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A Feasibility Study on Textile Sludge as a Raw Material for Sintering Lightweight Aggregates and Its Application in Concrete

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Abstract: This study aimed to investigate the feasibility of textile sludge as a raw material for sintering lightweight aggregates (LWAs) and its application in concrete. Three samples of different components were taken from the textile sludge, which came from different textile factories in Taiwan. The analysis of the chemical composition of the sludge shows that the total content of SiO_2, Al_2O_3, and Fe_2O_3 in the textile sludge was far lower than the recommended value in the literature, and that glassy melt could not be produced and sintered into LWAs alone. Therefore, the water purification sludge obtained from a water purification plant owned by the Taiwan Water Supply Company was used as the main raw material, and the textile sludge was used as the auxiliary raw material in addition amounts of 7.5%, 15.0%, and 22.5%. The test results showed that the LWAs sintered by adding textile sludge to water purification sludge could reach the particle density that is generally required for LWAs (between 0.2 and 1.8 g/cm^3). The 14-day compressive strength of the lightweight aggregate concrete made from textile-sludge-based LWAs was between 20 and 25 MPa. This means that textile-sludge-based LWAs can be used in secondary structural concrete.

Keywords: water purification sludge; textile sludge; sintering; lightweight aggregate; concrete

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Citation: Chen, H.-J.; Chang, W.-T.; Tang, C.-W.; Peng, C.-F. A Feasibility Study on Textile Sludge as a Raw Material for Sintering Lightweight Aggregates and Its Application in Concrete. *Appl. Sci.* **2023**, *13*, 6395. https://doi.org/10.3390/app13116395

Academic Editor: Syed Minhaj Saleem Kazmi

Received: 2 May 2023
Revised: 20 May 2023
Accepted: 22 May 2023
Published: 24 May 2023

1. Introduction

Textile sludge refers to the sludge that is produced by the textile industry in the secondary biological treatment equipment of wastewater, or it can refer to the sludge, which only contains animal and plant residues, that is produced in the production process [1,2]. In the textile industry, the dyeing and finishing processes produce the most wastewater and sludge [3]. The wastewater from these processes contains a variety of pollutants, such as slurry, grease, dyes, surfactants, and other substances that are difficult for microorganisms to decompose [4,5]. For sludge disposal in Taiwan, methods such as incineration, solidification, and burial are often adopted. However, because the water content of the sludge is too high and the amount of auxiliary fuel required is too great, disposal by incineration will increase the treatment cost. In addition, other harmful derivatives are easily produced during incineration. If a landfill is used for disposal, it is increasingly difficult to obtain landfill sites due to the limited land area in Taiwan. In view of this, in order to make sustainable use of resources and to reduce waste production, the development of resource reuse technology for textile sludge will be the best way to achieve sustainable social development [6].

With the raising of awareness in terms of environmental protection, the source of materials for the production of artificial lightweight aggregates (LWAs) has developed toward the direction of resource recycling. In addition to using industrial by-products such as slag [7] and fly ash [8], waste sludge, such as sewage sludge, is also used as raw materials for the production of LWAs [9–12]. The authors' previous research has successfully used renewable resources, such as reservoir sediments, waste TFT-LCD glass powder, paper residue sludge, tile grinding sludge, and water purification sludge, in Taiwan to produce LWAs [13–18]. Based on the aforementioned research results, this study continues to explore the feasibility of using textile sludge as a raw material for sintering artificial LWAs.

At present, there are many ways to reuse textile sludge, including recycled bricks, concrete, compost, and biochar [19–23]. Some scholars have used textile silt to replace certain raw materials in order to manufacture various floor tiles, such as concrete floor tiles, pavement tiles, fired clay bricks, and fly ash bricks [24,25]. It was found that the textile sludge itself contains organic matter, which can delay the setting time of cement and can affect the compressive strength. With the increase in its substitution amount, the slow setting phenomenon of the sample was particularly evident, and the compressive strength decreased accordingly [26,27]. Certain scholars have reused textile sludge in cement mortar as a substitute for cement [28–32]. The test results of Goyal et al. [28] showed that when the replacement amount of textile sludge was too high, a more porous microstructure was observed, consisting mainly of ettringite, voids, and less CSH gel. Goyal et al. [32] explored the reutilization of textile sludge stabilized with low-grade MgO as a replacement of cement in mortars. The results of their experiments revealed that a replacement of up to 10% of the cement with stabilized textile sludge was found to be optimal without negatively affecting the properties of the mortar. Furthermore, the SEM images revealed the densification of the microstructure after the addition of stabilized textile sludge to the mixture.

The sludge that is produced by the solid–liquid separation process in the tap water purification plant is water purification sludge. The chemical composition of water purification sludge will vary depending on the quality of raw water and the type of coagulant. The types of coagulants can be divided into iron series and aluminum series, which will lead to different contents of aluminum and iron in sludge. However, the water source of the water purification plant remains unchanged, and the other chemical components of the sludge will not change too much. Currently, water purification sludge is reused as raw materials for cement, raw materials for red brick, culture soil, construction materials, etc. [33–40]. He et al. [36] explored the effect of the water–binder ratio (w/b) on the strength, shrinkage, and microstructural characteristics of concrete containing drinking water sludge ash (DWSA). The results showed that recycling 10% DWSA in concrete improved the strength and shrinkage resistance of the samples. Recycling DWSA in concrete effectively reduced the overall carbon footprint and cost of the mix. The combined application of reducing w/b and adding DWSA effectively improved the economic and environmental benefits of concrete materials. In addition, the water purification sludge itself can be sintered into LWAs. Huang and Wang [41] used sludge from ten different water purification plants in Taiwan, and they successfully made LWAs using the preheating temperature of 500 °C and different sintering temperatures.

In 2016, the total amount of textile sludge waste generated in Taiwan was 42,509 metric tons. Currently, the treatment of textile sludge as fuel accounts for about 30% of Taiwan's annual textile sludge. This result shows that the textile sludge itself has a certain thermal matrix. However, approximately 20% of the ash produced by combustion still requires additional processing. The problem regarding the ash generated by heat treatment has caused many problems in the industry. In order to reduce the cost of pre-treating textile sludge and to solve the problem of the ash that is subsequently generated, the potential of textile sludge as an alternative raw material for LWA manufacturing processes was investigated. The textile sludge was mixed with purified water sludge and made into LWA green pellets. By sintering at a high temperature, i.e., above 1150 °C, the feasibility of reusing it in the production of lightweight aggregates was explored.

As mentioned earlier, the high production of textile sludge around the world has caused environmental problems. In view of this, this study sintered textile sludge into LWA by means of direct prototype reuse. The research results showed that this reuse method could completely dispose of textile sludge, without the problem of secondary waste disposal, and the produced LWA was also of economic value.

2. Experimental Procedure

2.1. Experimental Program

In this study, the research was divided into two stages: laboratory-scale sintering and large-scale sintering. In the laboratory-scale stage, the chemical composition of water purification sludge and textile sludge was first analyzed in order to evaluate their suitability for sintering them into LWAs. In addition, according to the chemical composition suggested in the literature, the proportion of lightweight aggregate raw materials for mixing the water purification sludge with different contents of textile sludge was planned. Then, the sintering test was carried out, and the optimal sintering temperature was analyzed based on the particle density, water absorption rate, and ignition loss of lightweight aggregate, so as to judge the feasibility of producing synthetic LWAs with textile sludge. After completing research trials in the laboratory, the feasibility of the large-scale production of LWAs using water purification sludge blended with textile sludge was evaluated in a commercially available kiln. Furthermore, the engineering properties of the concrete made from the produced LWAs were tested and examined. The overall process is shown in Figure 1.

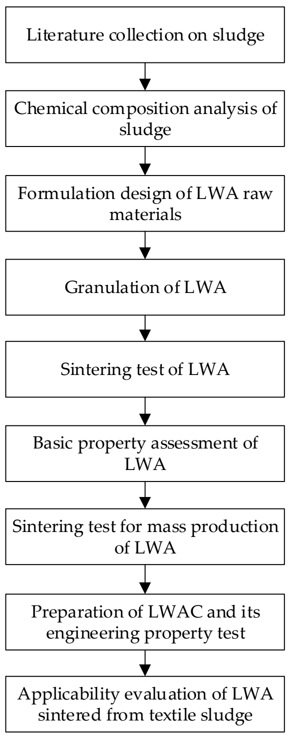


Figure 1. Research flow chart.

2.2. Materials

The three textile sludges used in this study were collected from different textile factories in Taiwan, as shown in Table 1. According to the difference in the main additives in the manufacturing process, Sample A was added with poly aluminum chloride (PAC) and polymer; Sample B was added with aluminum sulfate, polymer, and dilute acid (acetic acid and glacial acetic acid); and Sample C was added with PAC, polymer, and liquid alkali. The XRF chemical composition analysis results of the textile sludge showed that the textile sludge itself could not be used as a raw material alone in terms of being sintered into lightweight aggregates, but that it could only be added as an auxiliary raw material. The main raw material for this study was water purification sludge (WPS), which was obtained from a tap water purification plant in central Taiwan. The appearance of each sludge is shown in Figure 2. According to the results of the sludge chemical composition analysis, three different dosages of textile sludge (7.5%, 15.0%, and 22.5% by weight) were planned for artificial granulation.

Table 1. Main additives in textile sludge process.

Textile Sludge	Main Additives in the Manufacturing Process
Sample A	Poly aluminum chloride (PAC) and polymer
Sample B	Aluminum sulfate, polymer, and dilute acid (acetic acid and glacial acetic acid)
Sample C	PAC, polymer, and liquid alkali

(**a**) (**b**) (**c**) (**d**)

Figure 2. Appearance of each sludge: (**a**) WPS; (**b**) Sample A; (**c**) Sample B; and (**d**) Sample C.

2.3. Preparation of Aggregate Pellets and Sintering

The dried WPS and textile sludge were crushed into powder by a crusher, and then mixed with water in a mixer. The uniformly mixed sludge was granulated into green pellets with a diameter of around 12 mm, as shown in Figure 3. Using the two-stage rapid heating method, the dried green pellets were placed in an aluminum oxide basin for heat treatment. Two programmable high-temperature furnaces were used for preheating and for the sintering of the aggregates, respectively, as shown in Figure 4. The sintering process of the aggregate green pellets is shown in Figure 5. The green pellets were put into an oven and dried at 105 °C for 24 h. The preheating temperature was fixed at 500 °C, and the preheating time was 5 min. The sintering time was fixed at 12.5 min, and the sintering temperatures were 1150 °C, 1175 °C, and 1200 °C, respectively. Under the aforementioned conditions, the effects of different sintering temperatures on the properties of lightweight aggregates were discussed.

Figure 3. Appearance of aggregate pellets.

Figure 4. Self-designed electric laboratory furnace.

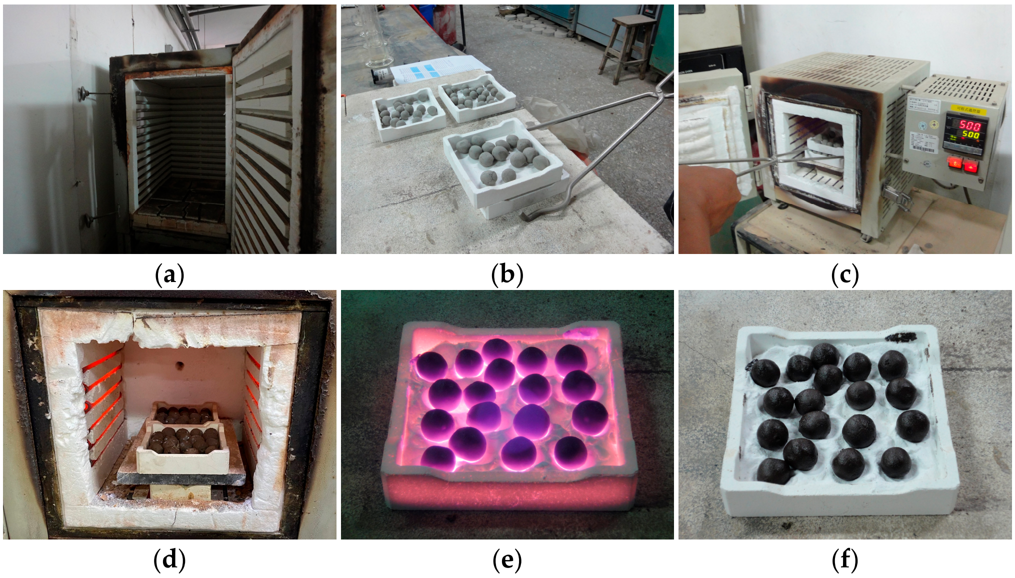


Figure 5. Sintering process of the aggregate green pellets: (**a**) drying in an oven, (**b**) dried pellets, (**c**) putting in the preheating chamber, (**d**) putting in the sintering chamber, (**e**) air cooling, (**f**) aggregates after cooling.

2.4. Test Methods

The loss on ignition for the LWAs was defined as the mass loss of the dried LWA green pellets after firing, and it was expressed as a percentage of its total initial mass. The sintered aggregate was immersed in water for 24 h to measure its water absorption. The water absorption was calculated as follows [42]:

$$\text{Water absorption} = \frac{m_s - m_d}{m_d} \times 100\% \tag{1}$$

where m_d is the dry mass (g) and m_s is the 24 h saturated surface-dry mass (g).

The particle density of the sintered aggregate was determined by the Archimedes principle, as is shown in the following formula [43]:

$$\rho_p = \frac{m_d}{m_s - m_i} \tag{2}$$

where ρ_p is the particle density (g/cm^3), m_d is the dry mass (g), m_i is the immersed mass (g), and m_s is the 24 h saturated surface-dry mass (g).

3. Results and Discussion

3.1. Chemical Composition Analysis

The key to the bloat of lightweight aggregates lies in two conditions [44,45]. One is that the material must produce a high-temperature glassy phase with a viscosity high enough to trap the gases released as the mineral decomposes. Another is that a substance must be present to release the gas at the temperature at which the glassy phase is formed. Riley proposed a three-phase diagram of the chemical composition of raw materials, as is shown in Figure 6 [46]. The "bloating area" suggested in the diagram can help identify whether the composition of the sludge material meets the requirements for bloating. Therefore, the content of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), fluxing oxides (fluxing), and the ratio of (SiO_2 + Al_2O_3)/fluxing of each sludge component will be discussed, respectively, in the following section in order to understand the feasibility of sintering these various sludges into lightweight aggregates. Table 2 shows the percentages of the various sludge chemical components that were obtained via XRF analysis.

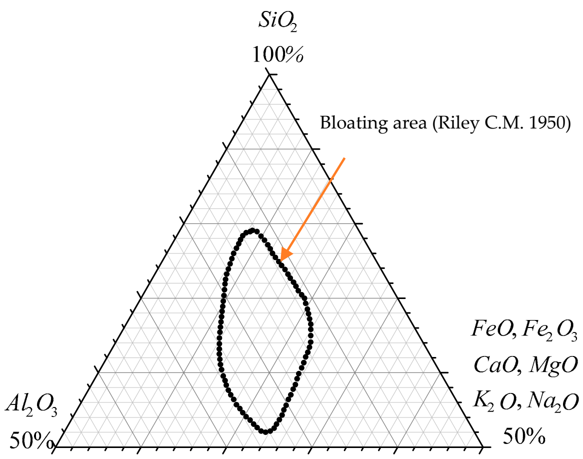


Figure 6. Bloating area in three-phase diagram.

Table 2. Chemical compositions of the different sludge sources.

Sludge Type	Chemical Constituent (%)								
	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	CaO	K_2O	Loss on Ignition	Other	Total
Sample A	14.35	44.83	0.59	6.76	0.45	7.29	19.70	6.03	100
Sample B	6.86	17.55	1.38	0.40	0.47	0.11	66.08	7.15	100
Sample C	4.43	24.07	0.71	0.21	1.25	0.04	59.77	9.52	100
WPS	58.84	19.30	6.63	1.15	1.75	3.55	4.94	3.84	100

3.1.1. Discussion on the Content of SiO_2, Al_2O_3, and Fe_2O_3

As far as lightweight aggregates are concerned, the main elements that affect its formation of glassy melt are SiO_2, Al_2O_3, and Fe_2O_3. With respect to the composition, when the content of SiO_2 accounts for more than 50% and the total content of Al_2O_3 and Fe_2O_3 accounts for around 10–30%, it is possible to produce glass at a high temperature, thus successfully producing lightweight aggregates [14,17,18,47]. Among the sludge components, SiO_2 will affect the viscosity of the vitreous material when the lightweight aggregate is sintered. When the SiO_2 content is high, the viscosity of the glass will increase, but the strength of the aggregate will be reduced. As far as Al_2O_3 is concerned, it will affect the sintering temperature, and the sintering temperature will be higher when its content is higher. When the content of SiO_2, Al_2O_3, and Fe_2O_3 is too low, it will affect the smoothness and strength of the shell of the sintered aggregate; however, when the content is too high, the melting point will increase, the viscosity will be higher, and the bloat will be poor [48].

It can be seen from Table 2 that the total content of the SiO_2, Al_2O_3, and Fe_2O_3 in the water purification sludge was 84.77%, and it was estimated that this could be sintered into lightweight aggregates with a smooth shell. However, regarding the textile sludge, the content of SiO_2, Al_2O_3, and Fe_2O_3 in Sample A was 59.77%, Sample B was 25.79%, and Sample C was 29.21%, all of which showed levels far below 75%. From this point of view, the textile sludge would not be able to produce glassy melt, and thus could not be sintered into lightweight aggregates. Therefore, this study only added textile sludge as an auxiliary ingredient.

3.1.2. Discussion on the Content of Fluxing Oxide Content

Fe_2O_3, sodium oxide (Na_2O), potassium oxide (K_2O), calcium oxide (CaO), and magnesium oxide (MgO) can all be called fluxes, which can reduce the temperature of melt formation during the firing of aggregates and can affect the temperature range of material softening [44–46]. It can be seen from Table 3 that the fluxing oxide content of Sample A was 15.09%. It can be expected that the addition of Sample A can reduce the sintering temperature of the aggregates. However, the fluxing contents of Sample B and Sample C were extremely low (2.36% and 2.21%, respectively), which means they may not be able to effectively reduce the sintering temperature of the aggregates.

Table 3. Fluxing oxide compositions of different sludge sources.

Fluxing Oxide	Code			
	Sample A	**Sample B**	**Sample C**	**WPS**
Fe_2O_3 (%)	0.59	1.38	0.71	6.63
Na_2O (%)	6.76	0.40	0.21	1.15
CaO (%)	0.45	0.47	1.25	1.75
K_2O (%)	7.29	0.11	0.04	3.55
Total (%)	15.09	2.36	2.21	13.08

3.1.3. Discussion on the Ratio of SiO_2 + Al_2O_3 Content to Fluxing Oxide Content

In the chemical composition of lightweight aggregate source materials, when the ratio of (SiO_2 + Al_2O_3)/fluxing is 3.5–10.0, it is a better-sintered material [48]. If the ratio is too small, the viscosity of the liquid phase becomes smaller, the bloating gas can more easily escape, and the bloat of the green pellets is poor. Conversely, if the ratio is too large, the required sintering temperature is high, and low-temperature sintering is not conducive to bloat. In other words, the bloating of green pellets consumes, relatively, more heat energy.

The (SiO_2 + Al_2O_3)/fluxing ratios of three kinds of textile sludge and water purification sludge are shown in Table 4. Sample A had a ratio of 3.92, Sample B had a ratio of 10.34, and Sample C had a ratio of 12.90. It can be seen from the data that although Sample A was within the range of a better-sintered material, the data were small, its liquid phase viscosity was small, and the bloating gas easily escaped from the surface, resulting in poor bloating performance. In contrast, Sample B and Sample C were not within the range of better-sintered material, indicating that the sintering temperature may need to be higher. Therefore, the three kinds of textile sludge were only added as auxiliary ingredients.

Table 4. (SiO_2 + Al_2O_3)/fluxing ratios of different sludge sources.

Item	Code			
	Sample A	**Sample B**	**Sample C**	**WPS**
SiO_2 (%)	14.35	6.86	4.43	58.84
Al_2O_3 (%)	44.83	17.55	24.07	19.30
Fluxing (%)	15.09	2.36	2.21	13.08
(SiO_2 + Al_2O_3)/fluxing	3.92	10.34	12.90	5.97

3.1.4. Analysis of the Three-Phase Diagram

Riley [46] conducted extensive research on SiO_2 + Al_2O_3 and flux oxides in the composition of lightweight aggregate source materials. He marked the proportions that can meet the bloating requirements in the three-phase diagram with dotted lines (shown in Figure 3). For the values within the marked area, it means that the composition of the material belongs to those lightweight aggregate materials that can produce high-plasticity fluid. Accordingly, among the chemical components of the water purification sludge and textile sludge samples, the contents of SiO_2, Al_2O_3, and fluxing oxide are counted in Table 5. According to the calculation results in Table 5, the three-phase diagram of the chemical composition of each sludge was drawn. As shown in Figure 7, only the results of the water purification sludge were located within the area of the three-phase diagram that indicate the appropriate melt viscosity and chemical compositions suggested by Riley. This result shows that the water purification sludge should have the potential, as raw materials, to be sintered into lightweight aggregates. In contrast, the SiO_2 contents of the three textile sludge samples, which exceeded the range of the three-phase diagram, were too low to be presented in Figure 7.

Table 5. Composition analysis based on the three-phase diagram.

Item	Range Proposed by Riley	Code			
		Sample A	Sample B	Sample C	WPS
SiO_2 (%)	53–79	14.35	6.86	4.43	58.84
Al_2O_3 (%)	12–26	44.83	17.55	24.07	19.30
Fluxing (%)	8–24	15.09	2.36	2.21	13.08
Total (%)	-	100	100	100	100

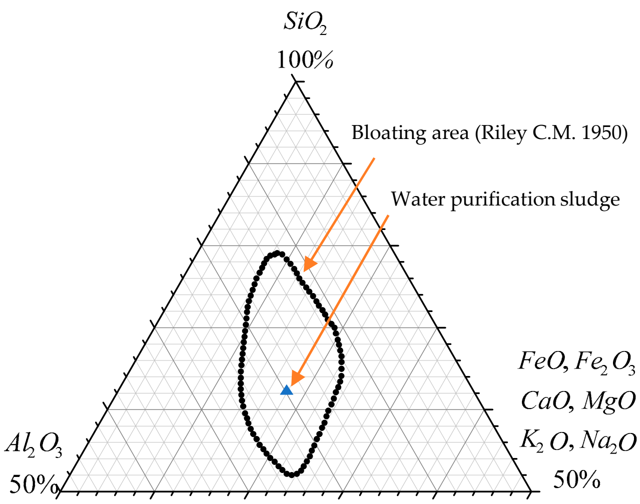


Figure 7. Three-phase diagram of the water purification sludge.

According to the above chemical composition analysis results, this study used water purification sludge as the main raw material. Textile sludge was used as an auxiliary raw material, and its blending amounts were 7.5%, 15%, and 22.5% (by weight). The chemical composition of each mixed sample is shown in Table 6. In addition, the calculation results of the chemical composition of each mixed sample were drawn into a three-phase diagram, as is shown in Figures 8–10. It can be seen from Figure 8 that after the water purification sludge was blended with the 7.5% and 15% textile sludge of Sample A, the compositions were within the "bloating area" and thus considered suitable for producing lightweight aggregates. It can be seen from Figures 9 and 10 that after the water purification sludge was blended with the 7.5% textile sludge of Sample B or Sample C, its composition was within the "bloating area" for sintering. However, the composition of the water purification sludge blended with a 15% and a 22.5% textile sludge was not within the "bloating area" for sintering.

Table 6. Chemical composition analysis of the different mixed samples.

Item	Code (Water Purification Sludge Blended with Textile Sludge Sample A)		
	A1 (WPS + 7.5% Sample A)	**A2 (WPS + 15% Sample A)**	**A3 (WPS + 22.5% Sample A)**
SiO_2 (%)	59.69	56.41	53.14
Al_2O_3 (%)	23.63	26.61	29.58
Fluxing (%)	16.68	16.98	17.27
Total (%)	100	100	100
Item	**Code (Water Purification Sludge Blended with Textile Sludge Sample B)**		
	B1 (WPS + 7.5% Sample B)	**B2 (WPS + 15% Sample B)**	**B3 (WPS + 22.5% Sample B)**
SiO_2 (%)	60.15	57.33	54.52
Al_2O_3 (%)	23.98	27.32	30.65
Fluxing (%)	15.87	15.35	14.83
Total (%)	100	100	100
Item	**Code (Water Purification Sludge Blended with Textile Sludge Sample C)**		
	C1 (WPS + 7.5% Sample C)	**C2 (WPS + 15% Sample C)**	**C3 (WPS + 22.5% Sample C)**
SiO_2 (%)	59.30	55.65	51.99
Al_2O_3 (%)	24.89	29.13	33.37
Fluxing (%)	15.81	15.22	14.64
Total (%)	100	100	100

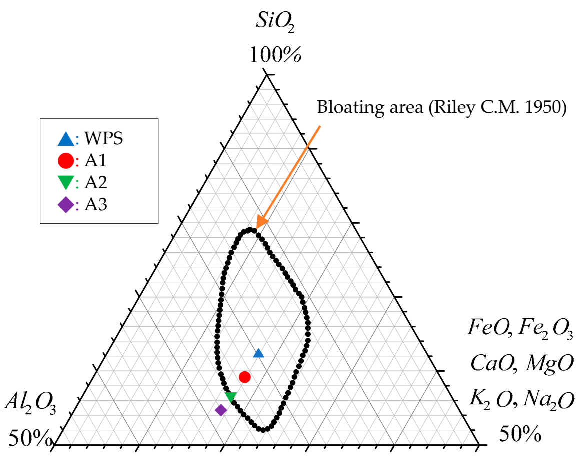


Figure 8. Three-phase diagram of the chemical composition of the water purification sludge and the Sample A sludge after blending.

3.2. Properties of Sintered Aggregates

As mentioned earlier, in the preheating stage, this study set the preheating temperature at 500 °C and the preheating time at five minutes. Then, different sintering temperatures were used as the control variables for the experiment. The green pellets were sintered at three different sintering temperatures (1150 °C, 1175 °C, and 1200 °C). The loss on ignition, water absorption, and particle density of the sintered aggregates are shown in Table 7.

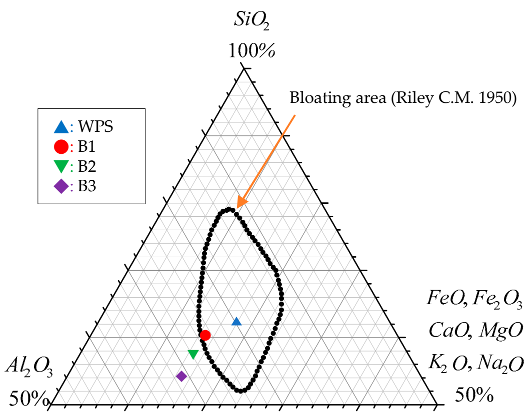


Figure 9. Three-phase diagram of the chemical composition of the water purification sludge and the Sample B sludge after blending.

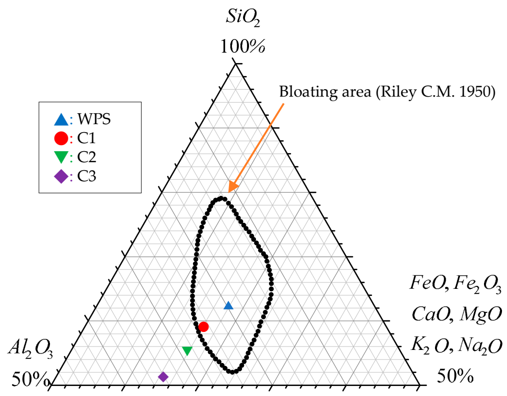


Figure 10. Three-phase diagram of the chemical composition of the water purification sludge and the Sample C sludge after blending.

Table 7. Properties of the sintered aggregates under different sintering temperatures.

Code	Preheating Stage		Sintering Stage		Loss on Ignition (%)	Aggregate Property	
	Preheating Temp. (°C)	Preheating Time (min)	Sintering Temp. (°C)	Sintering Time (min)		24 h Water Absorption Rate (%)	Particle Density (g/cm^3)
WPS	500	5	1150	12.5	5.72	10.91	1.77
			1175		5.77	8.84	1.92
			1200		5.81	5.07	1.90
A1	500	5	1150	12.5	11.14	10.70	1.10
			1175		10.88	9.18	0.85
			1200		10.97	13.29	0.54
A2	500	5	1150	12.5	19.92	12.93	1.09
			1175		15.52	10.65	0.90
			1200		15.74	12.14	0.58
A3	500	5	1150	12.5	21.17	16.21	1.08
			1175		20.47	13.40	0.81
			1200		21.19	10.37	0.54
B1	500	5	1150	12.5	10.88	14.29	1.00
			1175		10.21	15.33	0.82
			1200		10.91	16.49	0.60

Table 7. *Cont.*

Code	Preheating Stage		Sintering Stage		Loss on Ignition (%)	Aggregate Property	
	Preheating Temp. (°C)	Preheating Time (min)	Sintering Temp. (°C)	Sintering Time (min)		24 h Water Absorption Rate (%)	Particle Density (g/cm^3)
B2	500	5	1150 1175 1200	12.5	15.28 15.33 14.84	16.99 18.10 17.67	1.05 0.96 0.73
B3	500	5	1150 1175 1200	12.5	18.51 18.59 18.67	18.43 20.56 17.17	1.23 1.02 0.91
C1	500	5	1150 1175 1200	12.5	9.88 9.87 9.74	13.69 14.00 17.54	1.07 0.85 0.69
C2	500	5	1150 1175 1200	12.5	14.86 14.75 15.00	17.45 16.99 16.02	1.19 1.04 0.82
C3	500	5	1150 1175 1200	12.5	19.12 19.15 19.47	22.02 18.72 14.22	1.10 0.99 0.90

3.2.1. Loss on Ignition and Water Absorption Rate of the Sintered Aggregates

The loss on ignition of the sintered aggregate is plotted in Figure 11. It can be clearly observed from Figure 11 that—at the same sintering temperature—the more textile sludge that was added, the greater the loss on ignition, which was between 9.74% and 21.19%. Among them, regardless of the type of textile sludge, the loss on ignition was the largest when adding 22.5% of textile sludge. This means that there were many organic matter components in the textile sludge. Therefore, the more textile sludge that was added, the greater the loss on ignition.

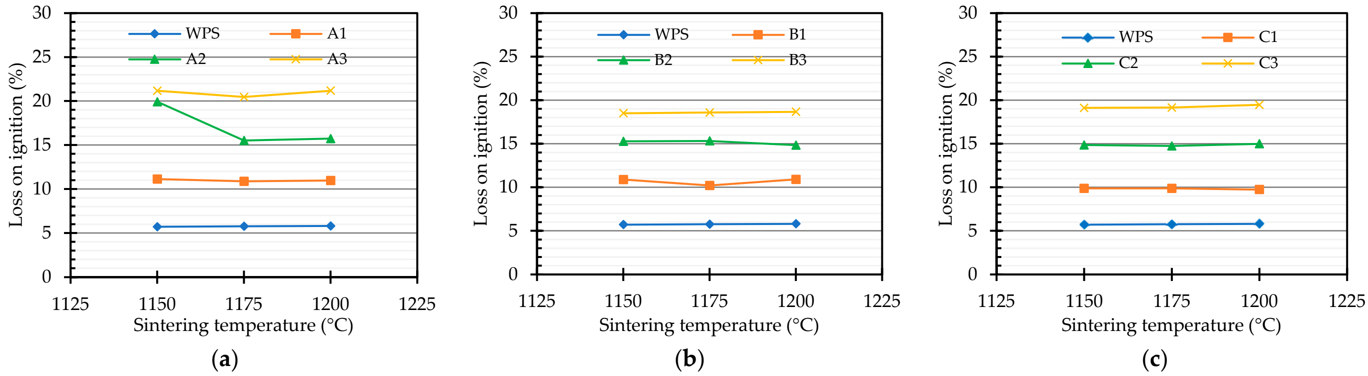


Figure 11. Relationship between the loss on ignition and the sintering temperature for water purification sludge blended with textile sludge: (**a**) Sample A; (**b**) Sample B; and (**c**) Sample C.

Further, the water absorption rate of the sintered aggregate is shown in Figure 12. It can be seen from Figure 12 that when the sintering temperature increased, the water absorption rate of the aggregate that used only WPS as the material source decreased from 10.91% to 5.07%. Regarding the rate of A1, A2, and A3, it ranged from 9.18% to 16.21%; B1, B2, and B3 ranged from 14.29% to 20.56%; and C1, C2, and C3 ranged from 13.69% and 22.02%. The results show that after water purification sludge was blended with textile sludge, the water absorption rate of the sintered aggregates increased. In particular, when the water purification sludge was mixed with the textile sludge from Sample B and Sample C, the water absorption rate of the sintered aggregates increased significantly.

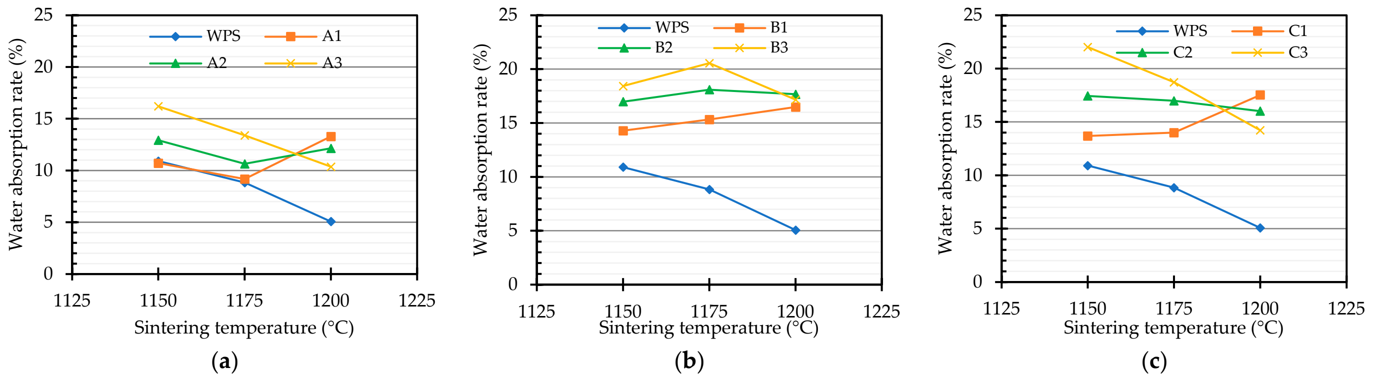


Figure 12. Relationship between the water absorption rate and sintering temperature for the water purification sludge blended with textile sludge: (**a**) Sample A; (**b**) Sample B; and (**c**) Sample C.

3.2.2. Particle Density of the Sintered Aggregates

The particle density of the sintered aggregate is plotted in Figure 13. It can be seen from Figure 13 that the particle density range of those that were sintered without adding textile sludge, i.e., those with only water purification sludge as the main raw material, ranged from 1.77 to 1.90 g/cm^3. During the sintering process, the particle density of the samples added with three kinds of textile sludge could be effectively reduced. Regardless of the type of textile sludge blended, the particle density of the sintered aggregates became smaller as the sintering temperature increased. At the sintering temperature of 1150–1200 °C, adding textile sludge from Sample A, Sample B, and Sample C resulted in the particle density ranges of the sintered aggregates being 0.54–1.1, 0.6–1.23, and 0.69–1.19 g/cm^3, respectively. Among them, after adding textile sludge from Sample A, the particle density of the sintered aggregate was lower than 1.1 g/cm^3. When the sintering temperature was increased to 1200 °C, the particle density of the sintered aggregate was even lower than 0.6 g/cm^3. However, at different sintering temperatures, the amount of added textile sludge from Sample A had little effect on the particle density of the sintered aggregates. Adding textile sludge from Sample B and Sample C could also significantly reduce the particle density of the sintered aggregate, and the higher the sintering temperature, the smaller the particle density of the sintered aggregates. Among them, the particle density obtained by adding 7.5% of textile sludge was the smallest. It can be seen from the test results that the particle density of the aggregates sintered by adding textile sludge to water purification sludge could meet the requirements of general lightweight aggregates (between 0.2 and 1.8 g/cm^3).

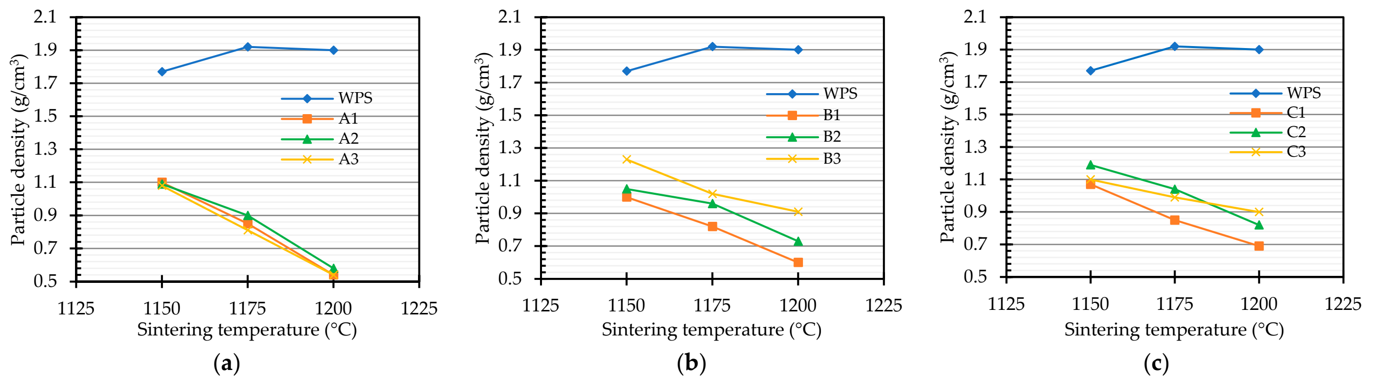


Figure 13. Relationship between the particle density and sintering temperatures for water purification sludge blended with textile sludge: (**a**) Sample A; (**b**) Sample B; and (**c**) Sample C.

3.2.3. Appearance of the Sintered Aggregates

The appearance of the sintered aggregates of the water purification sludges blended with textile sludge from Sample A, Sample B, and Sample C are shown in Figures 14–16, respectively. From the appearance of the aggregates in these figures, it can be seen that no matter what kind of textile sludge was used as an auxiliary material, the sintered product did not have a large volume change, and that no phenomenon of over-burning or sticky particles occurred. These are lightweight aggregates with complete particle sizes, and are suitable for use as concrete aggregates. However, compared with that at the lower sintering temperature of 1150 °C, the appearance of the aggregates sintered at 1200 °C was darker. It is presumed that the sintering temperature was close to the over-burning temperature, and the high temperature might cause the aggregate to be over-burned and deformed. Figure 16 shows that when textile sludge from Sample C was added, the appearance of the aggregate had obvious cracks. This result resulted in a greater water absorption in the aggregates (as shown in Table 7), which was not conducive for these aggregates to be used for structural concrete.

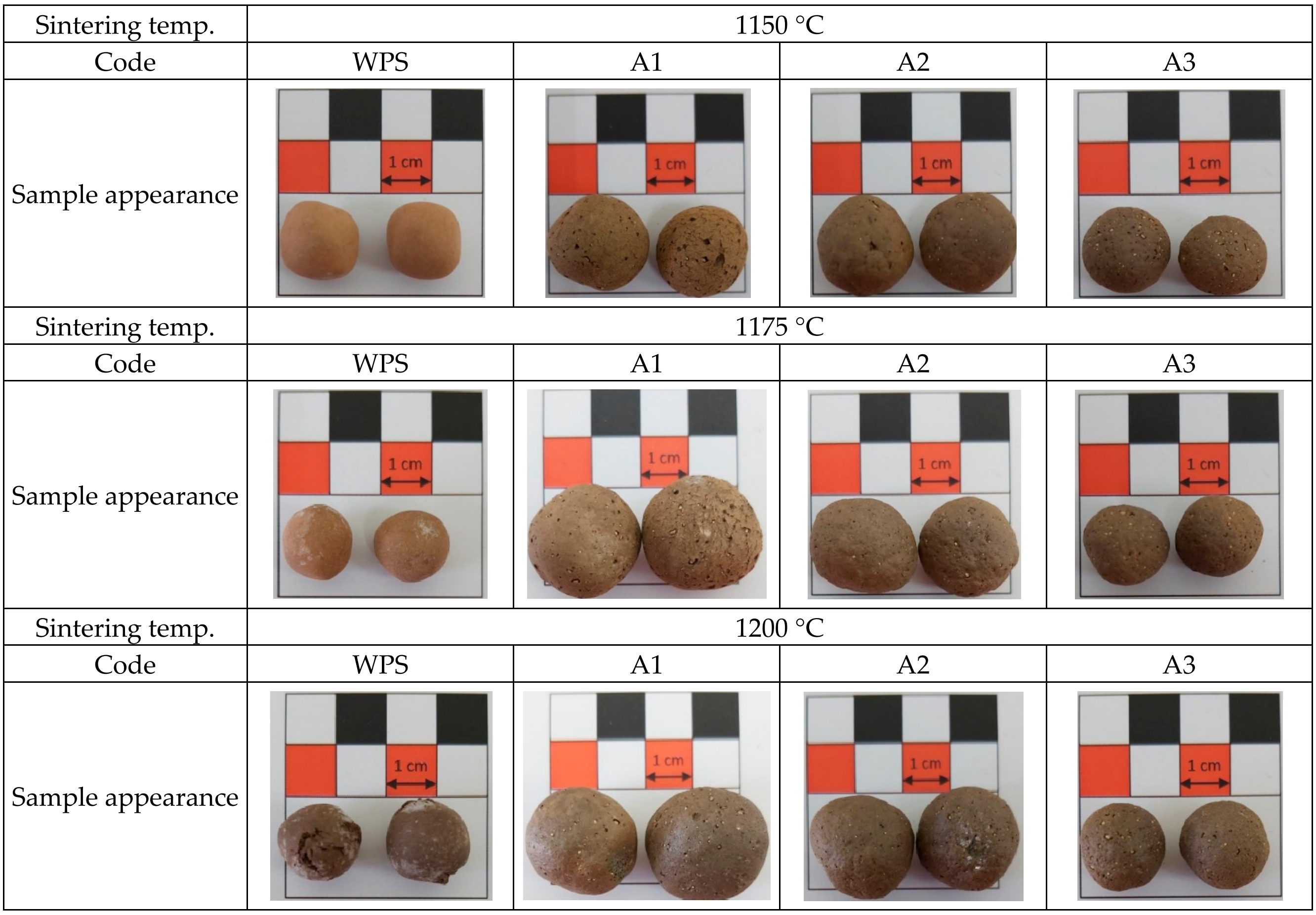


Figure 14. Appearance of the sintered aggregates of water purification sludge blended with textile sludge from Sample A.

3.3. Experimental Results of Textile-Sludge-Based LWA Concrete

According to the abovementioned lightweight aggregate test data, this study used water purification sludge blended with 15% of textile sludge from Sample A to conduct a large number of sintering tests at a sintering temperature of 1150 °C. The particle density of the sintered lightweight aggregate was 1.10 g/cm^3, and its water absorption rate was 12%. Then, three groups of lightweight aggregate concrete with different strengths (different water–binder ratios) were planned, as shown in Table 8, to verify the attainable strength of the textile-sludge-based lightweight aggregate concrete (LWAC).

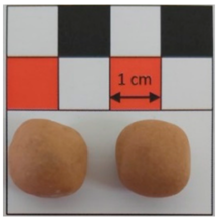
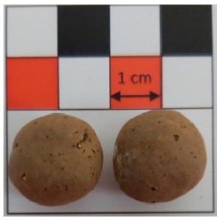
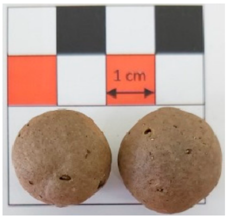
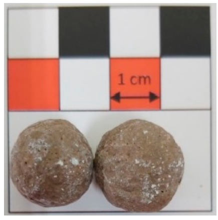
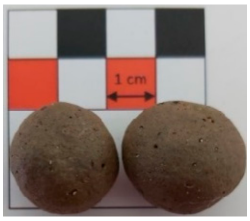
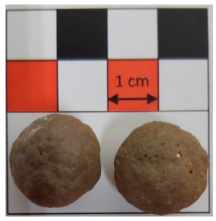
Sintering temp.	1150 °C			
Code	WPS	B1	B2	B3
Sample appearance				
Sintering temp.	1175 °C			
Code	WPS	B1	B2	B3
Sample appearance				
Sintering temp.	1200 °C			
Code	WPS	B1	B2	B3
Sample appearance				

Figure 15. Appearance of the sintered aggregates of water purification sludge blended with textile sludge from Sample B.

The test results show that the slump of each group of concrete was between 15 and 20 cm, and the fresh unit weight was between 1700 and 1750 kg/m^3. According to ACI Committee 213 [49], a structural LWAC is concrete that (a) has a minimum compressive cylindrical strength at 28 days of 17.24 MP, (b) has a corresponding air-dry unit weight not exceeding 1850 kg/m^3, and (c) consists of all LWA or a combination of LWA and normal weight aggregates. The results of the compressive strength test of the textile-sludge-based LWA concrete are shown in Figure 17. It can be seen from the figure that the 14-day compressive strength of the three groups of concrete could exceed 20 MPa, which thus reached the general strength requirement level of lightweight aggregate concrete. This result means that textile-sludge-based LWAs can be used in general building structures. The LWA produced from textile sludge has certain basic properties and can be applied to concrete for general secondary structures, such as steel bridge decks or lightweight partition wall panels for buildings. Its weight reduction effect is very good, which can greatly reduce the cost of construction.

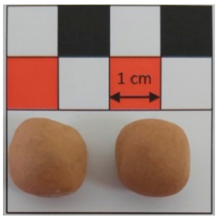
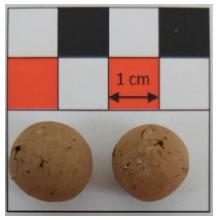
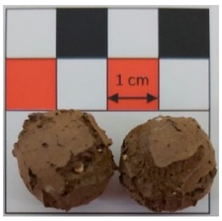
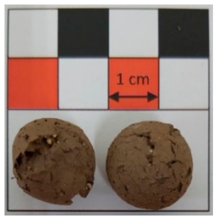
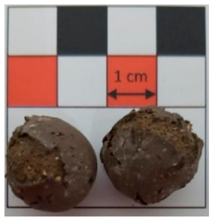
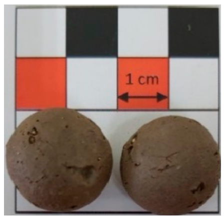
Sintering temp.	1150 °C			
Code	WPS	C1	C2	C3
Sample appearance				
Sintering temp.	1175 °C			
Code	WPS	C1	C2	C3
Sample appearance				
Sintering temp.	1200 °C			
Code	WPS	C1	C2	C3
Sample appearance				

Figure 16. Appearance of the sintered aggregates of water purification sludge blended with textile sludge from Sample C.

Table 8. Mix proportions of the textile-sludge-based lightweight aggregate concrete.

Mix No.	W/B	Water (kg/m^3)	Cement (kg/m^3)	Slag (kg/m^3)	Fly Ash (kg/m^3)	LWA (kg/m^3)	FA (kg/m^3)
LC1	0.36	210	350	175	58	370	584
LC2	0.39	210	323	162	54	377	615
LC3	0.43	210	293	147	49	382	649

Note: W/B, water–binder ratio; LWA, lightweight aggregate; and FA, fine aggregate.

3.4. Comprehensive Discussion of Test Results

In the selection of aggregates for cement concrete, although the mechanical and chemical properties of the aggregate must be considered, its physical properties such as specific gravity, bulk density, and water absorption are also very important. For example, the water absorption or water content of aggregates affects the workability of fresh concrete and affects the strength and durability of hardened concrete. Therefore, the moisture dynamics of the aggregate have a more profound effect than its hardness. In this study, nine kinds of raw material formulations were planned, and the tests of sintering LWAs in high-temperature furnaces were carried out at different sintering temperatures. The obtained results were compared with related literature using sludge as a raw material, as shown in Table 9. It can be seen from Table 9 that the results of the loss on ignition, water absorption rate, and particle density of sintered LWAs in this research were all within the scope of the relevant literature.

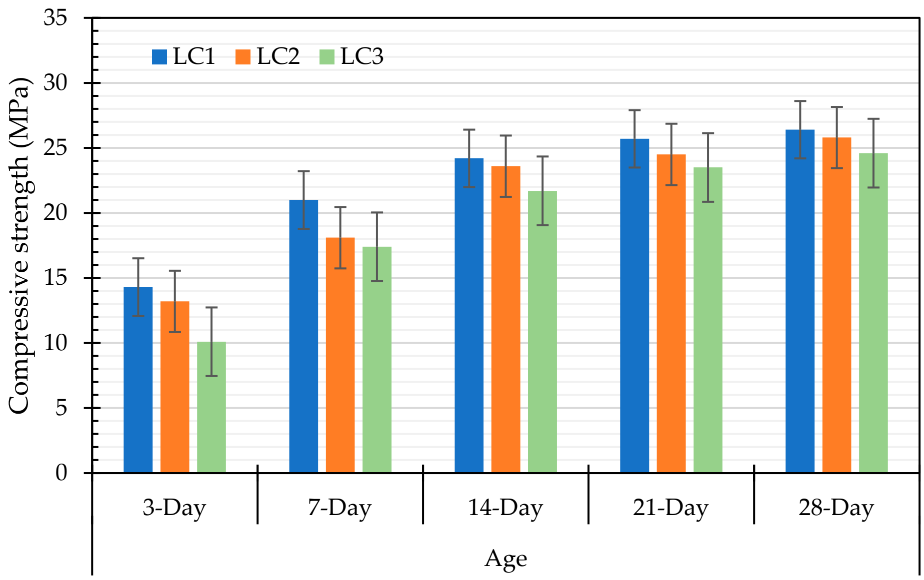


Figure 17. Compressive strength of the textile-sludge-based LWA concrete.

Table 9. Comparison of test results of sintered lightweight aggregates with related literature.

Literature	Raw Material	LOI (%)	Water Absorption (%)	Particle Density (g/cm^3)
[16]	Reservoir sediments and wastewater treatment sludge	9.8–28.9	1.2–20.3	0.41–1.63
[17]	Sediment clay and paper sludge	6–43	2–30	0.66–1.93
[18]	Reservoir sediments and tile grinding sludge	3.5–6.7	0.6–13.4	0.43–2.1
[41]	Water treatment sludge	-	0.5–15	0.65–2.05
[11]	Water treatment sludge and acid clay	-	2.5–20	0.8–1.2
This study	Water purification sludge and textile sludge	9.74–21.19	9.18–22.02	0.54–1.23

The appearance and texture of the LWAs sintered from different raw material formulations were roughly similar, as shown in Figures 14–16. The color of the aggregate was close to reddish brown, which was caused by the change in the valence of ferric ions in the sludge chemical composition at the expansion temperature. In addition, except that the LWAs sintered from Sample C had obvious cracks on the outside, the LWAs sintered from Samples A and B had no obvious cracks, but there were foaming pores inside.

Compared with the literature [16–18], the particle density of the textile-sludge-based LWAs fired in this study was between 0.54 and 1.23 g/cm^3, which was narrow and low. However, the particle density generally met the category of general LWAs. Particle density is the most important physical property of LWAs. Generally, the particle density of normal-weight aggregates is about 2.4–2.7 g/cm^3, and the unit weight of the concrete mixed with it is about 2300–2400 kg/m^3. LWAs can have different particle density requirements depending on the application. Generally, the unit weight of lightweight aggregate concrete must be lower than 2000 kg/m^3, so the corresponding particle density requirements for LWAs must be lower than 1.7–1.8 g/cm^3. If it is applied to non-structural LWAC or thermal insulation LWAC, the particle density of LWAs must be lower than 1.0 g/cm^3.

According to the difference in unit weight and strength, ACI divides lightweight concrete into three grades: low-density concretes (0.7–2.0 MPa), moderate-strength concretes (7–14 MPa), and structural concretes (17–63 MPa), as shown in Figure 18 [49]. Low-density concrete is generally used for thermal insulation buildings; medium-strength concrete is often used for concrete blocks and other structures that require a little strength; and structural concrete is used for structures that require strength. In addition, there is ultra-light lightweight concrete with a unit weight of less than 1000 kg/m^3; its strength is less than 6.9 MPa and its thermal conductivity is less than 0.3 W/m·K, and it is mainly used for heat insulation, such as roof insulation or firewalls. It can be seen from Table 7 that under the condition of a sintering temperature of 1150 °C, the particle density of the sintered LWA was greater than 1.0 g/cm^3. However, under the conditions of sintering temperatures of 1175 °C and 1200 °C, the particle density of the sintered LWA was less than 1.0 g/cm^3. From this point of view, the textile-sludge-based LWAs sintered in this study were more suitable for secondary structural LWAC or thermal insulation LWAC.

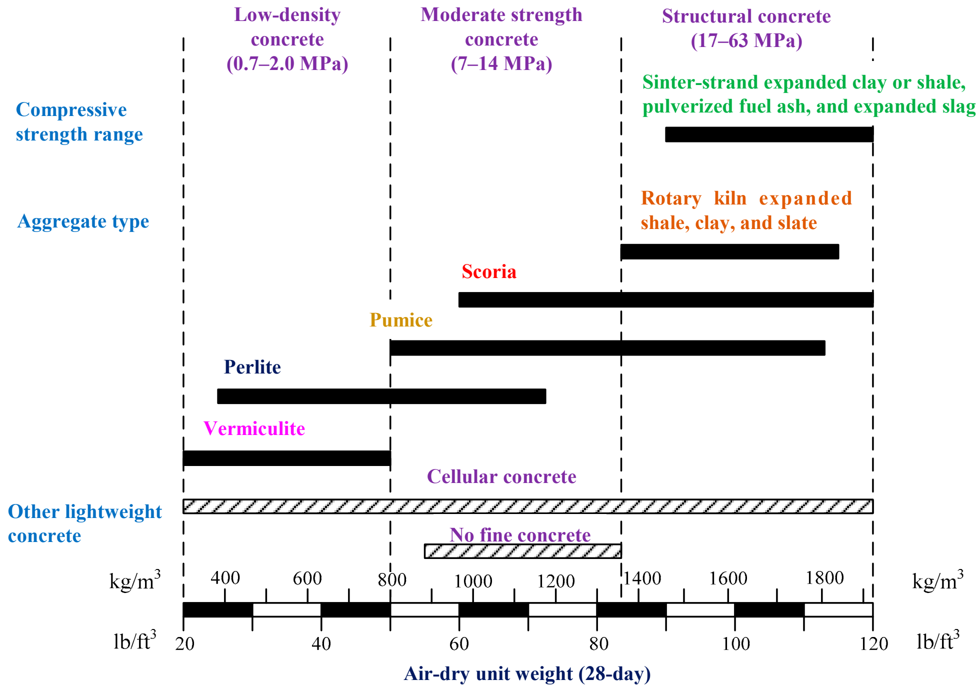


Figure 18. Unit weight and classification of lightweight concrete.

4. Conclusions

In this study, the feasibility study on textile sludge as a raw material for sintering lightweight aggregates was explored. According to the test results and analysis, the major findings are summarized as follows:

1. The total content of SiO_2, Al_2O_3, and Fe_2O_3 in the water purification sludge was 84.77%, which could be used as a source for the sintering of lightweight aggregates. In the textile sludge from Sample A, Sample B, and Sample C, the total contents of SiO_2, Al_2O_3, and Fe_2O_3 were 59.77%, 25.79%, and 29.2%, respectively, which were far lower than the required 75% threshold. As such, the selected textile sludge could not produce a glassy melt and could not be sintered into lightweight aggregates. Therefore, textile sludge can only be used as an auxiliary component for sintering lightweight aggregates;
2. Regarding the chemical composition of the raw materials used for sintering lightweight aggregates, the ratio of mineral composition (SiO_2 + Al_2O_3) to flux oxide content being within the range of 3.5 to 10.0 means that the material is considered a better raw material source. Among the textile sludge samples, the ratios of the (SiO_2 + Al_2O_3)/fluxing oxide content in Sample A, Sample B, and Sample C were 3.92, 10.34, and 12.90, respectively. Sample A showed a better range, while Sample B and Sample C were not within the preferred range;
3. According to the "bloating area" of Riley's three-phase diagram designed to assess the chemical composition of lightweight aggregate raw materials, it was feasible for the water purification sludge to be sintered into lightweight aggregates. In contrast, the SiO_2 content of the three textile sludge samples was too low to show up in the "bloating area";

4. After the water purification sludge was blended with 7.5% and 15% of textile sludge from Sample A, the compositions were within the “bloating area” and thus were considered suitable for producing lightweight aggregates. In addition, after the water purification sludge was blended with 7.5% of textile sludge from Sample B or Sample C, its composition did fall within the “bloating area”. However, the composition of the water purification sludge blended with 22.5% of textile sludge was not within the “bloating area”;
5. At the same sintering temperature, the more textile sludge that was added, the greater the loss on ignition of the aggregates that were sintered with water purification sludge blended with textile sludge (which was between 9.74% and 21.19%). Among them, the loss on ignition was the largest when adding 22.5% of textile sludge;
6. The textile-sludge-based LWAs had certain basic properties. At the sintering temperature of 1150–1200 °C and adding textile sludge from Sample A, Sample B, and Sample C, the particle density ranges of the sintered aggregates were 0.54–1.1, 0.6–1.23, and 0.69–1.19 g/cm^3, respectively;
7. The compressive strength of the lightweight aggregate concrete made from textile-sludge-based LWAs could meet the general strength requirements of lightweight concrete. This means that textile-sludge-based lightweight aggregate can be used in secondary structural concrete, such as steel bridge decks or lightweight partition wall panels for buildings. Its weight reduction effect is very good, which can greatly reduce the cost of construction.

LWA is generally manufactured by high-temperature sintering, which is an energy-consuming industry. However, the sintered LWA has the properties of green building materials, such as being lightweight, heat insulating, and earthquake resistant. In particular, textile sludge has a certain thermal matrix (high loss on ignition), which can provide part of the heat energy when sintering LWA, so it has economic benefits. Furthermore, in the future, non-sintered lightweight aggregates and their preparation methods should be developed, which do not involve tedious and energy-intensive steps such as high-temperature sintering in traditional processes, so as to improve production efficiency and reduce labor intensity and energy consumption.

Author Contributions: Conceptualization, H.-J.C. and W.-T.C.; methodology, H.-J.C.; validation, H.-J.C., W.-T.C., and C.-W.T.; formal analysis, C.-F.P. and W.-T.C.; investigation, C.-F.P.; resources, H.-J.C.; data curation, H.-J.C.; writing—original draft preparation, C.-W.T.; writing—review and editing, C.-W.T.; visualization, H.-J.C.; supervision, H.-J.C.; project administration, H.-J.C.; funding acquisition, H.-J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Technology of Taiwan, grant number: MOST 107-2218-E-005-009.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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