



Article

Reuse of Sintered Sludge from Municipal Sewage Treatment Plants for the Production of Lightweight Aggregate Building Mortar

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Abstract: In recent years, the sludge produced by municipal sewage treatment plants has become an important recyclable resource for producing green building materials. After the systematic processing of incineration and particle formation, the sintered sludge can be processed into fine lightweight aggregate to produce building mortar with the controlled leaching of heavy metals and radioactivity. In this paper, to increase its economic and environmental benefits, mortar with sintered sludge aggregate was made by cement admixing of fly ash or limestone powder. The water-to-binder ratio was set at three levels—0.82, 0.68, and 0.62—and either fly ash or limestone powder was used to replace equal masses of cement at 10%, 20%, or 30%. Eighteen groups of mortar were studied to evaluate their workability, air content, compressive strength, tensile adhesive strength, dry density, and thermal conductivity. The results indicate that with a proper water-to-binder ratio, and the replacement ratio of fly ash or limestone powder, the mortar can be produced with good workability, consistency, water-retention rate, layering degree, and setting time. The mortar made with sintered sludge lightweight aggregate, designated by the mix-proportion method for conventional lightweight aggregate mortar, did not meet the target strength, although the compressive strength of mortar was no less than 3.0 MPa, which meets the strength grade M2.5. The tensile adhesive strength reached 0.18 MPa. The mortar was super lightweight with a dry density less than 400 kg/m³, and a thermal conductivity within 0.30–0.32 W/(m·K). The effects of water-to-binder ratio and replacement ratio of fly ash or limestone powder on the above properties are discussed with test results. The study provides a basis for using sintered sludge lightweight aggregate for building mortar.

Keywords: municipal sewage sludge; sintered sludge; fine aggregate; super lightweight mortar; workability; dry density; air content; compressive strength; tensile adhesive strength; thermal conductivity



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1. Introduction

Sludge is a product of sewage treatment, which is a complex composition of extremely heterogeneous organic fragments, bacteria, inorganic particles, and colloids. The increased quantity of sewage sludge has become a global environmental solid waste pollution problem. Normally, four disposal methods of sludge are used: agricultural utilization, sanitary landscaping, incineration, and building materials [1,2]. With the increasing requirements of the green utilization of sludge to ensure environmental protection, the two former disposal methods of sludge have been prohibited to avoid potential secondary pollution in many countries in recent years. Therefore, the disposal trends of sewage sludge are its incineration and its utilization in building materials [3–6].

The possibility of using sewage sludge for building materials comes from the similarity of its mineral components of SiO_2 , Al_2O_3 , and CaO to conventional building materials. Therefore, raw sewage sludge can be used to directly replace clay and shale when producing bricks [7–13]. In this aspect, some of the expensive and energy-intensive stages of sludge disposal can be eliminated, and environmentally harmful waste can be transformed into safe and stable products [4,5,14]. Moreover, the organic-carbon-containing complexes of sewage sludge can be burned out, and the inorganic composites can then be reformed into ash or slag [6,15,16]. If blended with binder material, such as river sediment, to make pellets, a lightweight aggregate for concrete can be fabricated by incineration [17–20]. Comparatively, the sludge ash after incineration is always applied as a mineral additive to cement, or as a mineral admixture with concrete [16,21,22]. Slag treated as a fine-aggregate has been used in concrete products. Given the porosity and light weight of sintered sludge slag, the concrete products formed from it have better thermal and acoustic insulation properties so can be used for lightweight building walls [23–25].

As noted in a previous study [26], sintered sludge with the main component being silico-calcium was made from the municipal sewage produced by treatment plant of Zhengzhou City, China, by a systematic process of pellets formation and pyrolysis gasification at high temperature of about 1000 °C. Through the second processing of crushing and polishing of the large particles, the sintered sludge was produced into a lightweight fine aggregate with a required particle grading of middle-class sand. The study confirmed that the sintered sludge fine aggregate met the criteria for heavy metal content and the radioactivity index, with no risk of leaching or radioactivity when recycled as a lightweight sand. Based on above literature analyses, lightweight sand can be used for masonry mortar meeting the requirement for autoclaved aerated concrete blocks [27–29]. With the combination of the environmental utilization of fly ash and limestone powder in mineral admixtures, this mortar can be produced with better economic and environmental benefits [30–32]. In this study, fine lightweight aggregate produced from sintered sludge was used in the production of masonry mortar. Eighteen groups of mortar were prepared with changes to both the water-to-binder ratio and the replacement ratio of either fly ash or limestone powder for cement at equal mass [33–35]. The workability and air content of fresh mortar, and the compressive strength, tensile adhesive strength, dry density, and thermal conductivity of hardened mortar, were measured using standard test methods [36,37]. The effects of the test factors on the above properties of mortar are discussed based on the test results. The study indicates the feasibility of producing mortar with fine-aggregate sintered sludge, and provides a route to reuse the sewage sludge as a building material.

2. Experimental Work

2.1. Raw Materials

The fine aggregate was made of sintered sludge with continuous particles in grading that met the requirement for building fine aggregate, as presented in Figure 1. The physical properties of the fine aggregate are presented in Table 1. According to the specification of Chinese codes GB/T14684 and GB/T17431.1 [38,39], the fine aggregate belongs to middle sand with particle grading in region-II in the 900 density class. Due to the large percentage of apertures distributed on the surface of the aggregates, the fine aggregate is featured by fast saturation with water absorption. The water absorption at 15 min and 1 h was 17.1% and 17.4%, respectively, reaching about 87.7% and 89.2% at 24 hours, respectively.



Figure 1. Photos of sintered sludge: (a) a prototype of sintered sludge; (b) graded fine aggregate.

Table 1. Physical properties of the fine, lightweight aggregate sintered sludge.

Fineness Modulus	Apparent Density (kg/m ³)	Bulk Density (kg/m ³)	Mud Content (%)	Moisture Content (%)	Porosity (%)
2.6	2103	869	2.2	1.0	44.7

The binders used were grade 42.5 Portland cement, second-class fly ash (FA), and first-class limestone powder (LP). The chemical components are presented in Table 2. The physical and mechanical properties are presented in Tables 3 and 4. The properties met the specifications of Chinese codes GB/T1596, GB/T35164, and GB175 [31,32,40].

Table 2. Chemical compositions of cement, fly ash, and limestone powder.

Property	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	SO ₃	f-CaO	Loss on Ignition
Cement	20.81	3.28	5.99	60.12	2.13	2.23	0.67	3.5
FA	55.92	5.91	17.31	6.59	3.82	1.93	0.26	2.6
LP	0.89	1.44	6.27	47.78	0.48	27.38	6.65	5.51

Table 3. Physical and mechanical properties of cement.

Density (g/cm ³)	Water for Standard Consistency (%)	Specific Surface Area (m ² /kg)	Fluidity (mm)	Setting Time (min)		Compressive Strength (MPa)			Flexural Strength (MPa)		
				Initial	Final	3d	7d	28d	3d	7d	28d
3.09	27	360	164	170	215	27.5	39.2	58.5	5.4	6.8	8.3

Table 4. Physical properties of fly ash and limestone powder.

Material	Apparent Density (kg/m ³)	Specific Surface Area (m ² /kg)	Activity Index (%)		Water Demand Ratio (%)	Mobility Ratio (%)	Fineness: Residual on Sieve (%)	
			7 d	28 d			80 μm	45 μm
FA	2340	406	-	73.3	84	-	5.48	21.75
LP	2780	428	62.6	61.6	-	103	1.20	25.00

The plasticizer produced by Kezijie New Materials Co. Ltd. (Zhengzhou, China), was selected for the comparison tests. The consistency was 95.6 mm, the water-retention rate was 90.9%, and the compressive strength at 7 days was 2.05 MPa. The properties met the specification of Chinese code JG/T164 [41]. The mix water used was tap water.

2.2. Mix Proportion Design of Building Mortars

According to the design method for mixing proportions of masonry mortar, as specified in China code JGJ/T98 [33], building mortar with a strength grade of M2.5 and M5 should reach a target compressive strength of 3.0 and 6.0 MPa, respectively. After the calculations, three water-to-binder ratios were taken: 0.82, 0.68 and 0.62. The dosage of binder was 330, 380, and 420 kg/m³, respectively. After trial tests, the fly ash and limestone powder were separately used as the mineral admixture to replace cement in equal mass in percentage of 10%, 20%, or 30%. Under the condition of surface drying saturation of the fine aggregate in the mix design, the additional water computed for 1 hour water absorption was added for pre-wetting the fine aggregate before mixing. The mix proportion of the mortars is presented in Table 5.

Table 5. Mix proportions of the mortars with fine-aggregate sintered sludge.

Water to Binder Ratio	Dosage of Materials (kg/m ³)					
	Cement	FA or LP	Fine Aggregate	Water	Plasticizer	Additional Water
0.82	297	33	939	270	8.5	149.1
	264	66	939	270	8.5	149.1
	231	99	939	270	8.5	149.1
	342	38	939	260	8.5	149.1
0.68	306	76	939	260	8.5	149.1
	266	114	939	260	8.5	149.1
	378	42	939	260	8.5	149.1
0.62	336	84	939	260	8.5	149.1
	294	126	939	260	8.5	149.1

2.3. Test Methods

The fine aggregate was pre-wetted with the additional water in the mixer for 15 min. Then the binders, plasticizer, and mix water were added to mix together to prepare the mortar. As per China code JGJ/T70 [36], the workability of fresh mortar was detected, including consistency, layering degree, setting time and water-retention rate. The air content was measured to verify the rational plasticizer content. The dry density and compressive strength of the hardened mortar were measured in cubic specimens with a dimension of 70.7 mm. The tensile adhesive strength of hardened mortar was tested with 40 × 40 × 6 mm specimens. The thermal conductivity of the hardened mortar was determined using the transient plane heat source method [37], and cubic specimens with a dimension of 70.7 mm were used. Before detection, the specimen was dried to a constant weight, and the surface was polished. The diameter of the probe was 9.868 mm, and the over-rise of the temperature was 2–5 K.

3. Test Results and Discussion

3.1. Workability of Fresh Mortar

Figure 2 presents the test results of the workability of the fresh mortars. All mortars satisfied the target consistency of 60–80 mm and the water-retention rate of no less than 84% [34,35]. This indicates that the workability of the test mortars was less affected by the sintered sludge aggregate with features such as an irregular shape, multiple edges, and greater water absorption compared to the targets designated by methods for producing conventional and lightweight masonry mortar with common lightweight. The conventional relationships were observed of the increased consistency and decreased water-retention rate of mortar with the increase in water-to-binder ratio. Higher flowability of fresh mortar can be obtained with a larger water-to-binder ratio, while the layering degree was lower and the setting time increased. All mortars met the expected layering degree of no more than 30 mm [34,35]. With an expected setting time of 4 to 8 h, the water-to-binder ratio should be no more than 0.68 for the mortar without admixing fly ash or limestone powder.

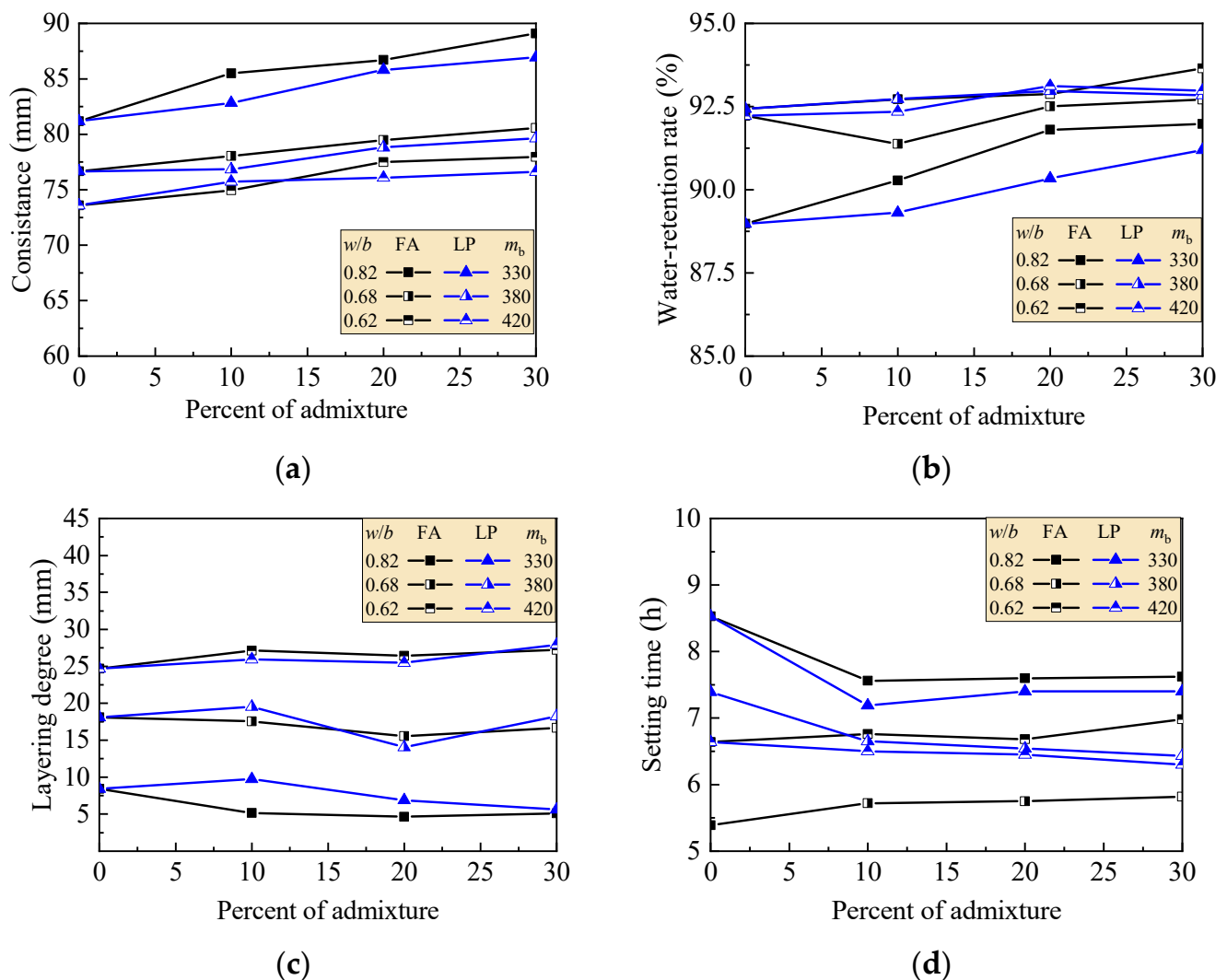


Figure 2. Test results of workability of fresh mortars: (a) consistency; (b) water-retention rate; (c) layering degree; (d) setting time.

With an increase in the replacement ratio of fly ash and limestone powder from 10% to 30%, the consistency and water-retention rate also increased. This resulted from the peculiarity of fly ash and limestone powder, having smaller particles and a greater surface area. The free water in fresh mortar increased due to the intervals being filled with smaller grains of fly ash or limestone powder becoming locked in the internal fresh mortar [30,42]. With good consistency and water retention, the layering degree of fresh mortar was slightly influenced by the replacement ratio of both fly ash and limestone powder. When the water-to-binder ratio was 0.62, the layering degree of fresh mortar tended to increase with the increasing replacement ratio of both fly ash and limestone powder. However, the layering degree of the mortars containing 30% fly ash or limestone powder was below the limit of 30 mm. The setting time for fresh mortars with a water-to-binder ratio of 0.82 became shorter due to the presence of either fly ash or limestone powder. This may have been a combined effect of the crystal nuclei in fly ash and limestone powder and specific pozzolanic activity [30,42,43], which accelerated the hydration of cement, leading to the formation of crystals.

3.2. Air Content

The changes in the air content of fresh mortars using a replacement ratio of fly ash or limestone powder are presented in Figure 3. Changing the replacement ratio in fresh

mortars with the same water-to-binder ratio had less of an influence on their air content. However, the air content in the fresh mortar increased with an increase in the water-to-binder ratio. This ensured that the mortar had better water retention when the water-to-binder ratio increased to 0.82. With an increase in the replacement ratio using fly ash, the air content increased about 1%. However, with a replacement ratio of limestone powder at 10%, the air content in the fresh mortar decreased. This was due to an aggregate effect of the limestone powder on the density of the binder paste [30,42]. The same effect happened in fresh mortar using a replacement ratio of limestone powder at 20% and a water-to-binder ratio of 0.82. When the replacement ratio increased to 30%, the fresh mortar's air content was almost higher compared with the mortar made without admixing fly ash or limestone powder.

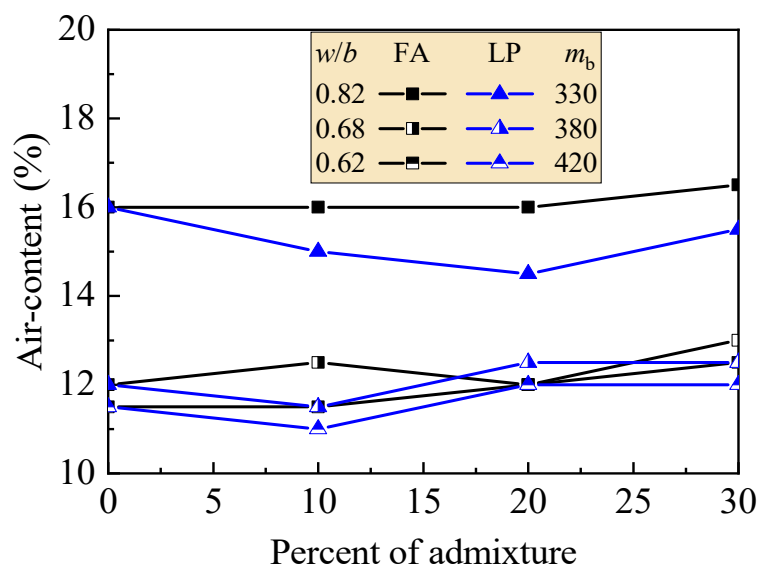


Figure 3. Test results of the air content of fresh mortars.

3.3. Compressive Strength

The test results of the compressive strength of mortar at curing ages of 14 and 28 days are presented in Figure 4. The conventional relationship shows that the compressive strength increased with the decrease in water-to-binder ratio for the mortar with sintered sludge lightweight aggregate. Compared to the test results at a curing age of 28 days, the compressive strength of mortar at 14 days was affected much more by the replacement of fly ash and limestone powder. Due to the differences in the chemical compositions and activity indices, different effects were observed for fly ash and limestone powder.

The compressive strength of mortar at the curing age of 14 days increased with the replacement ratio of 10% fly ash, due to the activity of fly ash from the second hydration of the main chemical constituent, SiO_2 , with the hydration product Ca(OH)_2 of cement [30,43]. When the replacement ratio increased continuously to 20% and 30%, the compressive strength of the mortar decreased. This may be due to the inadequate hydration product Ca(OH)_2 with the decrease in cement dosage in mortar. In this case, although the compressive strength of the mortar may be increased by the small aggregate effect of fly ash on the density of the mortar, the increase could not compensate for the decrease in compressive strength.

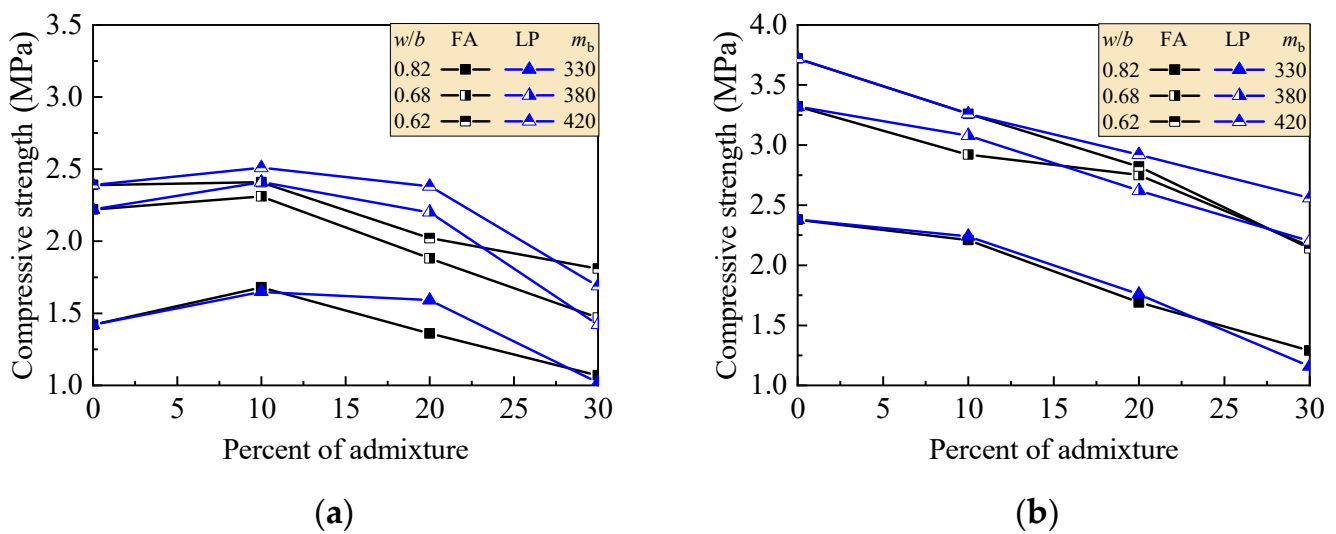


Figure 4. Test results of the compressive strength of mortars: (a) at a curing age of 14 days; (b) at a curing age of 28 days.

With a higher content of f-CaO and CaO, as presented in Tables 2 and 4, limestone powder had higher activity at an early age when used to produce cement stone. This resulted in an increase in the mortar's compressive strength at a curing age of 14 days when the replacement ratio was 10%. Combined with the crystal nuclei and tiny-aggregate filling effects, the mortar with a replacement ratio of 20% limestone powder had almost the same compressive strength as the mortar made without limestone powder.

Similar to the time-dependent compressive strength of concrete [44], the compressive strength of the mortar increased with the increase in curing age from 14 to 28 days. However, with the curing age of 28 days, the activity of fly ash and limestone powder no longer enhanced the compressive strength of the mortar. This trend of decreased compressive in appeared for the mortars with an increased replacement ratio of either fly ash or limestone powder. This indicates that the main source of crystals was the hydration of the cement. Due to a decrease in cement dosage, along with an increase in the replacement ratio of fly ash and limestone powder, the shortage of cement-forming crystals could not be accounted for by the contribution of fly ash and limestone powder with a combination of pozzolanic activity, crystal nuclei, and tiny-aggregate filling effects.

From the test results of compressive strength, no mortar met the target M5 strength requirement. This indicates that the mortar with sintered sludge lightweight aggregate had a lower compressive strength than the target designated by the mix-proportion method for mortars made with conventional lightweight aggregate. However, the mortars with a water-to-binder ratio of 0.62 and a replacement ratio of no more than 20% and those with a water-to-binder ratio of 0.68 and a replacement ratio of no more than 10% met the target strength of M2.5.

3.4. Tensile Adhesive Strength

The test results for the tensile adhesive strength of mortar at a curing age of 28 days are presented in Figure 5. Without admixing fly ash or limestone powder, the mortar's tensile adhesive strength increased with decreasing water-to-binder ratio. This relationship was maintained when limestone powder was added, but disturbed when fly ash was added. This reflects the different actions of fly ash and limestone powder in the mortar's internal structure [45]. However, with an increase in the replacement ratio of either fly ash or limestone powder, the mortar's tensile adhesive strength generally decreased. A lower tensile adhesive strength was found for the mortar with limestone powder at a water-to-binder ratio of no less than 0.68. Due to the lower activity of fly ash and limestone powder, no adequate crystals formed from their hydration of them to compensate for the decrease with the decreased dosage of cement.

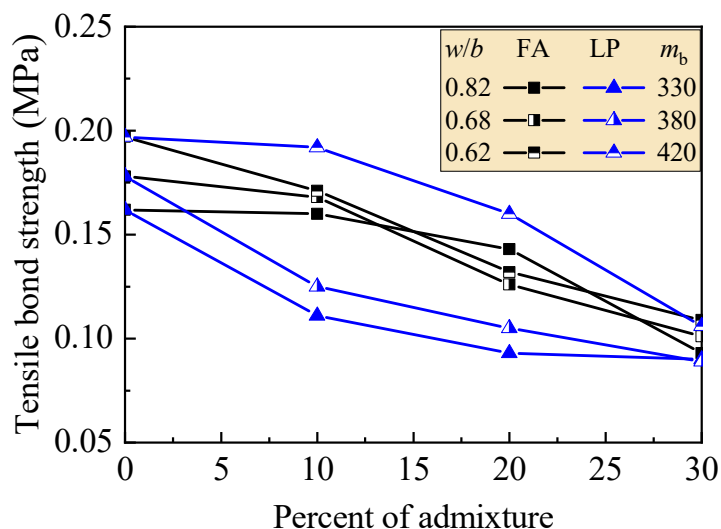


Figure 5. Test results of the tensile adhesive strength of mortars.

The mortar made with sintered sludge lightweight aggregate presented a lower tensile adhesive strength than the target. According to the test results for tensile adhesive strength, no mortar in this study met the target tensile adhesive strength of no less than 0.20 MPa for masonry mortar [34,35]. However, the mortars with replacement ratios of 10% fly ash with a water-to-binder ratio no more than 0.68 and the mortars with replacement ratios of 10% limestone powder with a water-to-binder ratio of 0.62 met the target value of 0.18 MPa for plastering mortar of autoclaved aerated concrete walls [35].

3.5. Dry Density and Thermal Conductivity

The test results of the dry density and thermal conductivity of the test mortars are presented in Figure 6. The dry density of mortar presents a decreased trend with the increase in the replacement ratio of either fly ash or limestone powder. This may be mainly due to the lower density of fly ash and limestone powder than that of cement, as presented in Tables 3 and 4. With an equal mass of cement, the volume of fly ash and limestone powder is larger than that of cement. So, the density of mortar is lower. In this study, the dry density of mortar was below 370 kg/m³. Therefore, a super lightweight mortar can be produced using the fine aggregate of sintered sludge.

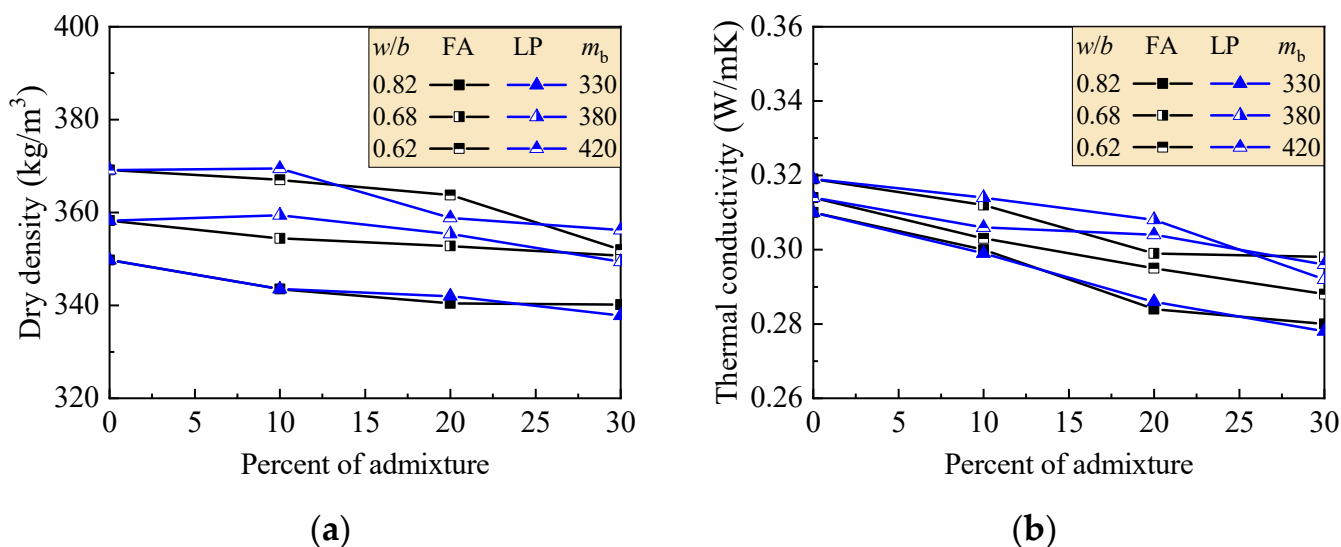


Figure 6. Test results of the compressive strength of mortars: (a) dry density; (b) thermal conductivity.

The mortar with a water-to-binder ratio of 0.82 presented the lowest thermal conductivity, while the mortar with a water-to-binder ratio of 0.68 presented the highest thermal conductivity. The mortar with a water-to-binder ratio of 0.62 had a value of thermal conductivity between the values stated above. This indicates that the thermal conductivity of mortar is not only related to its density, but that it is also dependent on its pore structure [24,27]. The mortar's air content presented in Figure 3 may be suitable at about 12% to form an ideal internal bubble distribution in the mortar. In terms of meeting the requirement of M2.5, the thermal conductivity of mortar can be controlled within 0.30–0.32 W/(m·K).

4. Conclusions

Based on the experimental investigation in this study, conclusions were drawn as follows:

- (1) The mortar made with fine lightweight aggregate of sintered sludge satisfied the target consistency of 60–80mm and the water-retention rate of no less than 84%. The workability of the test mortar was less affected by the sintered sludge aggregate with features such as irregular shape, multi-edges, and greater water absorption. However the consistency and water-retention rate increased with an increase in the replacement ratio of fly ash or limestone powder ranging from 10% to 30%.
- (2) A lower strength was obtained for the mortar made with sintered sludge lightweight aggregate than the target designed using the mix-proportion method for mortars made with conventional lightweight aggregate under the same conditions. The mortars with a water-to-binder ratio of 0.62 and a replacement ratio of no more than 20%, and the mortars with a water-to-binder ratio of 0.68 and a replacement ratio of no more than 10% met the target strength of grade M2.5. No mortar in this study met the target tensile adhesive strength of no less than 0.20 MPa for masonry mortar. However, the mortars with replacement ratios of 10% fly ash with a water-to-binder ratio of no more than 0.68, and the mortars with a replacement ratio of 10% limestone powder with a water-to-binder ratio of 0.62 met the target value of 0.18 MPa for plastering mortar used in autoclaved aerated concrete walls.
- (3) The dry density of the mortar was below 370 kg/m³. Therefore, a super lightweight mortar can be produced using a fine lightweight aggregate made from sintered sludge. The air content for mortar may be suitable at a value of about 12%. For cases of meeting the requirement of M2.5, the thermal conductivity of mortar can be controlled within 0.30–0.32 W/(m·K).
- (4) The experimental study in this paper is initial research into the feasibility of the use fine lightweight aggregate of sintered sludge in building mortar. To obtain further economic and environmental benefits from the recycling of solid waste, producing mortars made with sintered sludge lightweight aggregate by admixing fly ash or limestone powder is a valuable method. Further studies should be carried out to optimize the incineration techniques of sludge and the mix-proportion of mortar to meet the requirements of these specifications.

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