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Homogeneity of lightweight aggregate concrete assessed using ultrasonic-echo sensing

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Abstract. Dredged silt from reservoirs in southern Taiwan was sintered to make lightweight aggregates (LWA), which were then used to produce lightweight aggregate concrete (LWAC).This study aimed to assess the compressive strength and homogeneity of LWAC using ultrasonic-echo sensing. Concrete specimens were prepared using aggregates of four different particle density, namely 800, 1100, 1300 and 2650 kg/m^3. The LWAC specimens were cylindrical and a square wall with core specimens drilled. Besides compressive strength test, ultrasonic-echo sensing was employed to examine the ultrasonic pulse velocity and homogeneity of the wall specimens and to explore the relationship between compressive strength and ultrasonic pulse velocity. Results show that LWA, due to its lower relative density, causes bloating, thus resulting in uneven distribution of aggregates and poor homogeneity. LWAC mixtures using LWA of particle density 1300 kg/m^3 show the most even distribution of aggregates and hence best homogeneity as well as highest compressive strength of 63.5 MPa. In addition, measurements obtained using ultrasonic-echo sensing and traditional ultrasonic method show little difference, supporting that ultrasonic-echo sensing can indeed perform non-destructive, fast and accurate assessment of LWAC homogeneity.

Keywords : dredged silt; ultrasonic-echo sensing; lightweight aggregate concrete (LWAC); compressive strength; homogeneity.

1. Introduction

In Taiwan, the silt accumulated has amounted to 0.146 million m^3 per year (Lin 2002). Through hydration and high-temperature sintering, dredged silt can be made into lightweight aggregate (LWA) (Yen 2003, Hong *et al.* 2007), which is then employed to produce high-performance lightweight aggregate concrete (HPLWC) (Wang 2003, Wang and Tsai 2006). These wasted resources can be

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recycled and reused as construction materials to make up for the shortage of aggregates for manufacturing concrete. HPLWC is a very versatile and cost-efficient construction material with good strength and durability (Wang 2007). In addition to being light, it is also fire resistant and offers good insulation against sound and heat (Yen 2003, Lo *et al.* 2004). However, the low density of LWA will cause bloating during the mixing of LWAC. Bloating results in uneven distribution of aggregates, thus undermining the homogeneity of the concrete. LWAC has its obvious advantages in terms of high strength/weight ratio, good tensile strength, low coefficient of thermal expansion (Lo *et al*. 2004, Hossain 2004, Mouli and Khelafi 2008), and its strength and durability have also proven to be good (Haque *et al.* 2004, Chia and Zhang 2002). Addition of fly ash (20%) and slag (30%) gives rise to better surface resistivity and heat insulation and lower gas permeability of LWAC (Song *et al.* 2004). Furthermore, it has been demonstrated that the lightweight aggregate containing more water compensated for the slurry drying shrinkage and yielded less premature shrinkage (Sun *et al*. 2007). Being lightweight, LWAC is ideal for high-rise buildings and construction of long-span bridges (Rossignolo *et al*. 2003).

Non-destructive approaches are commonly adopted for testing concrete. One of these approaches is ultrasonic impulse-echo technique. Apart from flaw detection, this technique can also be employed to examine the pulse velocity of the ultrasonic wave as well as voids and homogeneity of the specimen (Wang and Tsai 2006, Jansohn *et al*. 1995). In addition, the thickness and depth of cracks in the specimen can also be calculated from the displacement of the longitudinal waveform of the back wall echo. From the ultrasonic pulse velocity and density of the slab materials, the elastic modulus (E) and Poisson ratio (ν) can be estimated using low-frequency ultrasonic wave (Carino and Sansalone 1990). In this study, ultrasonic-echo sensing is employed to measure the pulse velocity and examine the relationship between the compressive strength and homogeneity of the LWAC.

2. Experimental study

2.1. Materials

The materials for concrete mixing included cement, fly ash, slag, superplasticizer and sand. They were obtained locally from Taiwan and all met the specified requirements listed in CNS61 (2001), CNS3036 (2003), CNS12549 (1993), ASTM C494 TYPE-D (2005), CNS13961 (1997) and CNS1240 (2002), respectively. Type I cement with specific gravity of 3.15 was obtained from the Taiwan Cement Corporation. Table 1 and Table 2 present the chemical compositions and physical properties of the cement. Dredged silt from reservoirs in southern Taiwan was collected, dried, sieved and made into raw aggregate pellets. They were then fed into a kiln of 600-700°C and then sintered at

Table 1 Chemical composition of cement Unit: %

SiO_2 (S)	Al_2O_3 (A)	Fe_2O_3 (F)	S+A+F	CaO (C)	MgO (M)	SO_3 (S)
22.01	5.57	3.44	31.02	62.80	2.59	2.08

TiO_2 (T)	Na_2O (Na)	K_2O (K)	P_2O_5 (P)	LOI
0.52	0.40	0.78	3.04	0.91

Table 2 physical properties of cement

Fineness (m^2/kg)	365
Specific gravity	3.15
Initial setting time (h: min)	1.25
Final setting time (h: min)	2.31
28-day mortar cube strength (MPa)	47
Retention on 325 sieve (%)	9.4

Table 3 Physical property of aggregates

Physical Properties	LWA (I)	LWA (II)	LWA (III)	Coarse aggregate (IV)	Fine aggregate
Particle density (kg/m^3)	800-900	1100-1200	1300-1400	2650	2630
Absorption capacity (24 h) (%)	8.9	6.4	9.0	0.7	2.2
Max. size Dmax (mm)	13	10	13	25.4	2.4
Fineness modulus (FM)	6.65	6.18	6.50	6.88	2.72
Unit weight (kg/m^3)	542	885	900	1600	1650

1200°C into LWA. The aggregates used include both normal- and light-weight ones. Table 3 displays the physical properties of the aggregates obtained. In this study, the three manufactured LWA show particle density of 800, 1100 and 1300 kg/m^3, and the LWAC mixtures using these LWAs are classified as LA08, LA11 and LA13, respectively.

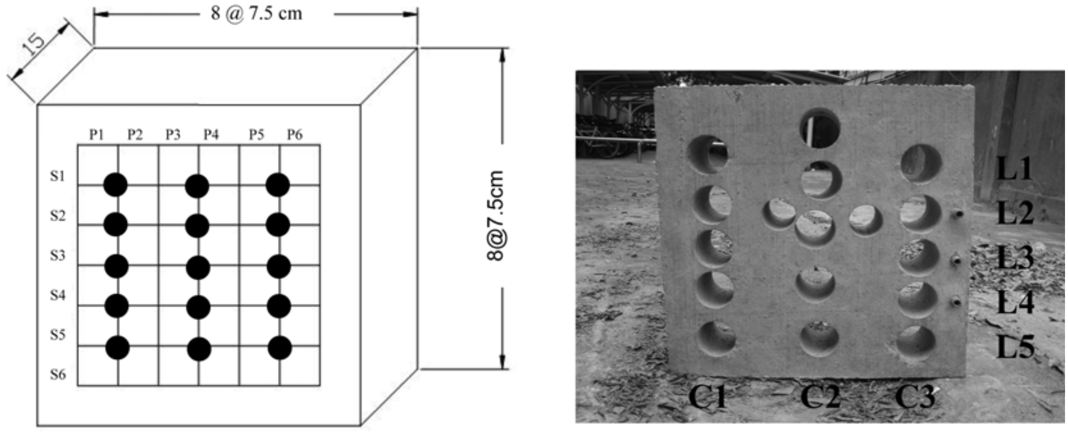
2.2. Mixture proportion for LWAC

This study employed both the American Concrete Institute (ACI) mix design method and the densified mixture design algorithm (DMDA). The ACI 211.1 design procedures are often used for mixing normal-weight aggregates. According to the mixture proportions listed in Table 4, all the raw materials are mixed into LWAC. As can be seen, the addition of other raw materials such as fly ash and sand fills the voids of the LWA, making it more densified. The raw materials used can be broadly categorized into two types: (1) aggregates, which include LWA, sand and fly ash; and (2) paste, which includes cement, water, slag and superplasticizer. Both coarse and fine aggregates are employed, one filling the void of the other. This reduces not only the voids present in the mixture, but also the amount of cement paste used, which serves to fill the voids besides lubrication.

Table 4 Mixture proportions of lightweight aggregate concrete Unit: kg/m^3

Batch	Particle density	Cement	Slag	L. Agg	Sand	Fly ash	Water	SP
LA08	800	385	20	304 (I)	716	126	160	10
LA11	1100	385	20	419 (II)	716	126	160	10
LA13	1300	385	20	472 (III)	716	126	160	10
NA26	2650	531	-	1001 (IV)	716	-	170	-

Note : w/b=0.32 w/c=0.44



(a) (b)

Fig. 1 LWAC wall specimen: (a) 36 points for ultrasonic measurement, (b) position of cores drilled

Concrete were mixed according to the DMDA. Details of the DMDA can be found in (Huang 2007, Chang 2004).

The optimum percentage of fly ash and slag used for void filling are 18% and 5%, respectively. The water-to-binder (w/b) ratio is 0.32 and the total amount of water used is 170 kg/m^3.

2.3. Specimen preparation

Specimens were prepared according to ASTM C31, C167 and C192 (1998). The cylindrical prepared were of ψ100 mm × 200 mm and subjected to CNS1232 (2002) compressive strength test. In addition, four groups of square wall specimens of 600 mm × 600 mm × 150 mm were prepared. They were dried and cured in open air prior to testing. As shown in Fig. 1, a 6 × 6 matrix was drawn on its surface showing 36 measurements points and 15 core specimens were drilled from it for testing and experimental measurement.

2.4. Testing methods

Ultrasonic-echo sensor (EPOCH4) were first filtered and then processed, with the vertical waves converted into horizontal ones. In other words, the energy of the vertical axis is 100% released. The horizontal axis represents the traveling time or distance of the energy and the waveform can reveal the location of flaws. Signals detected by the ultrasonic-echo sensor were analyzed using damped harmonic method (DHM). Energy will decay when transmitted between two media. The reflection generated in each medium also varies. Hence, transmission of energy in cycles will give rise to energy peak at the interface of the two media, which will shed light on the homogeneity of the material tested (Weng 2005). How densified the internal structure of concrete can be judged by the ultrasonic pulse velocity; the higher the velocity, the more densified the concrete is.

Through trial-and-error, found that the best waveform of the LWAC can be obtained by ultrasonic pulse of 75dB, with the length of the path, D, known and the time taken for measuring the waveform, t, obtained, the velocity, V, can be calculated using the following equation:

$$V = D / t \tag{1}$$

Experimental testing was also conducted using traditional ASTM C597 (1998) ultrasonic method for comparison and for assessing the relationship between compressive strength and homogeneity. In addition, homogeneity analysis was also performed using the core specimens drilled from the square concrete wall to examine the relationship between ultrasonic pulse velocity, waveform and compressive strength.

3. Results and discussion

3.1. Compressive strength

Fig. 2 shows the compressive strength of LWAC mixtures using LWA of different particle densities and cured for different durations. As can be seen, there exists a linear relationship between compressive strength and the other two, that is, compressive strength increases with increasing curing age and higher particle density. In addition, compressive strength in order is LA13 · LA11 · NA26 and LA08, both LA11 and LA13 groups of all curing durations have a compressive strength higher than that of the NA26 group.

With 28 days used as the baseline for comparison of compressive strength, shows that the compressive strength of the LWAC cured for 7 days has already reached 85% and rises to 125% (63.5 MPa) after curing for 91 days. The results indicate that LWAC can quickly attain high compressive strength after a short period of curing.

3.2. Relationship between compressive strength and ultrasonic pulse velocity

Fig. 3 depicts the relationship between compressive strength and ultrasonic pulse velocity at different particle density. Regression analysis performed on the data obtained shows that the values of R^2 reach 0.93 and above. At the same particle density, the higher the ultrasonic velocity, the greater the compressive strength will be. Table 5 compares the compressive strength measured

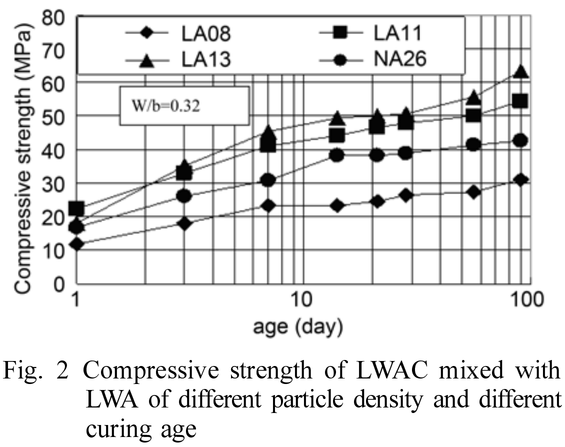


Fig. 2 Compressive strength of LWAC mixed with LWA of different particle density and different curing age

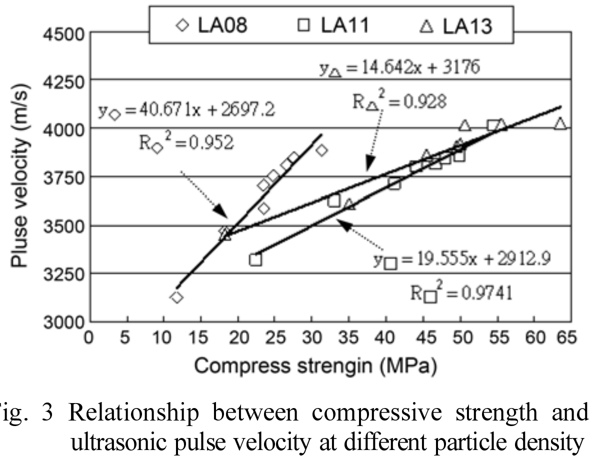


Fig. 3 Relationship between compressive strength and ultrasonic pulse velocity at different particle density

Table 5 Comparison of compressive strength obtained from experiments and that estimated by ultrasonic-echo sensing

No.	Compressive strength (MPa)					
	Obtained from experiments **[A]**			Estimated by ultrasonic-echo sensing **[B]**		
Age (Day) \ Batch	LA08	LA11	LA13	LA08	LA11	LA13
1	11.7	22.4	18.2	10.6	20.8	18.9
3	18.2	33.1	35.1	18.9	36.3	29.6
7	23.4(7)	41.2(1)	45.5(3)	21.9(7)	40.8(1)	46.9(3)
14	23.4	44.2	49.5	24.7	45.1	49.5
21	24.7	46.8	50.1	25.9	45.9	50.3
28	26.6(3)	48.1(1)	50.7(11)	27.4(3)	47.4(1)	57.1(11)
56	27.5(2)	50(4)	55.6(3)	28.2(2)	48.2(4)	57.6(3)
91	31.2(7)	54.6(3)	63.5(9)	29.1(7)	56.0(3)	58.3(9)

Note: The value in parentheses is the percentage difference between the above two measurements, i.e.

$$\left|\frac{[B]-[A]}{[B]}\right| \times 100\,\%$$

directly in experiments and that estimated by ultrasonic-echo sensing. The value in parentheses is the percentage difference between the two measurements. From the values calculated, there seems to be obvious relationship between compressive strength and particle density or curing age.

3.3. Distribution of LWA in core specimens

The LA13 group has the most even distribution of LWA at different levels compared with that of the LA08 and LA11 groups, both of which show varied distribution across the levels. In other words, the LA13 group has better homogeneity. In addition, in both LA08 and LA11 groups, the

Table 6 Average ultrasonic pulse velocity for wall specimens of different curing age Unit: m/s

Age (Days) \ Batch	LA08	LA11	LA13	NA26
7	3389 (93.4%)	3395 (93.6%)	3404 (93.9%)	3627 (100%)
14	3432 (93.5%)	3407 (92.8%)	3455 (94.1%)	3670 (100%)
21	3462 (94.1%)	3397 (92.3%)	3469 (94.3%)	3680 (100%)
28	3509 (95.1%)	3494 (94.7%)	3512 (95.2%)	3688 (100%)
91**	3772 (91.3%)	3818 (92.6%)	3827 (92.8%)	4123 (100%)

*Average value of the 36 measurement points on the square wall specimen
**Core specimen cured for 91 days

core specimens drilled at different levels, shown in Fig. 1, also show varied distribution of LWA. There is a greater concentration of aggregates in LWAC specimens at the upper levels and a greater concentration of the binder in specimens at the lower levels. Such bloating phenomenon is attributed to the lower density of LWA.

3.4. Homogeneity analysis

3.4.1. Ultrasonic pulse velocity of core specimens

Table 6 compares the average ultrasonic pulse velocity for core LWAC specimens of different curing age. As can be seen, all the LWAC specimens attain over 92% of ultrasonic pulse velocity compared with the NA26 specimens. In addition, the average ultrasonic pulse velocity of core specimens at lower levels of the wall is higher than that of specimens at higher levels. However, the

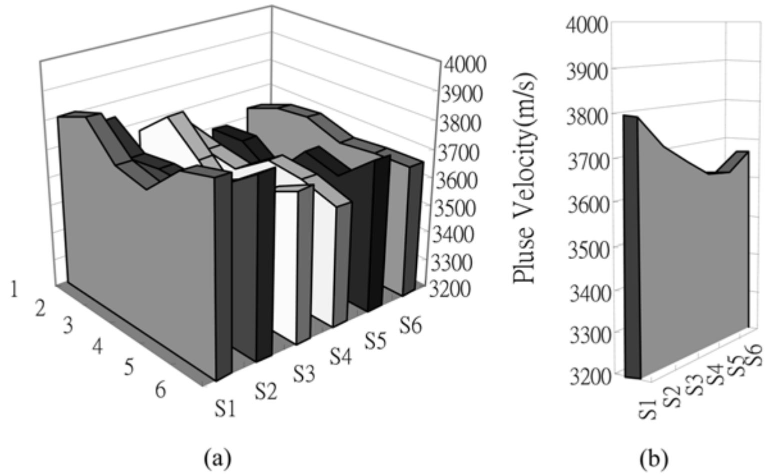


Fig. 4 Homogeneity of NA26 group (a) Ultrasonic pulse velocity of 36 measurement points, (b) Average ultrasonic pulse velocity of each row

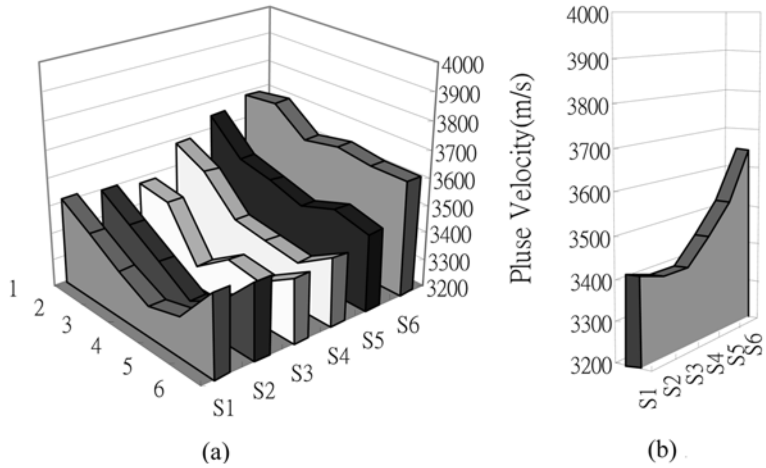


Fig. 5 Homogeneity of LA08 group (a) Ultrasonic pulse velocity of 36 measurement points, (b) Average ultrasonic pulse velocity of each row

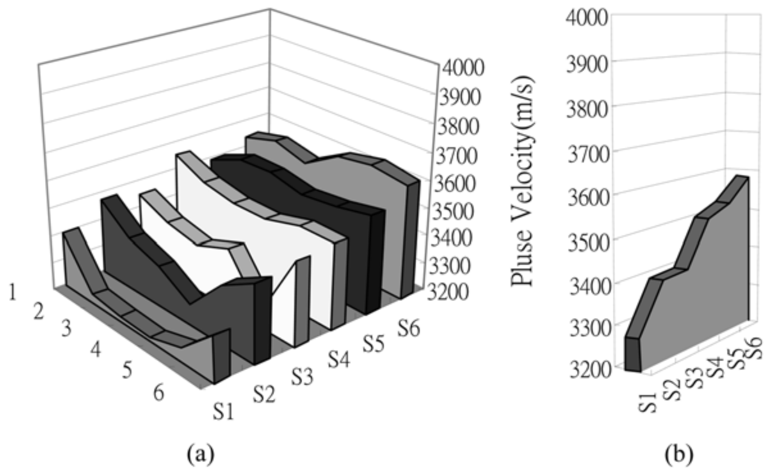


Fig. 6 Homogeneity of LA11 group (b) Ultrasonic pulse velocity of 36 measurement points, (b) Average ultrasonic pulse velocity of each row

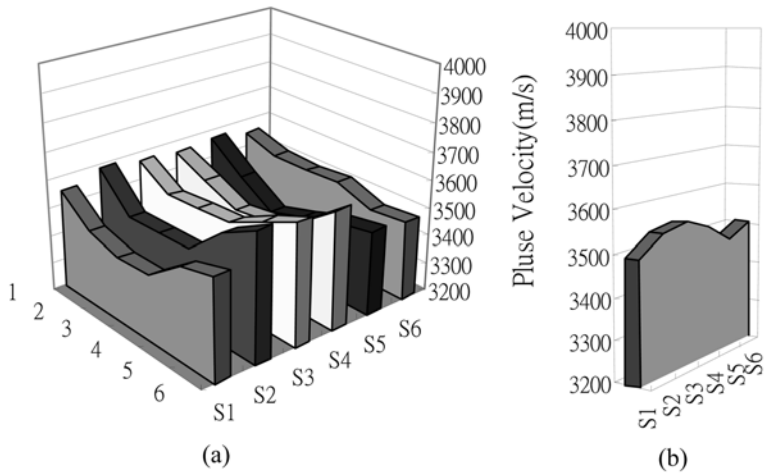


Fig. 7 Homogeneity of LA13 group (a) Ultrasonic pulse velocity of 36 measurement points, (b) Average ultrasonic pulse velocity of each row

difference in not very significant, implying that good mixture proportion can help reduce the uneven distribution of aggregates, which can achieve greater homogeneity.

3.4.2. Homogeneity of wall specimen

Figs. 4-7 displays the homogeneity of wall specimens made from NA26, LA08, LA11 and LA13 groups, respectively. As can be seen, the LWAC cured for 28 days show poorer homogeneity compared with the NA26. Among the three LWAC specimens, the LA13 group has the best homogeneity and also the highest ultrasonic pulse velocity. It may be because the LA08 group has lower relative density while the LA11 group shows greater difference in particle diameter. Comparing Figs. 4(b)-7(b) reveals that the LA13 group has more even distribution of aggregates and better homogeneity than the other two groups. Taking the average compressive strength of the

15 core specimens of the four groups indicates the following order: LA13 (63.5MPa) > NA26 (51.8 MPa) > LA08 (49.8 MPa) > LA11 (44.2 MPa). In other words, specimens of greater homogeneity also have higher compressive strength.

LWAC group achieve faster compressive strength. After being cured for 7 days, it can reach 85% of the 28 days compressive strength.

4. Conclusions

1. LWAC group achieve faster compressive strength. After being cured for 7 days, it can reach 85% of the 28 days compressive strength.
2. The quickness of the ultrasonic-echo technique is compared to some other unspecified technique. Furthermore, the accurate estimation of the compressive strength in this study is based on a fitting process.
3. The greater the particle density of LWA, the higher the compressive strength of the LWAC will be. The increase in compressive strength is also more marked with increase in curing age. For the same mixture proportion, there exists a linear relationship between ultrasonic pulse velocity and compressive strength.
4. Among the LWAC wall specimens, the LA13 group has more even ultrasonic velocity and compressive strength, which are also the highest. In addition, the LA13 group shows the best homogeneity.
5. Specimens of both LA08 and LA11 groups show greater variation in concentration of aggregates and density, which results in different quality.

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