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Study on durability of densified high-performance lightweight aggregate concrete

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Abstract. The densified mixture design algorithm (DMDA) was employed to manufacture high-performance lightweight concrete (LWAC) using silt dredged from reservoirs in southern Taiwan. Dredged silt undergoing hydration and high-temperature sintering was made into a lightweight aggregate for concrete mixing. The workability and durability of the resulting concrete were examined. The LWAC made from dredged silt had high flowability, which implies good workability. Additionally, the LWAC also had good compressive strength and anti-corrosion properties, high surface electrical resistivity and ultrasonic pulse velocity as well as low chloride penetration, all of which are indicators of good durability.

Keywords: densified mixture design algorithm; silt; lightweight aggregate; durability.

1. Introduction

Accumulation of silt is a common problem in Taiwan reservoirs and results in an annual decrease in water storage capacity. While it is unlikely for new reservoirs to be constructed in the near future, the government has increased its effort in dredging the silt with the intention to maintain a stable supply of water and extending the service life of the reservoirs (Lin 2002). Nevertheless, improper disposal or treatment of the dredged silt may have detrimental effects on the environment and arouse public discontent. Taiwan, being densely populated and having limited natural resources, has developed technologies to reuse dredged silt from the reservoirs (Yang 2003, Chou and Ren 2001, Yen 2003). Since sands and stones needed for cement mixing are in short supply, silt reuse in the manufacture of cement offers an economical and ecological alternative. Through hydration and high-temperature sintering, dredged silt is made into a lightweight aggregate, which is then used to make high-performance lightweight aggregate concrete (LWAC).

Previous research on the development and manufacturing techniques for LWAC has been abundant and fruitful (Chen and Chang 2003, Wang 2003, Huang, *et al*. 2003, Hsiao, *et al*. 2002, Tsai 2001, Hwang, *et al.* 1996). Offering a range of technical, economic and environment-enhancing and preserving advantages, LWAC is a very versatile and cost-efficient material for construction (Zhang and Gjorv 1991, Khaiat and Haque 1995, Alduaij, *et al.* 1999, Haque and Khaiat 2004). LWAC is lightweight, seismic, easy to use for water and fire resistant. It can also absorb sound, provide heat insulation

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and has good compressive strength, durability and reliability. Here, we aim to examine the durability of LWAC made using the densified mixture design algorithm (DMDA) and sintered silt dredged from a reservoir in southern Taiwan (Chang 2004, Wang and Tsai 1996). The results thus obtained will be a useful reference for the reuse of dredged silt from reservoirs as an alternative raw material for concrete manufacturing.

2. Experimental study

2.1. Materials

2.1.1. Cement, fly ash and superplasticizer

Materials used in this study include the ASTM C150 compliant Type I ordinary Portland cement (OPC), class F fly ash (Taipower), a blast-furnace slag (Chung Lien Factory), and the Type 1000 superplasticizer that complies with the ASTM C 494 type G admixture. The chemical composition and physical properties of the above mentioned materials are listed in Tables 1-2.

Table 1 Chemical compositions and physical properties of cement, fly ash and slag

	Items	OPC	Fly ash	Slag
Chemical composition (Wt. %)	SiO_2 (S)	22.01	54.22	34.86
	Al_2O_3 (A)	5.57	31.39	13.52
	Fe_2O_3 (F)	3.44	2.33	0.25
	S+A+F	31.02	-	48.63
	CaO (C)	62.80	2.81	41.77
	MgO (M)	2.59	0.59	7.18
	SO_3 (S)	2.08	0.01	1.74
	f-CaO	1.05	-	-
	TiO_2 (T)	0.52	1.42	-
	Na_2O (Na)	0.40	0.21	-
	K_2O (K)	0.78	1.16	-
	V_2O_5 (V)	0.05	-	-
	Loss on ignition (LOI)	0.51	2.39	0.31
	Insoluble residue	0.08	-	-
Potential clinker minerals	C_3S	40.10	-	-
	C_2S	32.80	-	-
	C_3A	8.90	-	-
	C_4AF	10.50	-	-
Physical properties	Fineness (cm^2/g)	2970	3110	4350
	Specific gravity (g/cm^3)	3.15	2.19	2.87
	Initial setting time (h:min)	1:25	-	-
	Final setting time (h:min)	2:31	-	-
	Retention on 325 sieve (%)	-	-	8.0

Table 2 Basic properties of superplasticizer

Properties	Type 1000 superplasticizer
Solid ingredient (%)	43.0
Chloride ion content (ppm)	50.1
Insoluble residue (%)	0.15
Specific gravity (g/cm^3)	1.18
PH value	6.93

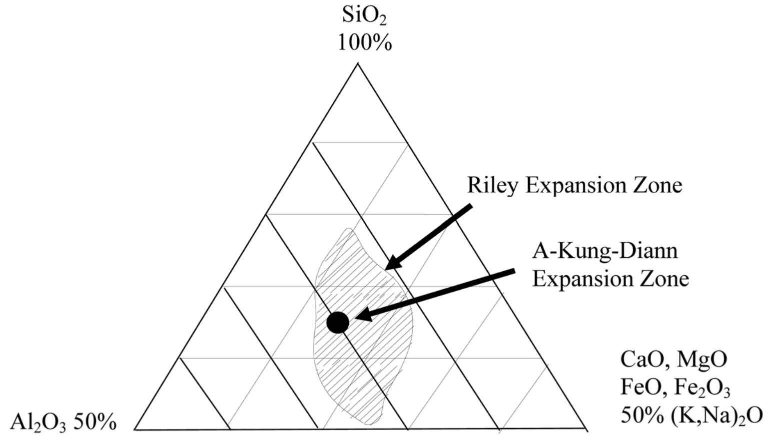

Fig. 1 The three-phase diagram of chemical composition of silt dredged from A-Kung-Diann Reservoir

2.1.2. Dredged silt

The silt used was dredged from the catchment area of A-Kung-Diann Reservoir in southern Taiwan. Fine and cohesive silt and clay accounted for 80% of the soil in the catchment area. The specific gravity is 2.73 g/cm^3 and the void ratio is 1.78. The chemical composition of the silt primarily includes SiO_2 (56.87%), Al_2O_3 (22.93%) and Fe_2O_3 (10.79%) as shown in the three-phase diagram of Fig. 1. It has been previously reported that the chemical composition of silt can influence the expansion properties and sintering temperature (Yen 2003). According to the findings of Riley (Riley 1990), the silt from the A-Kung-Diann Reservoir is an ideal raw material for sintering lightweight aggregate.

2.1.3. Lightweight aggregate

The lightweight aggregate is a synthetic aggregate manufactured from the dredged silt. Table 3 displays its physical properties. As the aggregate becomes more densified and increases in unit weight, the water absorption capacity of lightweight aggregate decreases, revealing an inverse relationship between the water absorption capacity and the unit weight. The rate of floating particles is indicative of the quality of the aggregate in terms of evenness. As shown in Table 3, when the particle density drops from 1.1 g/cm^3 to 0.8 g/cm^3, the rate of floating particles rises from 8% to 92%. This demonstrates that the coarse aggregate has a similar specific gravity and even quality.

Before the test materials were mixed, the fine normal-weight aggregates were prepared under saturated surface-dry conditions and the lightweight aggregates were stored under dry conditions.

Table 3 Physical properties of aggregates

Physical properties	Coarse aggregate		Fine aggregate (River sand)
	LWA (I)	LWA (II)	
Particle Density (g/cm^3)	0.8	1.1	2.6
Water Absorption Capacity (1 hr) (%)	4.2	4.9	2.5
Water Absorption Capacity (24 hr) (%)	8.9	6.4	4.0
Rate of floating particles (%)	92.0	8.0	-
Max. size D_{max} (mm)	12.7	9.5	2.38
Fineness Modulus (FM)	6.65	6.18	2.33
Unit weight (kg/m^3)	541.7	884.4	1675.0

Table 4 Mix proportions of lightweight aggregate concrete

No.	Particle Density	W/b	Water	Bulk density	Materials (kg/m^3)						
					Cement	Slag	Fly ash	Coarse aggregate	Fine aggregate	Moisture content	SP
1	0.8	0.28	140	1562	314	16.8	140.9	289.8	801	130.6	9.4
2	0.8	0.28	150	1584	335	18.0	140.9	289.8	801	113.9	9.9
3	0.8	0.28	160	1634	382	20.5	140.9	289.8	801	149.2	10.8
4	0.8	0.32	160	1584	335	18.1	140.9	289.8	801	152.7	7.3
5	0.8	0.40	160	1484	240	12.9	140.9	289.8	801	152.2	7.8
*6	0.8	0.40	197	1958	491	-	-	324.0	591	197.0	-
7	1.1	0.28	140	1898	244	13.2	211.2	229.7	1200	127.4	12.6
8	1.1	0.28	150	1936	280	15.5	211.2	229.7	1200	135.3	14.7
9	1.1	0.28	160	1952	315	16.9	211.2	208.8	1200	144.9	15.1
10	1.1	0.32	160	1889	256	13.7	211.2	208.8	1200	147	13.0
11	1.1	0.40	160	1799	170	9.1	211.2	208.8	1200	149.1	10.9
*12	1.1	0.40	204	1942	509	-	-	561.0	503	204	-

b: Binders including cement, fly ash and slag.
SP: Type 1000 superplasticizer ASTM C494 Type G, naphthalene-based.
SP (%): weight of superplasticizer to binder content ratio.
W: clean water including water in the superplasticizer.
*No.6 and No.12 are ACI
211.4R mix proportions.

2.2. Mix proportions

The DMDA was used to mix the LWAC using lightweight aggregate made from sintered silt dredged from the reservoir. Fly ash, slag and superplasticizer were added to reduce the amount of cement and mixing water needed. Three different water-to-binder (W/b) ratios (0.28, 0.32 and 0.40) and three different volumes of mixing water (140, 150 and 160 kg/m^3) were used to manufacture LWAC, which was then cured under water for various lengths of time. Tests were then conducted to examine the effect of different mix proportions on the hardness and durability of the LWAC. Table 4 displays the nine mix proportions for preparing LWAC.

2.3. Measurements

The specific gravity and absorption capacity of lightweight aggregate were tested according to ASTM C127. Lightweight concrete cylinders (100×200 mm) were cast following the ASTM C192. During casting, all the specimens were compacted by rodding and vibration. During the first 24 hrs, the specimens were kept in the molds. Afterwards, the specimens were removed and cured under water (25±2^{o}C) until the time of testing.

The slump test was performed according to the ASTM C134. The compressive strength of the cylindrical concrete specimens was tested following the ASTM C31. The velocity of the ultrasonic wave was measured according to the ASTM C597. The electrical resistivity of concrete was assessed using a resistivity gauge. The rapid chloride penetrability test was conducted in accordance with ASTM C1202. Three specimens of 100 mm diameter and 50 mm thickness conditioned according to the standard were subjected to 60-V potential for 6 h. The total charge that passed through the concrete specimens indicated the concrete resistance to chloride-ion penetration. The anti-corrosion property against sodium sulfide attack was evaluated following the ASTM C88-46T. After casting, the demolded specimens were immersed in saturated sodium sulfide solution for 16-18 hours. The weight of the specimens after drying for 12-16 hours was measured. The test cycle was repeated several times to assess the durability of the concrete under chemical corrosion. The micro-cracks and microstructure of the high-performance LWAC were also examined using scanning electron microscope (SEM) and energy dispersive analysis of x-rays (EDAX). Photos were taken to illustrate the results of carbonation.

3. Results and discussion

3.1. Properties of fresh concrete

Table 5 displays the properties of fresh concrete mixed with a constant W/b ratio of 0.40 and 160 kg/m^3 of mixing water using the DMDA. As can be seen, the slump of the concrete exceeds 260 mm and the slump flow is also above 530 mm. Under high particle density of 1.1 g/cm^3, the maximum size (D_{max}) of aggregate is 9.5 mm. Such small aggregate size implies better flowability. Hence, compared with concrete mixed using a traditional ACI mixture design algorithm, the DMDA achieved better workability.

Table 5 Properties of fresh LWAC

No.	Particle Density (g/cm^3)	W/b	Slump (mm)	Slump Flow (mm)
5	0.8	0.4	260	530
*6	0.8	0.4	120	210
11	1.1	0.4	280	580
*12	1.1	0.4	180	250

*No.6 and No.12 are ACI
211.4R mix proportions.

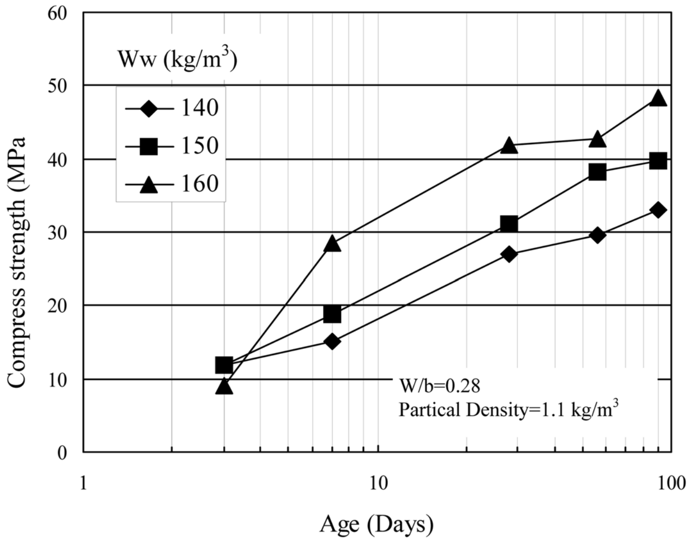

Fig. 2 Effect of different mixing water volume on compressive strength of LWAC

3.2. Compressive strength

Fig. 2 shows the effect of mixing water volume on compressive strength. When mixing LWAC, increases in the volume of mixing water will raise the cement paste content, which is conducive to strength development. That is, the more the mixing water, the greater the amount of cement paste and the better the compressive strength will be. During the early stage, the compressive strength of different specimens was similar. However, after 28 days of curing, the compressive strength of specimens mixed with 140, 150 and 160 kg/m^3 of water were 27, 31 and 41 MPa, respectively, indicating a linear relationship between amount of mixing water, quality of cement paste and compressive strength (Husem 2003).

3.3. Ultrasonic pulse velocity

Fig. 3 displays the relationship between W/b ratios and ultrasonic pulse velocity of LWAC at a particle density of 0.8 g/cm^3. As seen, the pulse velocities of specimens of different W/b ratios all exceed 3500 m/s after 28 days of curing. With the DMDA, using a low W/b ratio will result in a more densified cement paste (Hsiao, *et al.* 2002). Hence, high workability can be achieved leaving little chance for interface defects to occur with the more aggregate and less cement paste used. Consequently, the transmission path can be shortened, thus accelerating the ultrasonic pulse velocity.

3.4. Electrical resistivity

Fig. 4 shows the effect of different mixture design algorithms on the electrical resistivity of LWAC. The electrical resistivity of concrete mixed using ACI mixture design algorithm shows little growth with time, revealing the existence of more internal pores and defects (Khaiat and Haque, 1999). On Day 56, the electrical resistivity still remains below 12 kΩ-cm. In contrast, the electrical resistivity of concrete mixed using DMDA reaches 20 kΩ-cm after 28 days of curing. In addition,

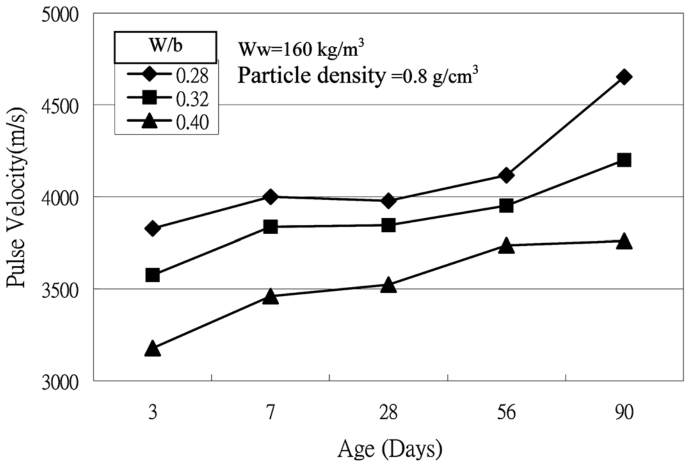

Fig. 3 Effect of different W/b ratios on pulse velocity of LWAC

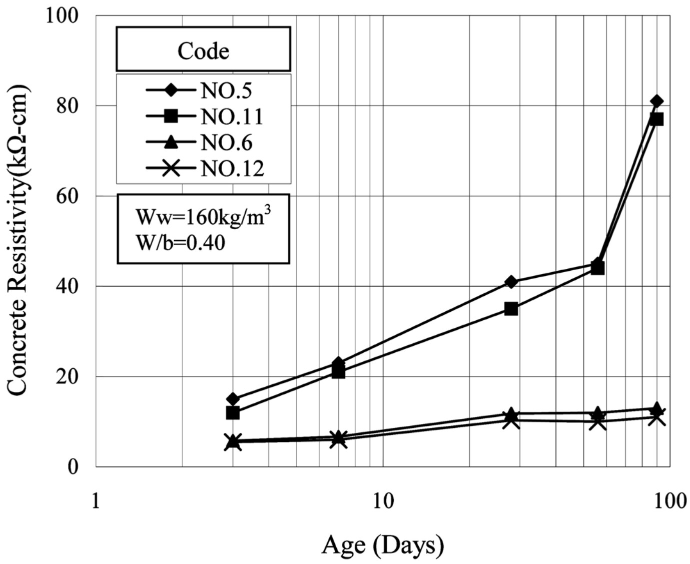

Fig. 4 Effect of different mixture design algorithms on electrical resistivity of LWAC

the electrical resistivity increases markedly with time. Under longer curing times, hydration becomes more complete resulting in lower porosity. On Day 90, the high-performance LWAC has an electrical resistivity of 80 kΩ-cm, indicating that DMDA can achieve better durability. This result is in agreement with previous findings (Chandra and Berntsson 2002, Chia and Zhang 2002).

3.5. Rapid chloride penetrability test

Fig. 5 summarizes the rapid chloride penetrability data of LWAC mixed with different W/b ratios and particle densities. As seen, a lower W/b ratio can enhance the quality of the cement paste, thus reducing the internal pores and keeping chloride penetration within the range of 300-500 coulombs. This result is consistent with that obtained by Chia and Zhang (2002). Briefly, the lower the W/b

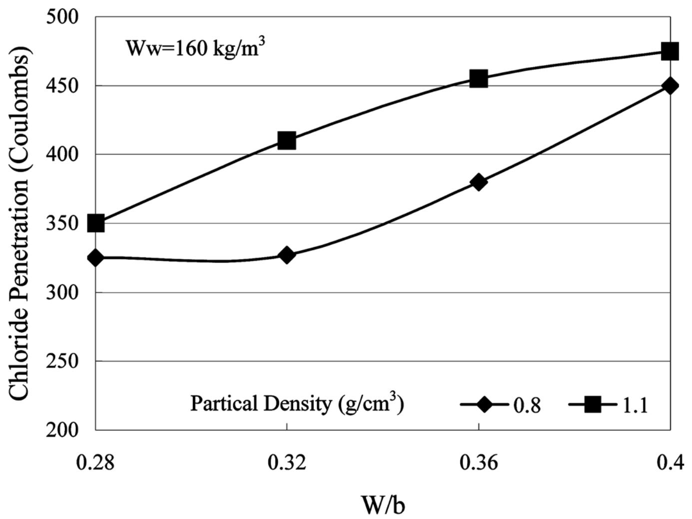

Fig. 5 Effect of different W/b ratios on chloride penetration

Table 6 Rapid chloride penetrability of LWAC

No.	W/b	Particle Density (g/cm^3)	Ww (kg/m^3)	chloride penetration (coulombs)
3	0.28	0.8	160	331
4	0.32	0.8	160	335
5	0.40	0.8	160	446
*6	0.40	0.8	197	564
9	0.28	1.1	160	385
10	0.32	1.1	160	427
11	0.40	1.1	160	492
*12	0.40	1.1	204	699

*No.6 and No.12 are ACI 211.4R mix proportions.

ratio, the better the cement paste quality, the less the internal pores and the lower the chloride penetration will be. Comparing the data shown in Table 6, we see that DMDA achieves better resistance than ACI mixture design algorithm against chloride penetration, which shows 564-699 coulombs of chloride penetration after a 90-day curing.

3.6. Anti-corrosion property

Fig. 6 shows the appearance of densified LWAC specimens after 15 cycles of immersion in sodium sulfate solution. Concrete mixed using 160 kg/m^3 of water and a constant W/b ratio of 0.28 shows more cracks. In addition, the gypsum reacts with the calcium sulfoaluminate hydrates forming ettringite. In contrast, concrete made using less mixing water (140 kg/m^3) has fewer cracks. This echoes the findings of (Haque, *et al.* 2004) who showed that LWAC mixed with a lower volume of

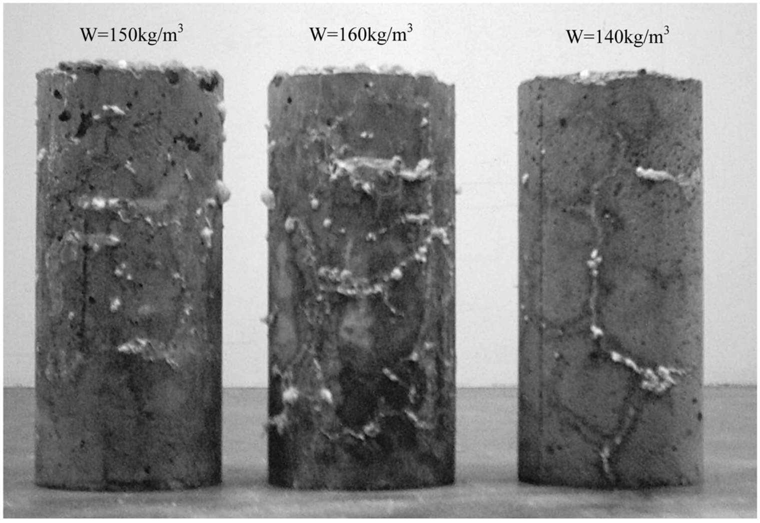

Fig. 6 Appearance of LWAC mixed with different volume of water after 15 cycles of immersion in sodium sulfide solution (W/b = 0.28)

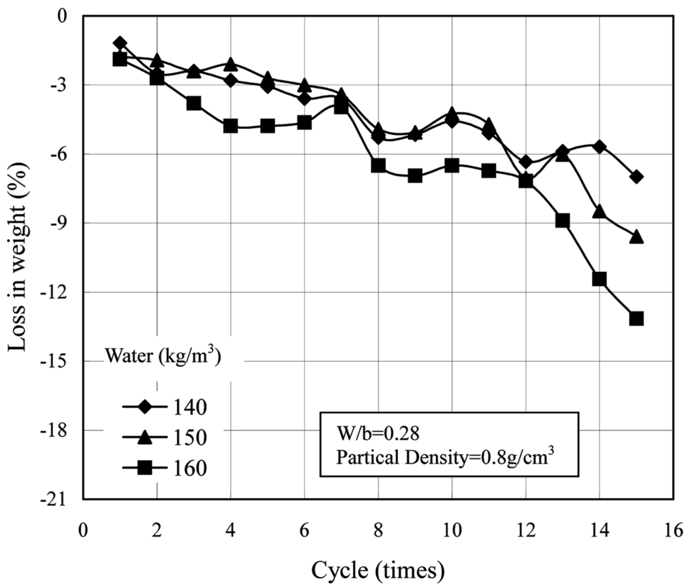

Fig. 7 Weight loss of LWAC mixed with different volumes of water after immersion in sodium sulfide solution

water has better durability. Fig. 7 displays the loss in weight after immersion in sodium sulfide solution. As seen, the specimens mixed with 140, 150, and 160 kg/m^3 of water lose 6.9%, 9.5% and 12.6% of weight, respectively, after 15 cycles. This indicates that the lower the amount of cement paste and pozzolanic material used, the densified LWAC will have a better anti-corrosion property.

3.7. Microstructure

Fig. 8 shows the SEM image of micro-crystallization of the LWAC interface. As seen on day 28, the addition of fly ash results in pozzolanic reaction, thus forming hydrated products. The C-S-H and C-A-H gel contained in the hydrated products becomes denser with a more even distribution of ettringites in the forms of pike and flower. In this way, the proportion of pores is reduced (Gao, *et al.* 2002). The corresponding EDAX results shown in Fig. 9 reveal Si and Ca content of 40.96% and 1.92%, respectively. In addition, LWAC mixed with higher W/b ratio (0.40) and more mixing water (160 kg/m^3) shows more obvious cracks and ettringite formation as seen in the SEM image of Fig. 10.

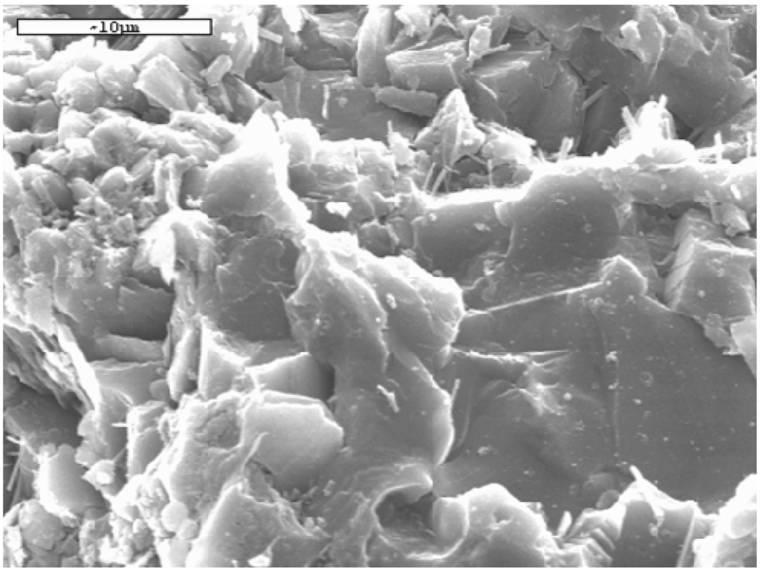

Fig. 8 SEM image of micro-crystallization of the LWAC interface on Day 28 (×3000) (particle density = 0.8 g/cm^3, W/b = 0.28, Ww=140 kg/m^3)

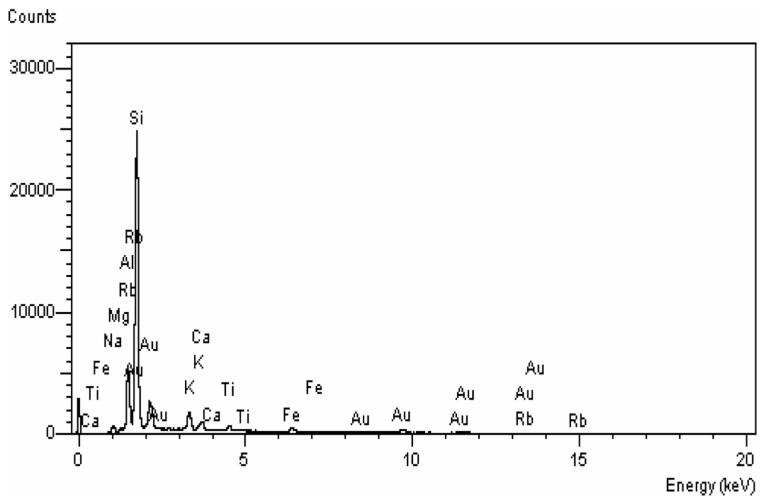

Fig. 9 EDAX analysis of LWAC on Day 28 (Particle density = 0.8 g/cm^3, W/b=0.28, Ww = 140 kg/m^3)

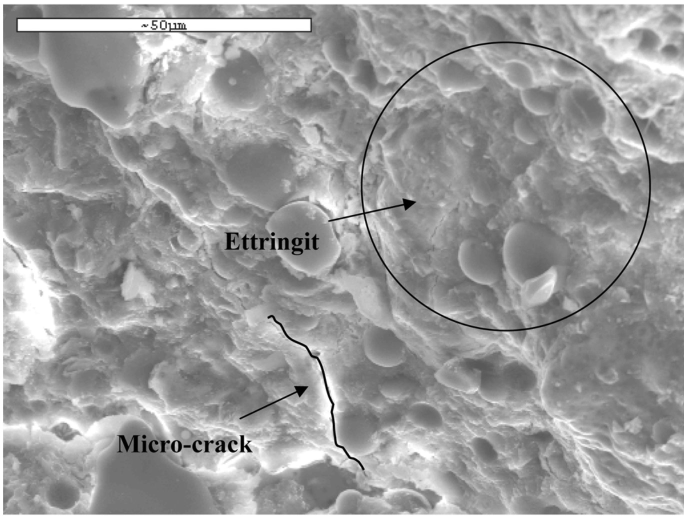

Fig. 10 SEM image of micro-crystallization of the LWAC interface on Day 28 (×1000) (Particle density=0.8 g/cm^3, W/b=0.40, Ww=160 kg/m^3)

4. Conclusions

According to the above mentioned results and discussion, the following results can be drawn:

1. According to Riley's standard, silt dredged from reservoirs in southern Taiwan can serve as ideal raw materials for sintering into lightweight aggregates of different particle densities.
2. Fresh concrete mixed using DMDA has slump above 260 mm and slump flow exceeding 530 mm, indicating good flowability. Greater aggregate density of 1.1 g/cm^3 also enhances workability of fresh concrete.
3. The more mixing water that is used in combination with a constant W/b ratio, the greater the cement paste content and the better the compressive strength.
4. Under a constant volume of mixing water, the density of the cement paste increases as the W/b ratio decreases, resulting in a higher ultrasonic pulse velocity.
5. For LWAC mixed using lightweight aggregate of different densities and cured for different durations, DMDA can achieve higher electrical resistivity and better resistance against chloride penetration than ACI mixture design algorithm.
6. Under repeated immersion in sodium sulfide solution, LWAC mixed with a greater water volume shows more cracks and ettringite formation as well as significant weight loss.
7. Under low W/b ratio and water content, LWAC mixed with added pozzolanic material will have more densified C-S-H gel and fewer pores. The greater the volume of mixing water causes formation of more cracks and hydrated products such as ettringite. EDAX reveals that the LWAC contains 40.96% of Si.

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