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Development of lightweight aggregate from sewage sludge and waste glass powder for concrete

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HIGHLIGHTS

- Manufacturing lightweight aggregate from wet sewage sludge and waste glass.
- Use of waste glass improved sintering temperature, failure point loading and bulk density, decreased water absorption.
- High quality LWA with bulk density <2 g/cm^3, water absorption <10% and failure point loading as high as 892 N.
- Workable lightweight concrete with the 28-day compressive strength of 49 MPa.

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ABSTRACT

In this study, wet sewage sludge was used as the principle material and waste glass used as the additive to manufacture lightweight aggregate (LWA). The effects of different mass ratios of waste glass to sewage sludge and sintering temperatures on the aggregate properties were investigated. The selected LWA was used as coarse aggregate for producing lightweight concrete (LWC) with high workability. Results showed that the used of waste glass improved sintering temperature, decreased water absorption and increased failure point loading and bulk density of aggregate. The addition of 30–50% of waste glass produced the high quality LWA with bulk density lower than 2 g/cm^3, water absorption lower than 10% and failure point loading as high as 892 N. Workable lightweight concrete with the 28-day compressive strength of 49 MPa was obtained. Results of surface resistivity and ultrasonic pulse velocity of LWC indicated that the produced LWC could be considered as good quality concretes.

1. Introduction

Concrete industry is facing with a declining availability of natural resources used as raw and construction materials, i.e. aggregates and cement. To deal with the problems, more attention has been paid to the development of many kinds of artificial lightweight aggregates (LWA) and geo-polymer binders [1,2] from different waste streams. The use of LWA in concrete provides several advantages such as handling the declining natural resources, reduction of dead load, production of lighter and smaller pre-cast elements, reductions in the sizes of columns and slab and beam dimensions, higher thermal insulation and better fire resistance [3].

Sewage sludge is the final by-product of the wastewater purification process in the treatment plants. Significant scientific research has conducted to evaluate the production of LWA from sewage sludge. Generally speaking, most previous studies have focused on the use of dewatered sewage sludge and sewage sludge ash [4–6]. However, when only sewage sludge ash was used, both combustion and sintering processes required. This leads to an increment of the cost of construction and operation and more energy consumption during production [5]. Conversely, in case of only sewage sludge was used, porous and loose aggregates were produced due to high organic matter and water content in sewage sludge [4,5]. Normally, no greater than 30% sewage sludge should be used [4]. In practical, in order to improve the performance of manufactured LWA, sewage sludge should be mixed with suitable materials such as sewage sludge ash [4], coal ash [5], clay [6], washing aggregate sludge and clay-rich sediment [7].

Reusing of waste glass poses a major problem for municipalities worldwide. In Taiwan, the amount of waste glass that is dumped

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into landfills has accumulated to approximately 0.52 million tons [8]. Many studies have focused on the reuse of waste glass as aggregates in concrete and as a supplementary material [8,9] through its good pozzolanic reactivity when fineness is suitable [10]. Waste glass contains high amount of Na_2O that can reduce sintering temperature resulting from its relatively low melting point [11]. Therefore, the addition of waste glass into raw materials in the production of LWA can lead to an enhancement of sintering reaction.

The feasibility of using wet sewage sludge as the principal material for production of LWA was conducted in this study. LWA was produced by adding 10–50% waste glass to the as-received sewage sludge from a local sewage treatment plant. The specific wet granulation process was applied to form pellets. The produced LWA was sintered in a commercial kiln under various temperatures in the range of 830–1100 °C. The properties of raw materials and the manufactured LWA were tested. Afterward, the selected LWA was used as coarse aggregates to make high flowing lightweight concretes (LWC). Additionally, the mechanical and durability properties of concretes were tested and examined according to relevant standards.

2. Experimental methods

2.1. Manufacture of lightweight aggregates

The sewage sludge used in this study was collected from a local sewage treatment plant in Taiwan. The moisture content of as-received sewage sludge was in range of 70–80% by mass. The waste glass was supplied by a local waste processing plant. The waste glass was oven-dried at temperature of 105 °C for 24 h and ground in a ball mill to particle sizes of less than 150 μm.

The manufacturing process for LWA is shown in Fig. 2. To produce a uniform paste, the as-receive sewage sludge was mixed with waste glass at various weight ratios (as shown in Table 1) by a food mixer. When the amount of waste glass was low, the paste could be used without the addition of water. When the amount of waste glass was high, it was necessary to add some water into paste in order to form cylindrical pellets. A special granulating pellet machine was used. There were two main steps to form the pellets in the process by the machine. First, the paste including sewage sludge and waste glass was intruded into a correlation system of this machine. Cylindrical pellets with about 0.6–1 cm in diameter and 30–50 cm in length were formed in this step. Second, the cylindrical pellets were intruded into another correlation system one by one for manufacturing sphere-shape pellets. By the method, 5 kg pellet could be produced for 0.5 h. Therefore, there is a feasibility of pellet production to be used in concrete industry. The freshly manufactured pellets were dried at 105 °C in an oven for 24 h and then sintered in the commercial electric kiln at various temperatures as shown in Table 1. 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 temperature as designed for a fixed period of 20 min, and then slowly cooled down to ambient temperature. It can be seen that the use of the manufacturing process results into less the cost of construction and operation and less energy consumption during production of LWA.

2.2. Quality tests of lightweight aggregates

The characteristics of the manufactured aggregates were determined, including the SEM micrograph, 24-h water absorption, bloating index and bulk density. The bloating index (BI) in this study was defined as the volume change after firing, calculated by the equation $BI = 100(d_2–d_1)/d_1$, where d_1 and d_2 are the diameters of the LWA before and after sintering, respectively [7]. For the aggregate strength, failure point loading that refers to as failure loading of a single aggregate in one single point was estimated. In such a way, each single LWA was pressed down by a steel puncheon unit until it was crushed, and then failure point loading was recorded. The test was done by the Acme Penetrometer with model of HM-570. The crushing strength was done according to the Chinese National Standards CNS 14779 for lightweight aggregate [12]. 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. The procedure of the method is similar to that of EN 13055-1:2002 standard [13]. The test was only done on the selected LWA for using in concretes.

Table 1
Mix proportion and sintering temperatures of lightweight aggregates.

ID	Sewage sludge (%)	Glass powder (%)	Sintering temperature (°C)
G10	90	10	880, 900, 930, 950, 970, 1000, 1050, 1070, 1100
G30	70	30	850, 880, 900, 930, 950, 970,1000
G50	50	50	830, 850, 880, 900, 930, 950, 970

Table 2
Chemical composition of raw materials (unit:%).

Item (%)	Cement	Fly ash	Sewage sludge	Glass powder
SiO_2	22.01	50.25	36.2	74.0
Al_2O_3	5.57	27.16	14.4	6.0
Fe_2O_3	3.44	6.3	9.2	0.3
CaO	62.80	4.71	6.6	9.7
MgO	2.59	1.55	2.9	0
SO_3	2.08	0.66	11.0	0.2
K_2O	0.78	0.85	2.5	0.8
Na_2O	0.40	0.42	0	8.2
TiO_2	–	–	1.2	0
P_2O_5	0.05	1.06	15.0	0

2.3. Concrete made with lightweight aggregates

2.3.1. Materials

ASTM Type I Portland cement confirming to ASTM C150 [14] and Class F fly ash confirming ASTM C618 [15] were used as binder in concrete. Their chemical compositions are shown in Table 2. Based on the bulk density and failure point loading results, the LWA with 30% waste glass sintered at 970 °C (G30-970) was selected to be used as coarse aggregate. The selected LWA with volume fraction passing 9.5 mm sieve and retained on 4.75 mm sieve was chosen for using in concrete. The properties of the selected LWA were specific gravity 1.20 g/cm^3, water absorption capacity 1.2%, crushing strength 5.27 MPa and loose bulk density 800.3 kg/m^3. Natural sand (modulus of fineness 3.0, density 2.65 and absorption capacity 1.4%) was provided from local quarries. The mixing water was tap water. ASTM C494 Type G superplasticizer [16], having 43% solid content with specific gravity of 1.06 ± 0.02, was used to achieve the desired workability for all concrete mixtures.

2.3.2. Testing program

Concrete was made with natural coarse aggregate and LWA. Water-to-binder ratio (w/b): 0.30 was chosen to test the effect of LWA on the properties of concrete. Mixture proportions of LWC are listed in Table 3. Due to high water absorption property of sintered LWA, additional water equivalent to 30 min water absorption capacity of aggregate was added to the concrete mixture. Concrete was mixed in a laboratory pan mixer. Firstly, Portland cement and fly ash were mixed with water followed by the addition of the natural sand. Then, the LWA was added. Finally, the superplasticizer (SP) was added to control slump of fresh concrete.

Slump and slump flow spread of LWC were controlled to meet the high flowing high performance concrete requirement of 230–270 mm and 500–700 mm, respectively. The concrete cylinders with dimension of 100 mm in diameter and 200 mm in height were used for the compressive strength, concrete electrical resistivity, and ultrasonic pulse velocity tests. The specimens were cured in saturated limewater at the temperature of 23 ± 2 °C. The compressive strength test was done according to ASTM C39 [17]. Since the degree of saturation of the concrete affected the pulse velocity and electrical resistivity, all specimens were tested in the saturated surface dry condition to evaluate the test results under the same conditions. A concrete electrical resistivity meter manufactured by the CNS Company in UK (Four-point Wenner Array Probe method) was used in this study for determining the electrical resistance. The ultrasonic pulse velocity test was conducted according to ASTM-597 [18].

3. Results and discussion

3.1. Properties of raw materials in the manufacturing process

As shown in Table 2, the chemical compositions of sewage sludge were: SiO_2 36.2%; Al_2O_3 14.4% and Flux (Fe_2O_3, CaO, MgO, Na_2O and K_2O) 21.2%, and those of waste glass were: SiO_2 74%; Al_2O_3 6.0% and Flux 19%. The compositions of each single raw material did not locate in the range of expansive clay (SiO_2: 48–