*Computers and Concrete, Vol. 7, No. 1 (2010) 53-62*
DOI: http://dx.doi.org/10.12989/cac.2010.7.1.053


# Performance characteristics of dredged silt and high-performance lightweight aggregate concrete

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*(Received August 20, 2009, Accepted December 15, 2009)*

**Abstract** Dredged silt from reservoirs in southern Taiwan was sintered to make lightweight aggregates (LWA), which were then used to produce high-performance lightweight aggregate concrete (HPLWC). The HPLWC was manufactured using different amounts of mixing water (140, 150, and 160 kg/m$^3$) and LWA of different particle densities (700, 1100, and 1500 kg/m$^3$) at different W/b ratios (0.28, 0.32, and 0.4). Results show that the lightweight aggregates of dredged silt taken in southern Taiwan perform better than the general lightweight aggregates. In addition, the HPLWC possessed high workability with a slump of 230-270 mm, and a slump flow of 450-610 mm, high compressive strength of over 40 MPa after 28 days of curing, good strength efficiency of cement exceeding 0.1MPa/kg/m$^3$, low thermal conductivity of 0.4-0.8 kcal/mh°C, shrinkage of less than $4.8 \times 10^{-4}$, and high electrical resistivity of above 40 kΩ-cm. The above findings prove that HPLWC made from dredged silt can help enhance durability of concrete and provide and an ecological alternative use of dredged silt.

**Keywords:** dredged silt; high-performance lightweight aggregate concrete (HPLWC); workability; durability.

## 1. Introduction

In Taiwan, there are 67 reservoirs, 25 of which are located in southern Taiwan. The total water storage capacity is 22.43 billion m$^3$, while the silt accumulated amounts to 0.146 million m$^3$ per year (Lin 2002). Due to its geological and weathering impacts on the environment, accumulation of silt has posed problems for reservoirs, resulting in increasing reduction in effective water storage capacity. Compared with the original water storage capacity upon the completion of reservoirs, the effective water retention volume had been reduced by 23% in 2001 (Yang 2003). Furthermore, dredged silt is dense and full of organic matter. Inappropriate disposal or treatment of sedimentary dredged silt may cause secondary pollution resulting in detrimental effects to the environment. However, these wasted resources can be recycled and reused as construction materials to make up for the shortage of aggregate for manufacturing concrete. Hence, reservoirs were selected and examined for the properties of their dredged silt. Through hydration and high-temperature sintering,

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dredged silt was made into lightweight aggregates (LWA) (Yen 2003, Hong *et al.* 2007). Using LWA made from recycled reservoir-sludge, not only can high-performance lightweight aggregate concrete (HPLWC) be produced (Wang 2003) as LWAC made from dredged silt can help enhance durability of concrete (Wang and Tsai 2006, Wang 2007), but it can also ameliorate the problem of the decreasing water storage capacity in reservoirs due to sludge accumulation (Tsai 2001). Finally, this method could also offer an economical and ecological alternative to using sand and stone in concrete production.

LWAC can absorb sound, provide heat insulation, and is lightweight. It is also seismic, water, and fire resistant as well as being easy to use (Nilsen and Aitcin 1992, Lin *et al.* 2007). In fact, LWAC is a very versatile material for construction. It offers a range of technical, economic and environment-enhancing and preserving advantages. Thus, its properties have been widely studied (Wang and Tsai 2006, Wang 2007). 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). Furthermore, it has been demonstrated that the light weight aggregate containing more water compensated for the slurry drying shrinkage and yielded less premature shrinkage (Song *et al.* 2004). Addition of fly ash (20%) and slag (30%) gives rise to better surface resistivity and heat insulation and lower gas permeability of LWAC (Sun *et al.* 2007). Being lightweight, LWAC is ideal for high-rise buildings and construction of long-span bridges (Rossignolo *et al.* 2003). If enough cement paste is used, then smaller paste amounts and denser packing of the aggregate results in a higher strength efficiency and electric resistance of the cement and lower chloride ion penetrability capacity of SCLWC (Hwang and Hung 2005). In view of its many technical, economic, environment-enhancing, and conserving advantages, it is worthwhile to explore the manufacturing of HPLWC. This research aims to study the properties of HPLWC mixed using lightweight aggregates made from sintered silt dredged from reservoirs. Moreover, lightweight aggregates of different densities and various water-to-binder (*W/b*) ratios were used to examine their influence on engineering properties of HPLWC.

## 2. Experimental study

### 2.1. Materials

Dredged silt was collected from seven reservoirs in southern Taiwan. Table 1 shows the physical properties of the sampled sludge. The liquid limit, plasticity index, and absorption capacity were as per ASTM D4318-84, and D427-83. The chemical oxides present in the sampled sludge are shown in Table 2. Heavy metals are also accumulated in the sludge, but at concentrations within acceptable range. Table 3 shows the physical and mechanical properties of the initial particles and LWA made from the dredged sludge. Different mixture proportions of materials and processes involved in manufacturing LWA will also affect the fresh and hardened properties as well as the durability of the concrete produced.

In this experimental study, freshly dredged silt from A-Gong-Tien Reservoir was first saturated with water, and then sintered at 1200°C in a rotary kiln. The rotary kiln was set to maintain four rotations per minute and LWA were obtained after 30 minutes of sintering at a kiln temperature of 1200°C. Table 4 shows the Physical properties of LWA.

Table 1 Physical properties of dredged silt from reservoirs in southern Taiwan

| Item / Reservoir | Soil classification | Specific gravity (Gs) | Liquid limit (LL %) | Plasticity index (PI %) | Absorption capacity (%) | Content of particles of different sizes (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Rock | Sand | Silt | Clay |
| A-Gong-Tien | CL | 2.73 | 47.8 | 25.2 | 21.31 | 0 | 0 | 31.9 | 68.1 |
| Ren-Yi-Tan | CH | 2.73 | 54.1 | 30.9 | 15.54 | 0 | 0.6 | 54.7 | 44.7 |
| Bai-Ho | ML OL | 2.72 | 46.1 | 26.7 | 17.22 | 0 | 22.2 | 55.3 | 22.5 |
| Chin-Mien | CL | 2.70 | 29.9 | 7.8 | 10.56 | 0 | 9.9 | 73.7 | 16.4 |
| Hu-Tou-Bei | SL | 2.73 | 37.2 | 19.3 | 11.40 | 0.3 | 2.4 | 59.7 | 37.6 |
| Chen-Chin Lake | CL | 2.72 | 53.0 | 26.0 | 59.93 | 1.5 | 6.9 | 45.6 | 46 |
| Fon-Shan | SM | 2.66 | 58.0 | 23.0 | 68.23 | 5.5 | 81.9 | 11 | 1.6 |

Table 2 Oxides present in dredged silt from reservoirs in southern Taiwan

| Composition (%) / Reservoir | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $K_2O$ | $Na_2O$ | Others |
|---|---|---|---|---|---|---|
| A-Gong-Tien | 56.87 | 22.93 | 10.79 | 2.66 | 0.33 | 6.42 |
| Ren-Yi-Tan | 69.65 | 10.74 | 5.57 | 1.92 | 0.26 | 11.86 |
| Bei-Ho | 60.74 | 19.79 | 9.14 | 2.40 | 0.34 | 7.68 |
| Chin-Mien | 71.85 | 15.35 | 6.19 | 2.05 | 0.35 | 4.21 |
| Hou-Tou-Bei | 72.65 | 15.74 | 6.77 | 1.78 | 0.34 | 2.72 |
| Cheng-Chin Lake | 65.73 | 18.78 | 4.35 | 2.01 | 0.32 | 8.81 |
| Fon-shan | 59.64 | 19.37 | 7.57 | 1.19 | 0.20 | 2.03 |

Table 3 Characteristics of particles and LWA

| Item / Reservoir | Ratio of gross weight | Expansion I* | Absorption capacity (%) | Particle density ($kg/m^3$) | Cylindrical crushing strength (MPa) | Gross weight of lightweight aggregates ($kg/m^3$) |
|---|---|---|---|---|---|---|
| A-Gong-Tien | 0.47 | G | 9.5 | 1200 | 3.1 | 574 |
| Ren-Yi-Tan | 0.48 | G | 9.8 | 1000 | 3.2 | 563 |
| Bai-Ho | 0.66 | I | 8.0 | 1600 | 5.5 | 865 |
| Chin-Mien | 0.83 | N | 9.8 | 1700 | 4.6 | 963 |
| Hu-Tou-Bei | 0.86 | N | 11.2 | 2100 | 4.7 | 973 |
| Chen-Chin Lake | 0.33 | G | 9.8 | 700 | 1.1 | 423 |
| Fon-Shan | 0.87 | G | 9.9 | 1100 | 3.2 | 743 |

Notes: *: G: good expansion; I: fair expansion; N: poor expansion.

Materials used in this study for making LWAC include the ASTM C 150 compliant Type I ordinary Portland cement (OPC), Class F fly ash from Taipower, blast-furnace slag from Chung Lien Factory, aggregates and natural sands according to ASTM C33, and Type 1000 superplasticizer (SP), which complies with the ASTM C 494 type G admixture.

Table 4 Physical properties of LWA by A-Gong-Tie

| Item | Properties |
|---|---|
| Partical Density (g/cm$^3$) | 0.8 |
| Absorption Capacity 1 hr (%) | 4.2 |
| Absorption Capacity 24 hr (%) | 8.9 |
| Rate of floating particles (%) | 92.0 |
| Dmax (mm) | 12.7 |
| Fineness Modulus (FM) | 6.65 |
| The gross weight (kg/m$^3$) | 541.7 |
| Gross unit weight (kg/m$^3$) | 574 |

Table 5 Mixture proportions of HPLWC

| Batch | W/b | Water | Cement | Slag | Fly ash | Sand | LWA | | SP | Unit weight |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Content | Particle Density | | |
| ACI | 0.32 | 159 | 498 | 0 | 0 | 503 | 410 | 1100 | 0 | 1570 |
| NO. 1 | 0.40 | 150 | 222 | 12 | 143 | 806 | 460 | 1100 | 6 | 1799 |
| NO. 2 | 0.32 | 150 | 315 | 17 | 137 | 773 | 441 | 1100 | 12 | 1845 |
| NO. 3 | 0.28 | 150 | 384 | 20 | 133 | 750 | 427 | 1100 | 25 | 1543 |
| NO. 4 | 0.32 | 140 | 283 | 14 | 141 | 795 | 453 | 1100 | 11 | 1837 |
| NO. 5 | 0.32 | 160 | 348 | 18 | 133 | 751 | 428 | 1100 | 7 | 1845 |
| NO. 6 | 0.32 | 140 | 285 | 15 | 138 | 780 | 613 | 1500 | 24 | 1995 |
| NO. 7 | 0.32 | 150 | 319 | 17 | 134 | 758 | 596 | 1500 | 12 | 1986 |
| NO. 8 | 0.32 | 160 | 352 | 19 | 130 | 736 | 579 | 1500 | 9 | 1985 |
| NO. 9 | 0.32 | 150 | 317 | 17 | 135 | 758 | 287 | 700 | 24 | 1688 |

### *2.2. Test variables*

Table 5 shows the nine mixture proportions for preparing HPLWC. Three different volumes of mixing water, 140, 150, and 160 kg/m$^3$ were employed to manufacture HPLWC, using LWA of different particle densities (700, 1100, and 1500 kg/m$^3$) at three *W/b* ratios (0.28, 0.32, and 0.40).

### *2.3. Test measurements*

The particle density and absorption capacity of LWA were tested according to ASTM C127. Test cylinders were cast following the procedure of ASTM C192. The slump and slump flow of the fresh concrete were determined in accordance with ASTM C143. The compressive strength of the cylindrical concrete specimens was tested following ASTM C31. The electrical resistance coefficient of HPLWAC was measured by the concrete resistivity meter (C.N.S. Electronics Ltd.). The dimensions of the specimen for compressive strength, and electric resistivity were 100×200 mm. Specimens of 40×200×200 mm were made according to DIN 51046, for measuring the coefficient of thermal conductivity on the surface at 10°C and 40°C, using a quick thermal conductivity meter (QTM-D2). The hydrated and shrunken specimens of 101.6×101.6×279.4 mm were demoded 24 hours after casting, and cured under water at a temperature of 23±2°C for 28 days.

## 3. Results and discussion

### *3.1. Properties of LWA*

#### *3.1.1. Composition and expansion*

Table 1 show that the dredged silt is composed mainly of silt and clay and has a specific gravity (Gs) of about 2.7. The oxide composition of the dredged silt from reservoirs influences both the expansion properties and sintering temperature (Yen 2003). As seen in Table 2, the dredged silt contains oxides including $SiO_2$ (57-73%), $Al_2O_3$ (11-23%) and $Fe_2O_3$ (4-11%). According to the proposed guidelines by Riley (1990), dredged silt from reservoirs in southern Taiwan can serve as an ideal raw material for sintering into LWA. Expansion of initial particles is dependent on the ratio of gross unit weight before and after sintering. As shown in Table 3, Better expansion results in lower ratio. The ratio of gross unit weight after sintering ranges between 0.33 and 0.87.

#### *3.1.2. Absorption capacity*

LWA have a porous structure (Lin *et al*. 2007) and thus high absorption capacity. Expanded materials after sintering have an absorption capacity of less than 10%, which is often higher than that of normal-weight aggregates (<3%), but much lower than that of LWA (20-40%) (Rossignolo *et al*. 2003). Table 3 shows that LWA sintered in a rotary kiln have an absorption capacity of less than 10%, except for those made using dredged silt from Hu-Tou-Bei. These results indicate that LWA obtained from sintered silt have a low absorption capacity, making them ideal for concrete production.

#### *3.1.3. Particle density*

LWA sintered at higher temperatures have more pores and lower particle density. Table 3 lists the particle density of LWA. Under the same sintering conditions in a rotary kiln, almost all LWA made of dredged silt have particle density ranging between 700 and 1700 kg/m$^3$, with only that made from silt taken from Hu-Tou-Bei being higher than the rest (2100 kg/m$^3$).

#### *3.1.4. Compressive strength of single LWA particle*

Aggregates with higher strength and hardness can enhance the strength and durability of concrete produced. When pressure is exerted on the concrete, the main supporting system is borne by the cement mortar. The support of the LWA varies with the modulus of elasticity and stress distribution (Chen *et al.* 1999). The aggregate crushing strengths and cylinder crushing strength were tested to Chinese National Standard GB2842-81. Oven-dried samples of the aggregate were placed in a steel cylinder with an internal diameter of 115 mm and a height of 145 mm. The strengths of the samples were measured under compression by a steel plunger to a prescribed distance of 20 mm. In this study, the compressive strength of a single LWA particle ranges from 5.9 to 41 MPa, as shown in Table 3. The gross unit weight of LWA is between 423-973 kg/m$^3$. As can be seen heavier the gross unit weight results in greater cylindrical crushing strength and higher compressive strength of a single LWA particle.

### 3.2. Properties of HPLWC

#### 3.2.1. Slump and slump flow

In this study, HPLWC of different mixture proportions have a slump between 230-270 mm, and a slump flow of 450-610 mm. Such workability of the fresh concrete meets design requirements.

#### 3.2.2. Rheological properties

Fig. 1 shows that a lower W/b ratio will produce larger torque of the HPLWC. In addition, after the mixing time, cement hydration occurs and after 60 minutes, torque value tends to increase. Mixed high viscosity has high initial torque, although after stirring the torque becomes smaller. Thus, the use of slurry with proper viscosity to support aggregates would increase the performance and reduce the popping up (Hsiao *et al*. 2002).

#### 3.2.3. Compressive strength

As seen in Fig. 2, the compressive strength of HPLWC reaches 60 MPa after 56 days of curing, The mixes satisfy the concrete strength criteria of structural lightweight concrete as per ASTM C330 (2000), which requires a minimum 28-day cylinder compressive strength of 17 MPa. This is

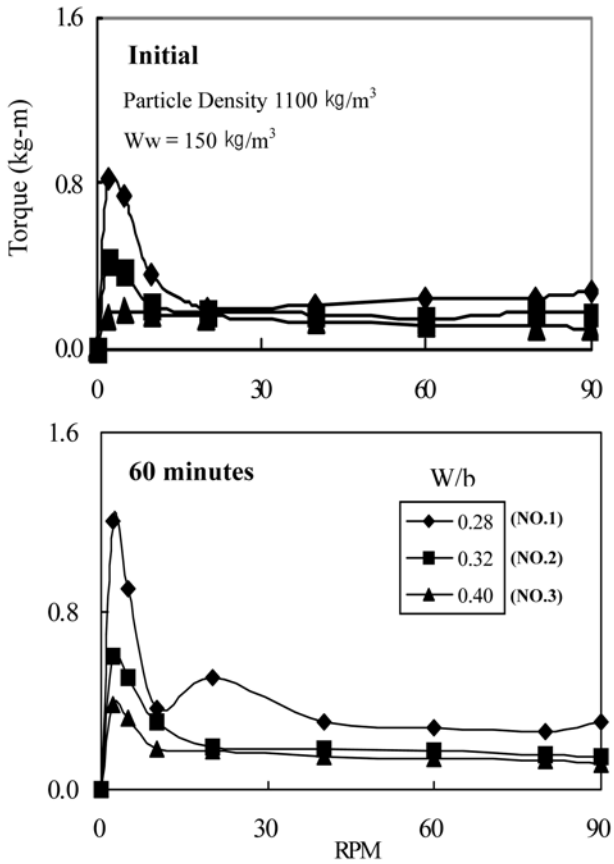


Fig. 1 Relationship between torque of HPLWC and rotation speed for different *W/b* ratios

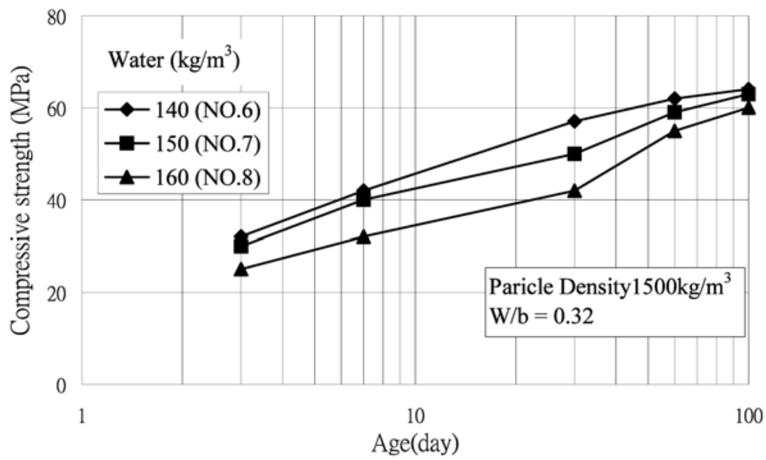


Fig. 2 Changes in compressive strength of HPLWC with different amounts of mixing water used

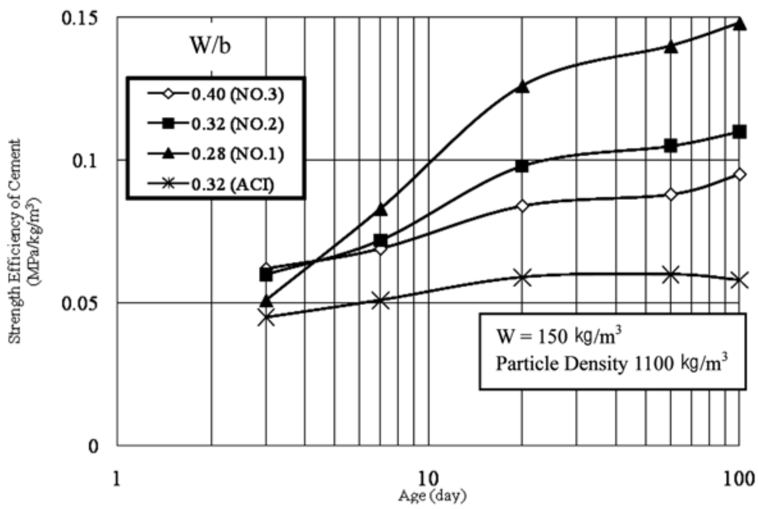


Fig. 3 Effects of *W/b* ratios on strength efficiency of cement

in agreement with the results obtained by Rossignolo *et al.* (2003). Because the strength of LWA is lower than that of cement slurry, splitting tension may occur, as noted by Gerrits (1998) according to the result of cleaving damage model.

### 3.2.4. Strength efficiency of cement

Fig. 3 shows that with *W/b* ratio of 0.32 and 0.4 and LWA of particle density 1100 kg/m$^3$, the strength efficiency of cement exceed 0.1 MPa/kg/m$^3$, showing better performance than that of cement mixed according to the traditional ACI design.

### 3.2.5. Thermal conductivity coefficient

The thermal conductivity of HPLWC ranges between 0.4-0.8 Kcal/mh°C in this research, which is comparatively lower than that of normal-weight concrete (1.0-1.5 Kcal/mh°C). The lower thermal

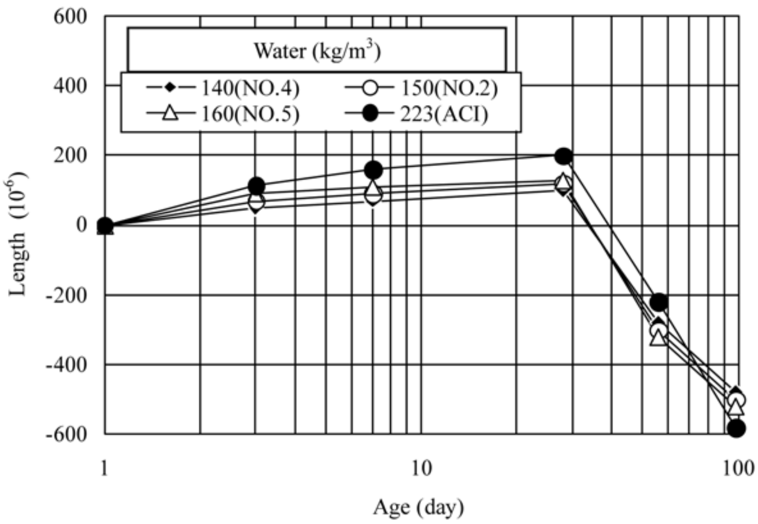


Fig. 4 Changes in length of HPLWC specimens during the 28-day curing and under Drying conditions

conductivity of LWA can be attributed to its denser structure with fewer internal pores. Hence, using LWA for construction can help reduce power consumption for air-conditioning in hot summers.

### 3.2.6. Shrinkage

Fig. 4 shows the expansion of HPLWC at 28 days and its shrinkage at 98 days. As can be seen, HPLWC shrinks less than $4.8\times10^{-4}$. In both circumstances, the increase in amount of mixing water attenuates the volumetric changes. In other words, during swelling, the observed increase in length is proportional to the quantity of mixing water used; while during shrinkage, larger quantities of

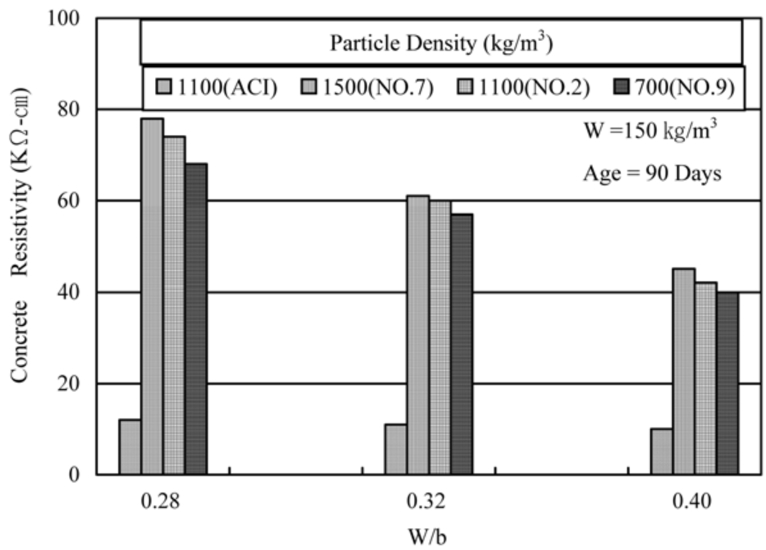


Fig. 5 Relationship between electrical resistivity with different aggregate densities and *W/b* ratios

mixing water correlated with greater reductions in length. With a constant *W/b* ratio, excess mixing water will lead to an increase in cement paste.

### *3.2.7. Electrical resistivity*

Fig. 5 shows the change in electrical resistivity of HPLWC with different *W/b* ratios. As can be seen, compared with the HPLWC, which reaches 40 kΩ-cm on Day 90, concrete mixed according to traditional ACI design (12 kΩ-cm) has much lower electrical resistivity. In addition, a lower *W/b* ratio correlates with a higher electrical resistivity.

## 4. Conclusions

1. Dredged silt from reservoirs in southern Taiwan is composed mainly of silt and clay, and has a specific gravity (Gs) of about 2.7. It is also composed of oxides including $SiO_2$ (57-73%), $Al_2O_3$ (11-23%), and $Fe_2O_3$ (4-11%), which are well suited for the sintering process.
2. Fresh HPLWC can meet the requirement of workability with a slump of 230-270 mm, and a slump flow of 450-610 mm, while retaining suitable viscosity.
3. With the same unit weight and lower *W/b* ratio, hardened HPLWC has higher compressive strength, which reaches 60 MPa after 56 days of curing, and high strength efficiency of cement, exceeding 0.1 MPa/kg/$m^3$.
4. With decreased W/b less mixing water used, the HPLWC has better volumetric stability. In addition, the HPLWC has electrical resistivity above 40 kΩ-cm.
5. Dredged silt from reservoirs can serve as suitable materials for making LWA and HPLWC.

## Acknowledgments

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No.NSC 98-2221-E-151-055.

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