commercial electric rotary kiln at 1070, 1100, 1120 and 1150 °C. The temperature was increased at a fixed rate of 5 °C/min by a programmable kiln up to desired temperatures. The kiln temperature was maintained at the desired temperatures as designed for a fixed period of 20 min, and then slowly cooled down to ambient temperature.

2.3. Quality tests of lightweight aggregate

The characteristics of the manufactured aggregates were determined, including the TCLP and total concentrations of heavy metals, chemical compositions, SEM micrographs, water absorption, and specific gravity. For the strength aggregate tests, failure point loading that refers to the failure loading of a single aggregate in one single point were estimated. In such a way, the single manufactured aggregate was pressed down by a steel puncheon unit it was crushed, and then failure point loading was recorded. The test was done on the Acme Penetrometer with model of HM-570. The crushing strength was done according to Chinese National Standards 14779 for lightweight aggregate (CNS 14779). In this test, LWA was placed in a steel cylinder with an internal diameter of 115 mm and a height of 145 mm. The load value was recorded when a steel plunger reached a prescribed distance of 20 mm. The crushing strength value was calculated as the ratio between the load and the cross-sectional area of the cylinder, in stress units.

2.4. Concrete made with lightweight aggregate

2.4.1. Materials

ASTM C150 type I Portland cement and ASTM C618 Class F fly ash from *Xingda* thermal power plant in Taiwan were used. Four LWA types: F10S90-R1150, F10S90-R1100, F30S70-R1120 and F50S50-R1100 were selected to use as coarse aggregates in this investigation. Natural sand (modulus of fineness 3.0, density 2.65 and absorption capacity 1.4%) was provided from local quarries. The mixing water was local tap water. Type-G superplasticizer, having 43% solid content with specific gravity of 1.06 ± 0.02, was used to achieve the desired workability for all concrete mixtures. All materials conform to the related ASTM standards.

2.4.2. Testing program

Three water-to-binder ratios (w/b): 0.24; 0.32; and 0.40 were done with natural coarse aggregate and LWA. In order to assess the effect of w/b on concrete properties, F50S50-R1100 was selected to use as coarse aggregate for all three water-to-binder ratios. The mixtures were prepared by replacing the same amount of cement with fly ash at all w/b ratios. The effects of different LWAs were measured using a w/b of 0.32. All selected aggregates were used. For each w/b ratio, the amount of sand, fly ash and cement were kept the same in the mix proportions with natural coarse aggregate and LWA. Mix proportions of SCLWCs are listed in Table 4. Due to high water absorption property of LWA, additional water equivalent to 30 min water absorption capacity of aggregate was added to the concrete mixture.

Slump and slump flow spread of SCLWC were controlled to meet the HPC requirement with high workability which is 230–270 mm and 500–700 mm, respectively. The compressive strength, concrete resistivity and ultrasonic pulse velocity tests were conducted according to the relevant ASTM standards. The tests for hardened SCLWC were carried out at the age of 1, 3, 7, 14, 28 and 56 days.

Table 3
Mixtures and properties of lightweight aggregates.

Mix.	MSWI fly ash[a] (%)	Reservoir sediment (%)	Sintering temperature (°C)	Specific gravity (g/cm^3)	Failure point loading (kgf)	Crushing strength (MPa)	Water absorption (%)
F10S90-R1070	10	90	1070	1.69	52.98	10.39	11.5
F10S90-R1100			1100	1.67	56.20	11.02	9.6
F10S90-R1120			1120	1.11	38.85	8.32	8.1
F10S90-R1150			1150	0.88	22.68	6.59	7.6
F30S70-R1070	30	70	1070	1.37	21.77	5.89	21
F30S70-R1100			1100	1.40	35.38	8.30	16.6
F30S70-R1120			1120	1.48	68.44	13.42	8.4
F50S50-R1070	50	50	1070	1.38	9.53	5.32	29
F50S50-R1100			1100	1.46	13.61	5.73	25.6
F50S50-R1120			1120	1.48	18.14	5.99	20.8

[a] MSWI fly ash with a ratio of cyclone ash: scrubber ash is 1:3.

Table 4
Mix proportions of SCLWCs (unit: kg/m^3).

Mix.	Type of LWA	w/b	LWA	Sand	Fly ash	Cement	Water^{SSD}
Ctr0.24	Natural aggregate	0.24	1028.6	739.6	106.9	429.3	143.3
F50S50-0.24	F50S50-R1100		502.7	739.6	106.9	429.3	281.8
Ctr0.32	Natural aggregate	0.32	1028.6	739.6	106.9	362.0	166.3
F50S50-0.32	F50S50-R1100		502.7	739.6	106.9	362.0	304.8
F30S70-0.32	F30S70-R1120		587.8	739.6	106.9	362.0	209.8
F10S90-0.32(1)	F10S90-R1100		634.2	739.6	106.9	362.0	206.6
F10S90-0.32(2)	F10S90-R1150		471.8	739.6	106.9	362.0	175.2
Ctr0.40	Natural aggregate	0.40	1028.6	739.6	106.9	309.7	183.1
F50S50-0.40	F50S50-R1100		502.7	739.6	106.9	309.7	321.8

3. Results and discussion

3.1. Test results of lightweight aggregate

3.1.1. Chemical compositions, TCLP and concentrations of heavy metals

The chemical compositions of LWA are shown in Table 5. The chemical compositions of LWA depend on the initial compositions of raw materials and on the proportions of the MSWI fly ash and reservoir sediment used. LWA was mainly composed of SiO_2, CaO and Al_2O_3.

TCLP results and concentrations of heavy metals in LWA are shown in Table 6. Due to high concentrations of heavy metals in MSWI fly ash, the concentrations of heavy metals in LWA increase as MSWI fly ash content increases. However, the TCLP leaching concentrations of the LWAs all meet the Taiwan EPA regulatory requirements.

3.1.2. Water absorption and specific gravity of lightweight aggregate

A particle with connected or open pores tends to absorb water like a sponge whereas one with isolated pores or a vitrified surface coating will absorb little water. The 24 h water absorption and specific gravity of sintered LWA are shown in Table 3. The water absorption of LWA decreases as the temperature increases. After the formation of a vitrified layer on the particle surface that drastically reduces the permeability of the LWA, the water is blocked from entering the pores with measured water absorption of LWA decreases. The results show that the water absorption of LWA increases as the proportion of MSWI fly ash in the raw pellets increases. During heating, gases easily escape from the non-vitrified surface of the pellets with different proportions of MSWI fly ash, resulting in an increase in the open porosity of the granules [20].

In comparing with normal weight aggregate, the artificial LWA retains a higher percentage of voids so that its density is lower, surface area and water absorption ratio are higher. The specific gravity decreases as the MSWI fly ash increases, while it increases as the reservoir sediment increases. Among all the series, only F10S90 series shows a reduction in specific gravity with an increase in heating temperature. This is due to the bloating that only this series experiences. When the amount of MSWI fly ash added is more than 10%, such as F30S70 and F50S50 series, LWA undergoes a progressive increase in specific gravity as the heating temperature increases. This demonstrates that the vitrification temperature of the F30S70 and F50S50 aggregates is greater than 1120 °C, indicating by the powdery film on the surface of the sintered products as shown in the SEM micrographs of produced LWA in Fig. 2.

Between 1100 °C and 1120 °C, there are slight changes in color of LWA due to the sintering agent content as shown in Fig. 3. The surfaces of LWA produced are not vitrified. This is because the sintering temperature was not hot enough to produce vitrification of the surfaces. The surface texture is smoother in F10S90 and F30S70 series than in F50S50 series, and becomes rougher in F50S50 series. External fissures are visible on the surface of some F10S90-R1120 and F30S70-R1120 samples.

3.1.3. Strength of lightweight aggregate

The failure point loading and crushing strength of LWA are presented in Table 3. F10S90 series shows a reduction in failure point loading and crushing strength with an increase in heating temperature. This is due to the bloating which happened in the series. When more MSWI fly ash is added, i.e. 30% and 50%, under the sintering conditions from 1070 °C to 1120 °C, the crushing strength of LWA increases. The failure point loading of the LWA also increases when sintering temperature increases.

Table 5
Chemical compositions of lightweight aggregates (unit: %).

Type	SiO_2	Al_2O_3	Fe_2O_3	CaO + MgO	K_2O	Na_2O
F10S90-R1100	75.34	0.00	9.72	8.12	4.95	1.87
F10S90-R1150	61.29	23.07	5.73	5.39	3.38	1.14
F30S70-R1120	55.56	19.74	4.90	17.19	2.62	0.00
F50S50-R1100	40.00	22.15	6.49	28.40	0.82	1.72

Table 6
TCLP results and heavy metal content for lightweight aggregates.

Element	Pb	Cd	Cr	Cu	Zn	Ni
TCLP (mg/L)						
F10S90-R1150	0.04	ND	ND	ND	2.26	ND
F10S90-R1100	0.02	ND	ND	ND	0.08	0.39
F30S70-R1120	0.01	ND	ND	0.63	2.89	0.49
F50S50-R1100	0.29	0.41	3.64	1.11	0.03	1.59
Regulatory limits (mg/L)	5	1	5	15	–	–
Heavy metals in material (mg/kg)						
F10S90-R1150	78.57	ND	764.29	ND	235.71	328.57
F10S90-R1100	85.71	ND	671.43	42.86	921.43	278.57
F30S70-R1120	92.86	ND	742.86	142.86	1964.29	350.00
F50S50-R1100	100.00	935.71	571.43	1014.29	1285.71	300.00

ND: below detection limit.

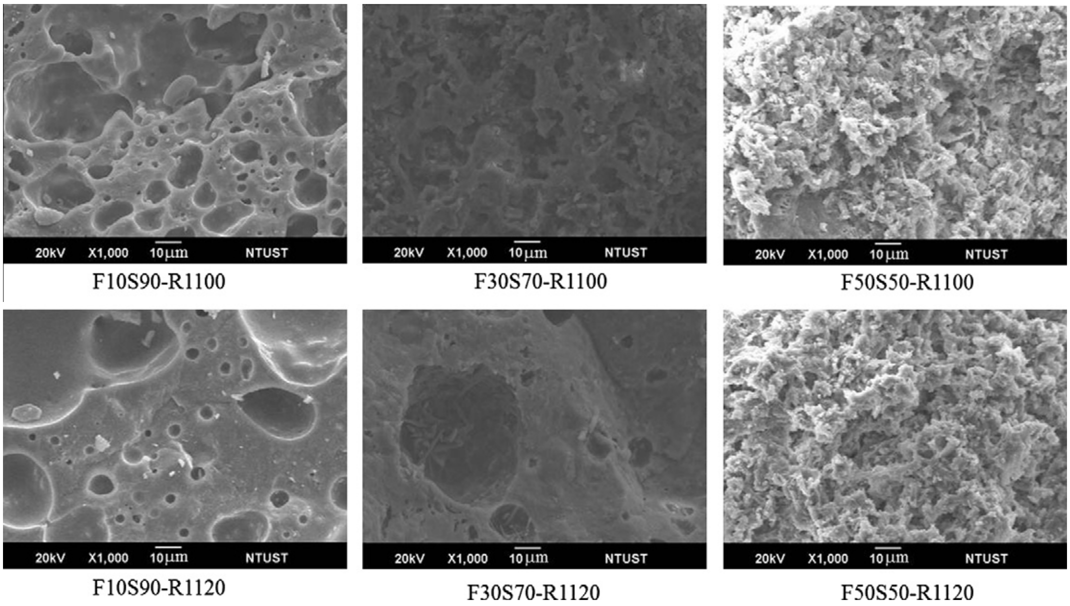

Fig. 2. SEM micrographs of produced LWA at 1100 °C and 1120 °C.

Fig. 3. External appearance and surface texture of produced LWA at 1100 °C and 1120 °C.

The results also show that both the failure point loading and crushing strength of F10S90 aggregates reaches the highest values at 1100 °C, while F30S70 and F50S50 aggregates still undergoes an increase in the failure point loading and crushing strength up to 1120 °C. It can be seen that the sintering reaction in F10S90 has happened at 1100 °C, while F30S70 and F50S50 have not reached the sintering reaction up to 1120 °C. This finding is in good agreement with specific gravity and SEM results. The finding is also in agreement with Chen et al. [1] findings.

3.2. Application of lightweight aggregate in concrete

3.2.1. Fresh properties of lightweight concrete

In this study, SCLWC with excellent flow-ability is easily obtained as shown in Fig. 4. High-slump flowing concrete was obtained without bleeding or segregation. Slump, slump flow and flowing time of fresh SCLWC are excellent as shown in Table 7. Initial slump varied between 230 mm and 290 mm. Slump flow ranged from 450 mm to 710 mm. Generally, the tendency to form bleeding capacity of aggregate is higher in elongated and flat particles than rounded ones and to produce the same workability, the elongated and/or angular particles require more cement paste than rounded particles [21]. The open pores in LWA will surely adsorb water, and affect the concrete strength and the workability of SCLWC. Good-quality LWA with a layer of burning glazing shell and close system reduces water adsorption and crushing possibility of LWA during mixing process. In comparison, when natural coarse aggregates were replaced fully with LWA, there was significant reduction in the unit weight of fresh concrete. The unit weight of SCLWC ranged from 1878 kg/m^3 to 2057 kg/m^3. The unit weight of fresh SCLWC is slightly high. The reason may be due to the use of natural sand as fine aggregate, which caused all SCLWCs to exceed the ACI minimum limitation for density of LWC.

3.2.2. Compressive strength of lightweight concrete

The compressive strength of LWC is controlled by the features of LWA, as indicated in ACI 213 codes as the strength ceiling of LWC. The compressive strength of LWC can be divided into two

Fig. 4. Performance of fresh SCLWC (F10S90-0.32(1)).

phases. The mortar phase containing cement, water and sand mainly supports the strength of LWC, and the LWA phase mainly reduces the density of LWC.

The w/b ratio is an important factor determining the compressive strength of LWC [22]. In this study, with different w/b ratios, the SCLWC with F50S50-R1100 has significantly lower compressive strength than the normal concrete due to higher porosity and lower strength of the LWA used as shown in Fig. 5. The replacement of the natural aggregate in concretes with the F50S50-R1100 aggregate resulted in 64.9%, 62.2% and 64.6% reduction in the 28-day compressive strength for w/b ratio of 0.24, 0.32 and 0.40, respectively. Reduction ratios decreased in 56-day strength by 60.1%, 57.5% and 63.8%, respectively.

Fig. 6 shows the effect of different LWA types for a given w/b ratio. For the given w/b ratio of 0.32, the 28-day compressive strength of concretes with F30S70-R1120, F10S90-R1100, F10S90-R1150, and F50S50-R1100 aggregates, respectively, were observed as 18.3%, 21.1%, 23.8%, and 62.2% reduction compared to plain concrete. Reduction ratios decreased 56-day strength by 15.3%, 22.5%, 26.6%, and 57.5%, respectively. This is due to the fact that the strength of LWA is the primary factor affecting the compressive strength of the LWC [22]. Due to very low qualities of F50S50 aggregate, the compressive strength of SCLWC containing the aggregate is lowest. The compressive strength of SCLWC with the F30S70-R1120, F10S90-R1100 and F10S90-R1150 aggregates is equivalent. However, the compressive strength of SCLWC can be sorted in ascending order, i.e. concretes with F30S70-R1120, F10S90-R1100, F10S90-R1150, and F50S50-R1100 aggregates. In summary, it can be concluded that the 28-day compressive strength ranging from 25.4 to 54.9 MPa for all mixtures satisfied the strength requirement of ASTM C330 and ACI 318 for structural LWC requiring a minimum 28-day compressive strength of 17.2 MPa. The F30S70-R1100, F10S90-R1100, and F10S90-R1150 can be used as good LWAs for HPC.

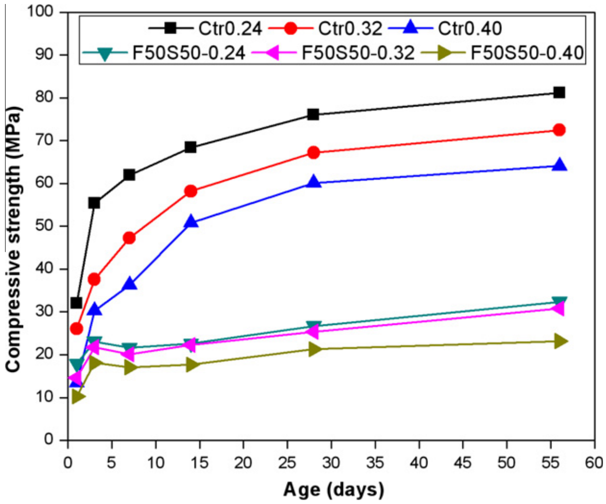

Fig. 5. Strength development of SCLWC with different w/b ratios.

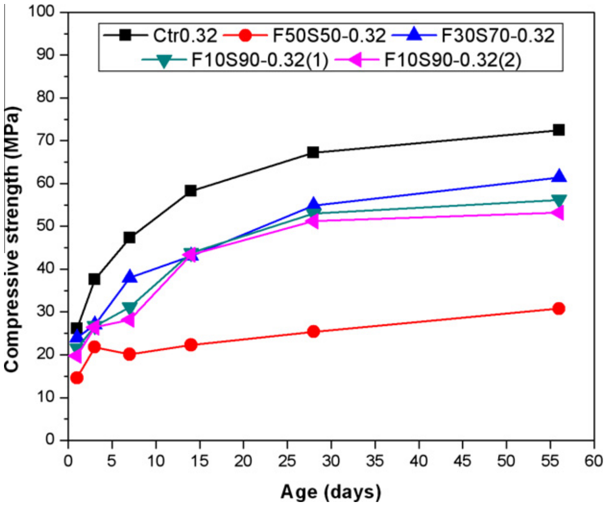

Fig. 6. Strength development of SCLWC with different LWA types.

3.2.3. Electrical resistance of lightweight concrete

The electrical resistance of concrete is an effective measuring standard for concrete durability [23]. As a general rule, the higher the concrete resistivity, the greater the corrosion endurance will be [24]. There are many threshold limit values of electrical resistance of concrete suggested. According to Hope et al. [25], the minimum value beyond which corrosion cannot occur is 8.5 kΩ cm, while Buenfeldet al. [23] recommend a value of 20 kΩ cm, which corresponds to the special specification of HPC. Kayali and Zhu have

Table 7
Properties of fresh LWC.

Mix.	w/b	Slump (mm)	Slump flow (mm)	Flow time (s)	Unit weight (kg/m^3)	SP (%)
Ctr0.24	0.24	240	460	47	2403	1.65
F50S50-0.24		260	470	60	2044	1.00
Ctr0.32	0.32	230	450	37	2383	1.13
F50S50-0.32		270	530	33	2036	0.75
F30S70-0.32		270	560	70	2034	0.68
F10S90-0.32(1)		265	610	30	2057	0.63
F10S90-0.32(2)		260	650	60	1878	0.75
Ctr0.40	0.40	235	470	16	2352	1.03
F50S50-0.40		290	710	13	1970	0.50

suggested that a value of resistivity of 8.5 kΩ cm, as suggested by Hope et al. [25], is a reasonable value, and practical for real world corrosion resistance [26].

Fig. 7 shows the development of electrical resistivity of SCLWC with different w/b ratios for F50S50-R1100 aggregate. The electrical resistivity of all SCLWCs is lower than that of control mixtures. As expected, there is enhancement in the electrical resistivity with lower w/b ratio. Concrete with F50S50 aggregate shows a slow development of electrical resistivity during early curing. The 56-day electrical resistivity of SCLWC with w/b ratio of 0.24, 0.32, and 0.40 were measured as 15.98, 10.85, and 9.17 kΩ cm, respectively. The low electrical resistivity may be due to low crushing strength, low failure point loading and high water absorption of F50S50 aggregate.

For the same w/b ratio of 0.32 with different LWA types as shown in Fig. 8, the electrical resistivity results vary depending on the qualities of LWA used. Among all the mixtures, only SCLWC with F10S90-R1150 aggregate has higher electrical resistivity than the control mixture at all ages. The 56-day electrical resistivity of all SCLWCs reached above the suggested value of 8.5 kΩ cm. Therefore, the SCLWCs have good corrosion endurance.

3.2.4. Ultrasonic pulse velocity of lightweight concrete

The pulse velocity methods have been used to assess the uniformity and relative quality of concrete, to indicate the presence of voids and cracks, and to evaluate the effectiveness of crack repairs [27]. Generally, high pulse velocity reading in concrete is indicative of concrete of good quality. Leslie and Cheesman [28] have given the pulse velocity ratings for concrete. They have suggested that concrete has good quality when its pulse velocity value is in the range of 3660–4575 m/s.

Fig. 9 shows the changes of UPV of SCLWC with different w/b ratios for F50S50-R1100 aggregate. The UPV of all SCLWCs is lower than that of the control mixtures at all ages. The trend with regard to the hardening properties of SCLWC is: the lower the w/b ratio is, the higher the UPV will be [29,30]. All SCLWCs with w/b ratio of 0.24, 0.32, and 0.40 reached 56-day UPV above 3700 m/s. Fig. 10 illustrates the UPV of SCLWC with different LWA types. Similar to electrical resistivity, the UPV of SCLWC with various LWA types is lower than that of the control mixtures at all ages. Comparing the kinds of LWA, the concrete with F10S90-R1150 aggregate is the most effective, following by F30S70-R1120, F10S90-R1100 and F50S50-R1100 aggregates, but the difference between UPV values of concrete with these aggregates is negligible. Due to the

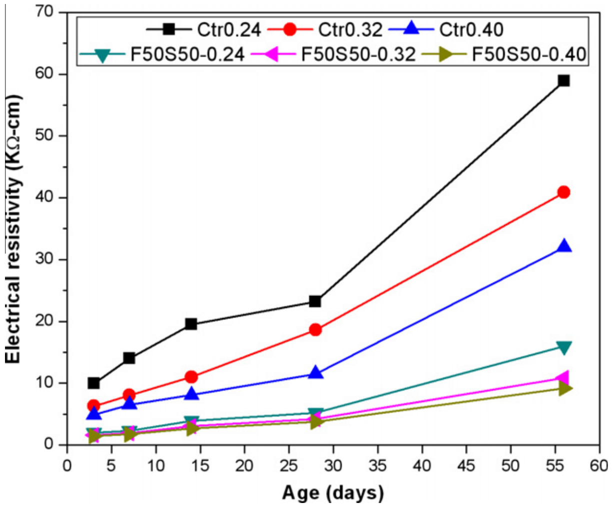

Fig. 7. Electrical resistivity of SCLWC with different w/b ratios.

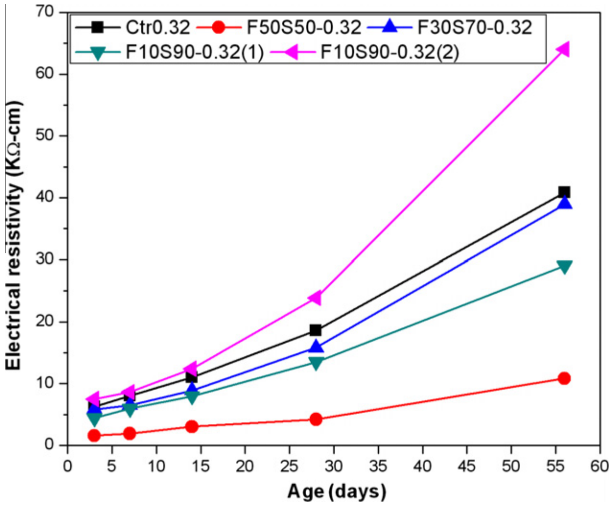

Fig. 8. Electrical resistivity of SCLWC with different LWA types.

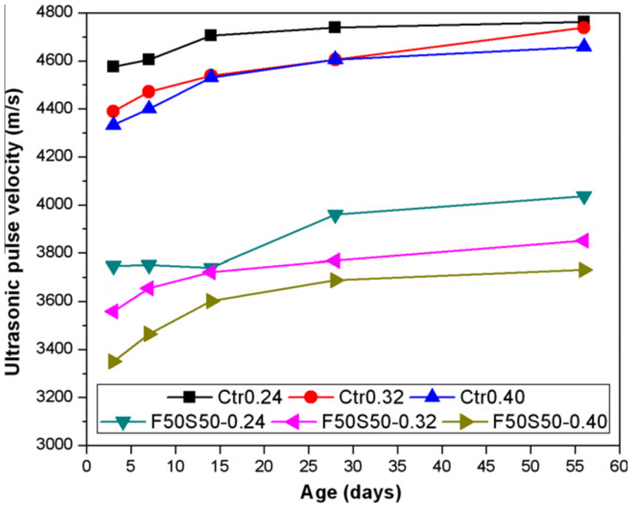

Fig. 9. Ultrasonic pulse velocity of SCLWC with different w/b ratios.

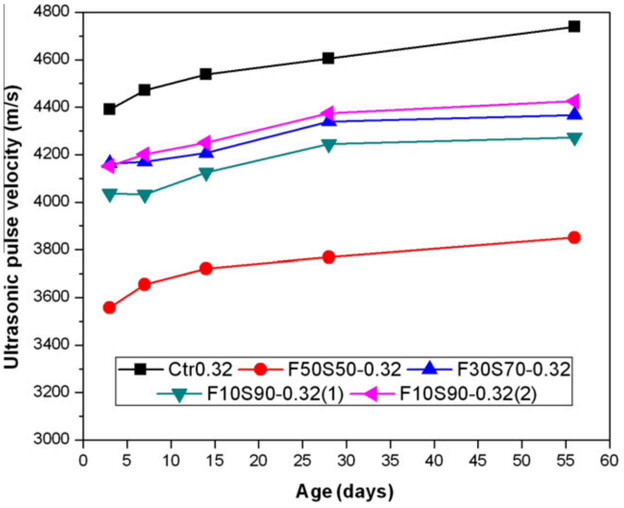

Fig. 10. Ultrasonic pulse velocity of SCLWC with different LWA types.

poor quality of F50S50-R1100 aggregate, the concrete with this aggregate shows lowest UPV in comparison with other ones. The 56-day UPV of the SCLWC with F10S90-R1150, F30S70-R1120, F10S90-R1100 and F50S50-R1100 aggregates were measured above 3800 m/s, respectively. It is clear that all concretes produced were classified as good as all values were greater than 3660 m/s [28].

4. Conclusions

According to the results in this study, a number of conclusions can be drawn:

1. The reservoir sediment can be used as primary source materials for making expanded lightweight aggregates, since its chemical composition falls within Riley's expansion region. The MSWI fly ash (the mixture of cyclone ash and scrubber ash) should only be used as additives.
2. The TCLP leaching concentrations of the raw materials all meet Taiwan's EPA regulatory requirements. Similarly, the TCLP of all LWAs produced meets Taiwan's EPA regulatory requirements. The heavy metal leaching concentrations for LWA increases as the amount of MSWI fly ash increases.
3. The water absorption of LWA increases as the proportion of MSWI fly ash in the raw pellets increases. The specific gravity of LWA with 10% MSWI fly ash decreases from 1.69 g/cm^3 to 0.88 g/cm^3 with an increase in heating temperature from 1070 °C to 1150 °C. Conversely, with an increase in heating temperature from 1070 °C to 1120 °C, the specific gravity of LWA containing 30% or 50% MSWI fly ash increases from 1.37 to 1.48 g/cm^3.
4. The LWAs with 10% MSWI fly ash show a reduction in the failure point loading and crushing strength as heating temperatures increase from 1070 °C to 1150 °C. On the other hand, both the failure point loading and crushing strength of the LWAs containing 30% or 50% MSWI fly ash increase when heating temperatures increase from 1070 °C to 1120 °C. The sintering reaction in LWA with 10% MSWI fly ash happened at 1100 °C. Based on the properties of all LWA produced it can be concluded that the MSWI fly ash addition should not exceed 30%.
5. SCLWC with excellent flow-ability is easily produced. High-slump flowing concrete was obtained without bleeding or segregation. The unit weight of SCLWC ranged from 1878 kg/m^3 to 2057 kg/m^3. The unit weight of fresh SCLWC is slightly high for LWC due to the use of natural sand as fine aggregate.
6. The 28-day compressive strength of all SCLWCs ranged from 25.4 to 54.9 MPa. This satisfied the strength requirement of ASTM C330 and ACI 318 for structural LWC requiring a minimum 28-day compressive strength of 17.2 MPa.
7. The electrical resistivity and UPV of SCLWC reached above the suggested values of 8.5 kΩ cm and 3660 m/s, respectively. Therefore, the SCLWCs produced have good corrosion resistance and can be classified as good quality.

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