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Research Article

Investigating the Properties of Foamed Mixture Lightweight Soil Mixed with Bauxite Tailings as Filler

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To make better use of large amounts of discarded bauxite tailings (BTs), a foamed mixture lightweight soil mixed with BTs as filler (FMLSB) was proposed. Using the orthogonal experimental design method, the effects of various contents of cement, BTs, and foam on the fluidity, wet density, unconfined compressive strength, water absorption, and microstructure of FMLSB were studied. The experimental results indicate that the wet density and unconfined compressive strength increase as the contents of cement and BTs increase but decrease as the foam content increases. Water absorption increases with the reduction of the wet density, but the unconfined compressive strength exponentially increases as the wet density increases. With an increase in the contents of cement and BTs and a decrease in the foam content, fewer pores are present, and the pores are not connected with each other. The results of the range analysis show that the main factor affecting the wet density and unconfined compressive strength of the FMLSB is the foam content, followed by the cement content, and meanwhile, BTs can maintain the lightweight and high strength of FMLSB. Based on the intended engineering applications and standard specifications, the optimum composition of the FMLSB mixture is proposed. Overall, the results indicate that BTs have the potential to be used as filler to produce FMLSB and that applications of FMLSB will lead to great economic and environmental benefits in engineering construction.

1. Introduction

In recent years, foamed mixture lightweight soil (FMLS) has been widely used because of its lightweight, regulatory of density and strength, good workability, self-reliance after hardening, good durability, impermeability, good heat and sound insulation, and superior environmental protection. For example, FMLS has been successfully used in the field of heat preservation and insulation, underground pipe and cavity filling, and foundation pit and subgrade backfilling, especially in highway subgrade filling [1, 2], and its use in these applications significantly shortens the construction duration and reduces the project investment. Japanese researchers have proposed the use of FMLS as early as the early 1980s and conducted a series of indoor and outdoor experimental studies. The results show that FMLS is a very convenient material in the field of civil engineering [3, 4]. Experimental studies have mainly focused on the wet density, unconfined compressive strength, stress-strain characteristics, pore structure, fibre reinforcement, and durability of FMLS [5, 6]. Although more progress has been made, new and improved FMLS materials still need to be studied. Generally, fly ash, silica fume, and fibres are often added to foamed concrete mixtures to customise the mechanical properties of the resulting material [7, 8]. Fly ash has been used in concentrations of 30~70 wt.% [7], and silica fume (up to 10 wt.%) has been added to intensify the cement strength [8]. However, fly ash, fibres, and other materials are too expensive, and thus, it is necessary to explore more economical primary materials to produce FMLS.

Bauxite tailings (BTs) generated during the flotation-Bayer process, which is used in China to produce alumina from medium- and low-grade bauxite ore [9], are a type of waste product. The flotation method is a common technique used to separate the valuable minerals from ores containing Al, Cu, Pb, and Zn. In recent years, Feng et al. have proposed many methods to improve the flotation efficiency, for example, the enhanced adsorption of sulphide species onto cerussite by surface modification with chloride [10], the surface modification of malachite with ethanediamine [11], and the surface modification of smithsonite with ammonia [12]. However, it is reported that 0.2 t of BTs is generated from every 1 t of bauxite ores processed by flotation. In China, large quantities of BTs are stored in tailing reservoirs after flotation [13]. Unfortunately, most of these BTs are deposited on land without any further treatment, which not only occupies landmass but also potentially causes leaching and heavy metal runoff, and as a result, secondary effects, such as deforestation, soil erosion, increases in water turbidity [14], and disturbances of the hydrology cycle [15] , may occur. BTs have a good viscosity and plasticity due to their high concentration of highly viscous kaolin [16], which can replace aggregates, such as fine sand, gravel, and other materials, used to prepare cement slurries to shorten the slurry setting time. As a result, some research and experiments performed in recent years have focused on utilizing BTs in cement [17, 18], building materials and ceramics [12, 14], alloy materials [19], and absorbent materials [20, 21], such as 4A zeolite [22] and CaO-based sorbents [15, 23]. The application of BTs will bring great economic and environmental benefits to engineering construction. However, there is a perceived lack of research on the FMLS mixed with BTs (FMLSB). Therefore, it is of great importance to explore the physical, mechanical, and hydraulic properties of FMLSB. This paper provides a scientific basis and application guidance in the field of FMLS.

The main objective of this paper is to provide basic information on the properties of FMLSB. Using the orthogonal experimental design method, the effect of the contents of cement, BTs, and foam on the fluidity, wet density, unconfined compressive strength, water absorption and microstructure of FMLSB was investigated. According to the range analysis, the affecting magnitude of the factors affecting the wet density and unconfined compressive strength of FMLSB and the optimum mixture proportion of FMLSB was obtained. The novel contribution of this paper is to provide scientific basis of how to recycle large amounts of discarded BTs for use as raw materials in the production of FMLS and to reduce the total quantity of primary materials used. Furthermore, recycling waste materials greatly limits the negative effects of waste products on the environment.

2. Experimental Details

2.1. Materials. FMLSB is made by mixing BTs, cement, foam, and water in a specific proportion. The BTs used in this study were collected from the #1 tailings reservoir of China, Aluminium Co. Ltd., Guangxi. The soil samples were collected from the overwet tailings clay located in the centre of the reservoir depression. The particle-size distribution of the BTs is shown in Figure 1, and the physical properties are summarized in Table 1.

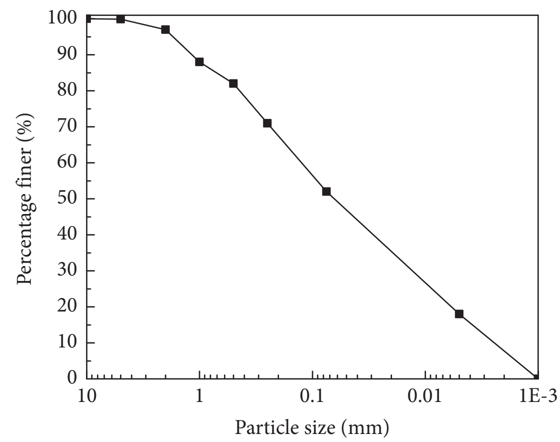

Figure 1: Particle-size distribution curve of the BTs.

The chemical and mineral compositions of the BTs were analysed by X-ray diffraction (XRD) and full-spectrum fitting analysis, and the results are shown in Table 2. Table 2 shows that the BTs contain a large amount of high-viscosity kaolinite (37.9%), as well as diaspore and other oxides.

A composite polymer foaming agent, which is a colourless alkaline liquid with a high foaming rate, low absorption rate, and high strength and persistence, was used to produce FMLSB in this research [24]. In addition, Grade 42.5 Ordinary Portland Cement was used as the cementing material (the chemical composition is shown in Table 2), and Table 2 shows that the cement contains a large amount of CaO (64.52%). Tap water was used to mix the FMLSB.

2.2. Mix Proportions. The amount of each material of the FMLSB is calculated according to the following equations [25]:

$$\frac{m_c}{\rho_c} + \frac{m_w}{\rho_w} + \frac{m_f}{\rho_f} + \frac{m_b}{\rho_b} = 1, \tag{1}$$

$$m_c + m_w + m_f + m_b = 100\gamma, \tag{2}$$

where m_c, m_w, m_f, and m_b are the amounts (kg) of the cement, water, foam, and BTs per cubic meter of FMLSB, respectively; ρ_c, ρ_w, ρ_f, and ρ_b are the densities of the cement, water, foam, and BTs, respectively, which correspond to $3100\,kg/m^3$, $1000\,kg/m^3$, $50\,kg/m^3$, and $1680\,kg/m^3$, respectively; and γ is the wet unit weight (kN/m^3), which is generally equal to $3{\sim}15\,kN/m^3$.

The water consumption per cubic meter of FMLSB is calculated according to the following equation [25]:

$$m_w = \frac{W}{B}\left(m_c + m_b\right), \tag{3}$$

where W/B is the water-binder ratio per cubic meter of FMLSB, which is between 0.55 and 0.65.

The foam volume per cubic meter of FMLSB is calculated according to the following equation [25]:

Table 1: Physical properties of the BTs.

Density ρ (g/cm^3)	Water content w (%)	Void ratio e	Permeability coefficient k (cm/s)
1.68	87.6	0.96	2.44×10^{-6}

Table 2: Chemical compositions of the BTs and cement.

Chemical composition	BTs (%)	Cement (%)
Calcium oxide (CaO)	—	64.52
Kaolinite ($H_4Al_2Si_2O_9$)	37.9	—
Quartz (SiO_2)	8.0	20.20
Diaspore ($HAlO_2$)	20.3	—
Aluminium oxide/alumina (Al_2O_3)	—	4.85
Lepidocrocite ($HFeO_2$)	20.3	—
Ferric oxide (Fe_2O_3)	—	3.62
Gibbsite ($Al(OH)_3$)	10.7	—
Sulphur oxide (SO_3)	—	2.85
Anatase (TiO_2)	1.67	0.31
Zeolite ($Al_{0.8}Si_{10.2}O_{21.6}$)	0.52	—

$$V_f = 1000\left(1 - \left(\frac{m_c}{\rho_c} + \frac{m_w}{\rho_w} + \frac{m_b}{\rho_b}\right)\right), \tag{4}$$

where V_f is the foam volume (L) per cubic meter of FMLSB.

The main factors affecting the wet density and unconfined compressive strength of FMLSB are the contents of the cement, BTs, and foam. Four levels of each affecting factor were evaluated in this test, and the proportion of each component is shown in Table 3. In addition, the orthogonal experimental design method was adopted to study the influence of each component of FMLSB on the resulting physical, mechanical, and hydraulic properties and to determine the optimum FMLSB composition. The amount and combination of each component are shown in Table 4.

2.3. Sample Preparation. The following steps were used to prepare the FMLSB: First, the cement, BTs, and water were weighed according to the specified proportions, and the cement slurry was obtained by evenly mixing these precursors. Then, the foaming agent was diluted with water in a ratio of 1 : 40, and a foaming machine (model BL168-8) purchased from Hefei Baile Energy Equipment Co., Ltd., China, was used. Then, volumes of the prepared cement slurry and foam determined by the volume ratio were transferred to a blender to produce a uniform mixture. The mixture was loaded into a cube mould with 10 cm × 10 cm × 10 cm dimensions. Finally, the samples were covered with a plastic film and placed in an incubator chamber at 20°C; the samples were demoulded after incubating for 24 hours. Eventually, the samples were wrapped in plastic after they were removed from the mould and stored in an environmental simulation laboratory (95 ± 3% relative humidity, 22 ± 2°C) to cure until testing, as shown in Figure 2.

2.4. Testing Methods. Referring to Chinese Standard CJJ/T 177-2012, "Technical specification for foamed mixture lightweight soil filling engineering," when FMLSB is used as filling or backfilling materials, the main design indexes are the wet density and unconfined compressive strength, and the fluidity should be controlled between 160 mm and 200 mm.

Table 3: Four levels of each affecting factor.

Level	Cement (kg/m^3)	BTs (kg/m^3)	Foam (L/m^3)	W/B
1	200	50	750	0.6
2	300	100	600	0.6
3	400	150	450	0.6
4	500	200	300	0.6

Before the mixture was put into the mould, the wet density of the mixture was measured 3 times by a measuring cup, and the average of these 3 measurements was used as the wet density of the FMLSB mixture. The unconfined compressive strength of samples cured for 28 d was measured with a microcomputer-controlled electrohydraulic servo universal testing machine (model WAW-600), and the loading rate was 2 kN/s. The unconfined compressive strength of the FMLSB samples was calculated from the arithmetic mean of the values measured for three samples.

Triplicate soil samples cured for 28 days were soaked in distilled water for 60 days at a constant temperature of 20°C. The weights of the soil samples after soaking for 0, 1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 25, 30, 40, 50, and 60 days were measured. The sample density was calculated according to the volume and weight, and the average of the values calculated for three samples was taken as the wet density. Finally, the change in the wet density and water absorption of the FMLSB samples was obtained as a function of soaking time. The water absorption is calculated according to the following equation [26]:

$$\mathrm{VA} = \frac{m_i - m_0}{\rho_w V_0} \times 100\%, \tag{5}$$

where VA = the volumetric absorption of water by the FMLSB sample, V_0 = the initial volume of the FMLSB sample (m^3), m_i = the weight of the FMLSB sample immediately after i days of soaking (kg), and m_0 = the weight of the FMLSB sample prior to the absorption test (kg).

Scanning electron microscope (SEM) observations were conducted by using an S-3400N scanning electron microscope produced by Hitachi Limited, Japan. The middle of each blank sample was removed by a soil knife, and the blank with its natural structural surface was cut into 4 mm × 8 mm × 4 mm SEM samples with a blade. These SEM samples were then placed in a plastic bag containing a silica gel desiccant. Finally, after drying, dehydrating, and coating with gold, the samples were observed using SEM to obtain the microstructural images.

3. Test Results and Discussion

3.1. Flow Ability. After stirring the FMLSB mixtures, the fluidity was measured by sampling, and the results are shown

Table 4: Orthogonal table.

Test number	Affecting factor			Test results		
	Cement	BTs	Foam	Flow ability (mm)	Wet density (kg/m^3)	Unconfined compressive strength (MPa)
1	1	1	1	179	450	0.40
2	1	2	2	163	540	0.50
3	1	3	3	161	640	0.45
4	1	4	4	156	790	1.05
5	2	1	3	190	690	1.25
6	2	2	4	175	940	2.35
7	2	3	1	170	590	0.55
8	2	4	2	167	740	0.85
9	3	1	4	197	940	3.05
10	3	2	3	187	890	2.75
11	3	3	2	173	840	1.35
12	3	4	1	165	690	0.65
13	4	1	2	183	840	1.30
14	4	2	1	183	740	1.10
15	4	3	4	185	990	2.80
16	4	4	3	168	940	2.65

Figure 2: Sealed curing of the FMLSB samples.

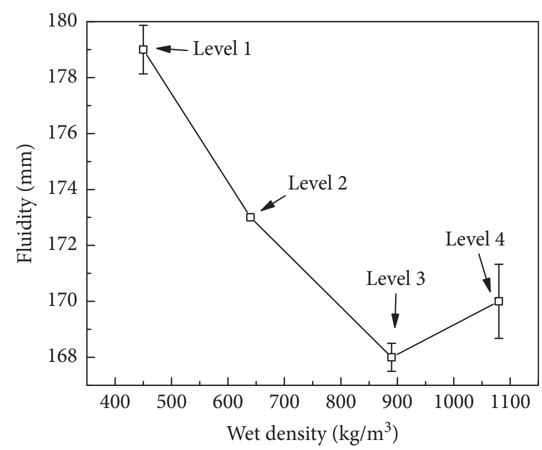

Figure 3: Change of the fluidity of FMLSB under different wet densities.

in Table 4. Table 4 shows that the fluidity of the FMLSB mixtures at all volume ratios is between 160 mm and 200 mm, which meets the requirements defined by Chinese Standard CJJ/T 177-2012, "Technical specification for foamed mixture lightweight soil filling engineering," and thus, the test data are reliable. The mean value of the fluidity at different levels of each affecting factor is shown in Figure 3.

Figure 3 shows that the fluidity decreases with the increase of the wet density up to 890 kg/m^3 and increases with the increase of the wet density above 890 kg/m^3. The reason is because BTs have a higher absorptivity than cement. Therefore, the fluidity increases with the increase of the ratio of BT replacing cement. When the wet density is 890 kg/m^3, the ratio of BT replacing cement is 27.3%, which is lower than when the wet density is 1080 kg/m^3 (28.6%). Therefore, the fluidity increases with increasing wet density above 890 kg/m^3. The results are similar to results reported in the previous research [27, 28], whereby increasing amounts of solid particles in a mixture increased the stiffness of the resulting cement paste, which has occurred due to the higher absorptivity of the BT particles. Table 4 also shows that the fluidity decreases with the increase of the ratio of BT replacing cement.

3.2. Wet Density and Unconfined Compressive Strength. The wet density and unconfined compressive strength test results of FMLSB are shown in Table 4. To compare the effect of various factors on the wet density and unconfined compressive strength, the mean values of the wet density and unconfined compressive strength at different levels of each affecting factor were calculated, and the results are shown in Figures 4–6. In addition, the experimental wet density and unconfined compressive strength data were fitted (as shown in Figure 6).

Figures 4 and 5 show that the wet density and unconfined compressive strength of FMLSB increase with increasing cement and BT contents, and it appears that cement acts as a cementing material and is also the primary source of the strength of the FMLSB sample. Because BTs contain large amounts of kaolinite, which has a high viscosity, BTs act not only as aggregates but also as cementing

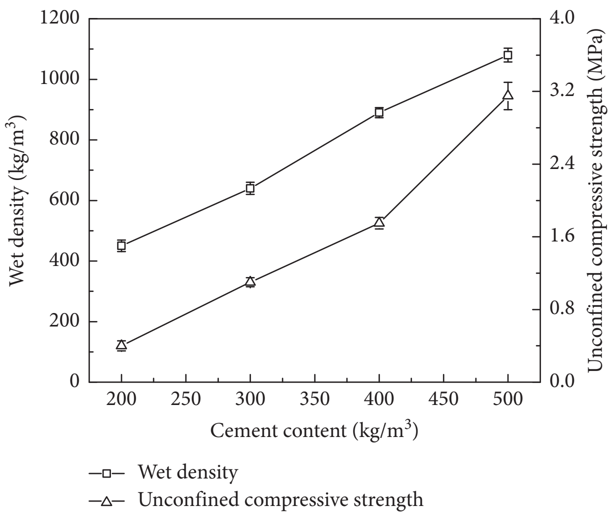

Figure 4: Influence of the cement content on the wet density and compressive strength of FMLSB.

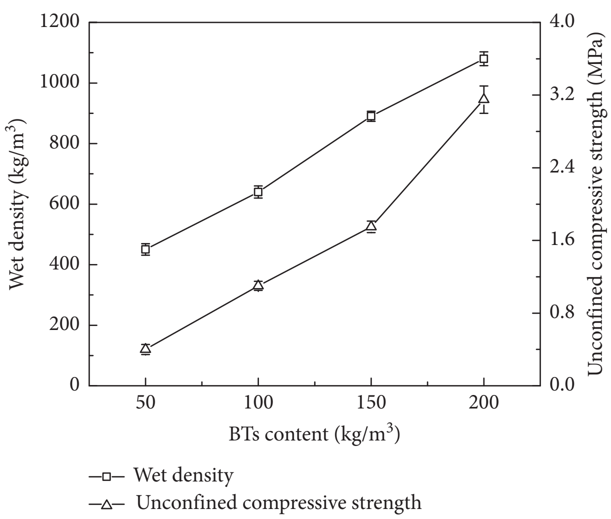

Figure 5: Influence of the BT content on the wet density and compressive strength of FMLSB.

materials. It could therefore be inferred that BTs can replace some cement while improving the compactness and strength of FMLSB. However, Figure 6 shows that the wet density and unconfined compressive strength of FMLSB decrease as the foam content increases. It is apparent that the existence of foam may cause a large number of bubbles to be generated inside the soil, and the porosity of FMLSB significantly increases, resulting in both the wet density and unconfined compressive strength decrease. Specifically, the experimental results show that the wet density of FMLSB changes in the range of 450 kg/m^3 to 1080 kg/m^3. The minimum value of the unconfined compressive strength is 0.4 MPa, while the maximum unconfined compressive strength can reach 3.15 MPa. In contrast, the unconfined compressive strength of FMLSB is qualitatively similar to FMLS mixed with either fly ash [24] or silica fume [5] to achieve the same wet density, but it is evident that BTs are less expensive and more

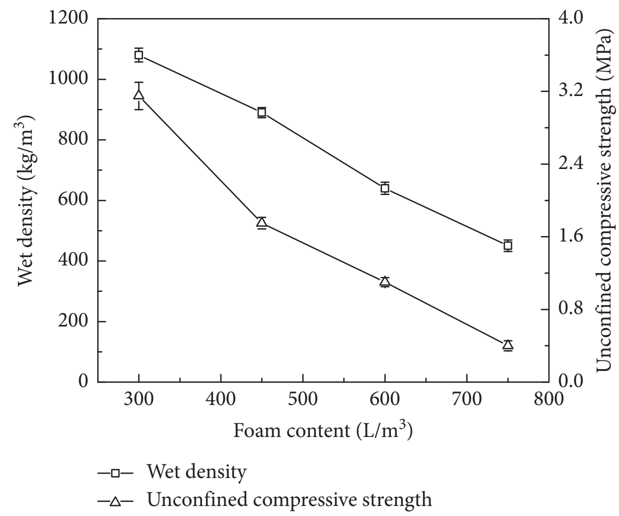

Figure 6: Influence of the foam content on the wet density and compressive strength of FMLSB.

abundant. In general, FMLSB has obvious advantages of being a lightweight material whose density and strength can be controlled, but FMLSB is also inexpensive and widely available. Note that the content of each affecting factor should be controlled to avoid the unconfined compressive strength from being too low, which may not meet the needs of a project.

Figure 7 shows that there is an approximate exponential function relating the unconfined compressive strength to the wet density; that is, the unconfined compressive strength exponentially increases as the wet density increases, and the fitting formula is as follows: $f_{28} = 6.11737E - 9 \times \rho^{2.87865}$, where f_{28} is the unconfined compressive strength after 28 days of curing and ρ is the wet density. It is likely that when the wet density of FMLSB is small, the number and diameter of internal pores is large, even when the internal pores are connected to each other. Therefore, the skeleton can bear less pressure, and the unconfined compressive strength is also correspondingly small. On the contrary, as the wet density increases, there are fewer pores present in FMLSB, and the structure is relatively dense. Therefore, the pressure that the skeleton can bear increases, and the unconfined compressive strength increases accordingly.

3.3. Water Absorption. The curves showing the change in the wet density and water absorption of FMLSB as a function of soaking time are shown in Figure 8. We observe from Figure 8(a) that the wet density of the FMLSB samples increases significantly after soaking for one day. In addition, after the wet densities becomes stable, the wet density corresponding to level 1 changes the most (213 kg/m^3) over the soaking times examined, while the wet density corresponding to level 4 changes the least (63 kg/m^3). Figure 8(b) shows that, except for level 1, the water absorption of the other samples increases rapidly on the first day: the largest water absorption occurs for level 2 (reaching 5.4%), followed by level 3 (4.5%), and the smallest water absorption occurs for level 4 (1.9%). After that, the water absorption increases slowly and becomes stable after

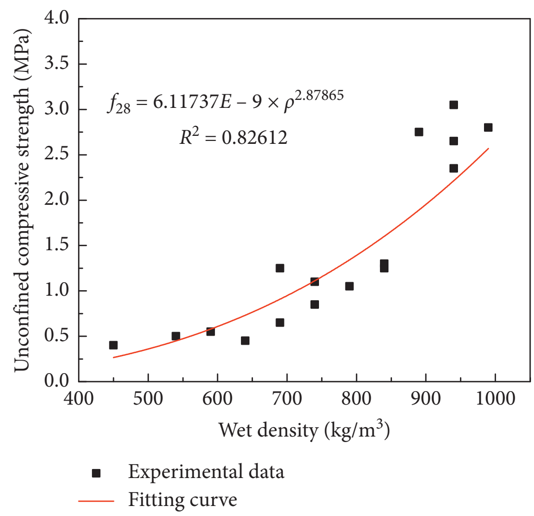

Figure 7: Fitting of the experimentally obtained wet density and compressive strength.

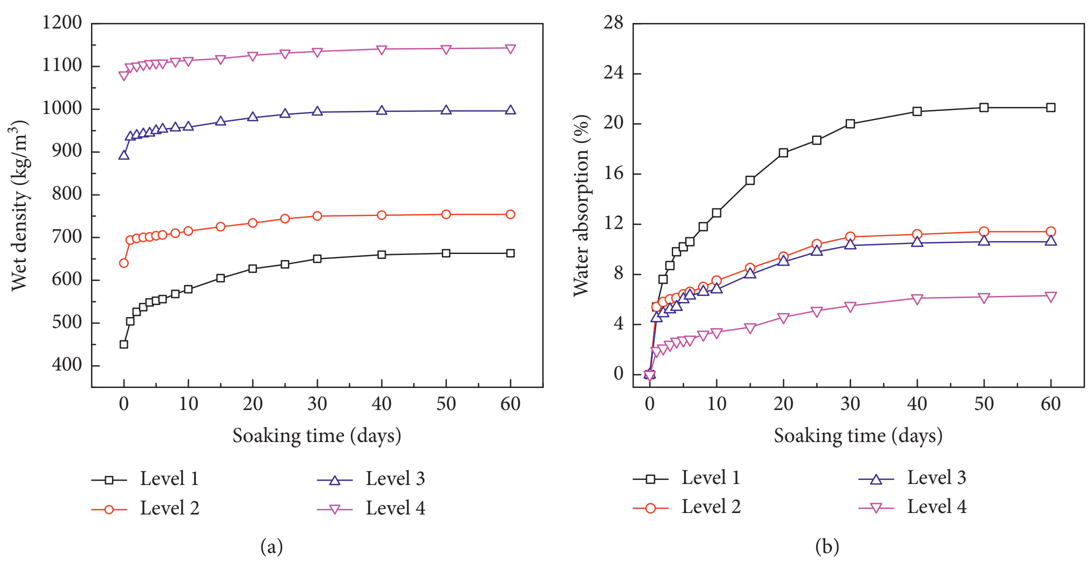

Figure 8: Change in the (a) density and (b) water absorption of FMLSB with soaking time.

40 days, where the water absorption after 40 days for levels 2, 3, and 4 is 11.4%, 10.6%, and 6.3%, respectively. For level 1, the water absorption reaches 9.8% after 4 days of soaking, which is followed by a slow increase in the water absorption and then becomes stable after 40 days, where the water absorption by level 1 is 21.3%. An important observation is that the water absorption increases with the decrease of the wet density of FMLSB. Specifically, when the wet density is 450 kg/m^3 (level 1), the water absorption is 21.3%, which is 15% larger than the water absorption measured when the wet density is 1080 kg/m^3 (level 4). Other researchers have made similar observations, affirming that the water absorption of FMLS increases as the density decreases [29, 30]. These results demonstrate that the high content of foam and low content of cement and BTs (as represented by level 1) will result in more internal pores and more interconnections between pores, so the water resistance will be poor.

3.4. SEM Observation. The pore structure of FMLSB is crucial to its wet density and unconfined compressive strength, and the SEM observations are shown in Figures 9 and 10.

It can be seen from the 50x magnification SEM images shown in Figure 9 that the foam content has a great influence on the internal pore structure of FMLSB. When the foam content is large, a large amount of foam causes the pore diameter of FMLSB to be generally larger, and the pores are more numerous and interpenetrating, resulting in a decrease in the density and a significant weakening of the strength. As the foam content decreases, the number of pores gradually decreases, and the structure becomes denser, which greatly enhances the strength. By analysing the foam action mechanism, the conclusion discussed in Section 3.2 can be verified; that is, the strength of level 4, which has the lowest foam content, can be as high as

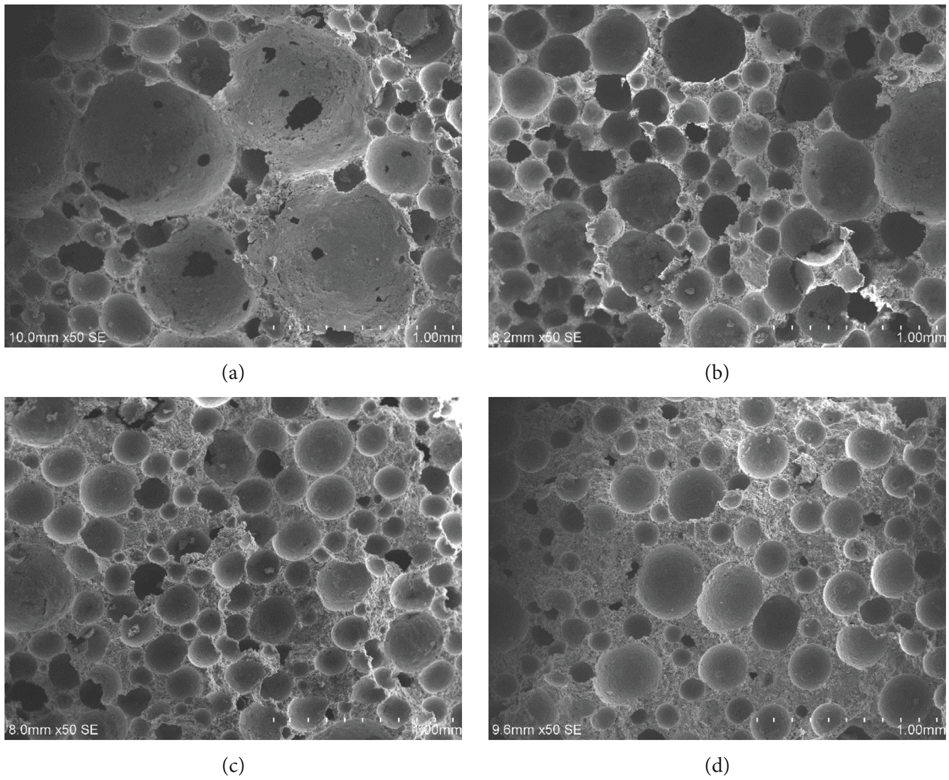

Figure 9: SEM images of FMLSB samples at a 50x magnification. (a) Level 1 (foam content = 750 L/m^3). (b) Level 2 (foam content = 600 L/m^3). (c) Level 3 (foam content = 450 L/m^3). (d) Level 4 (foam content = 300 L/m^3).

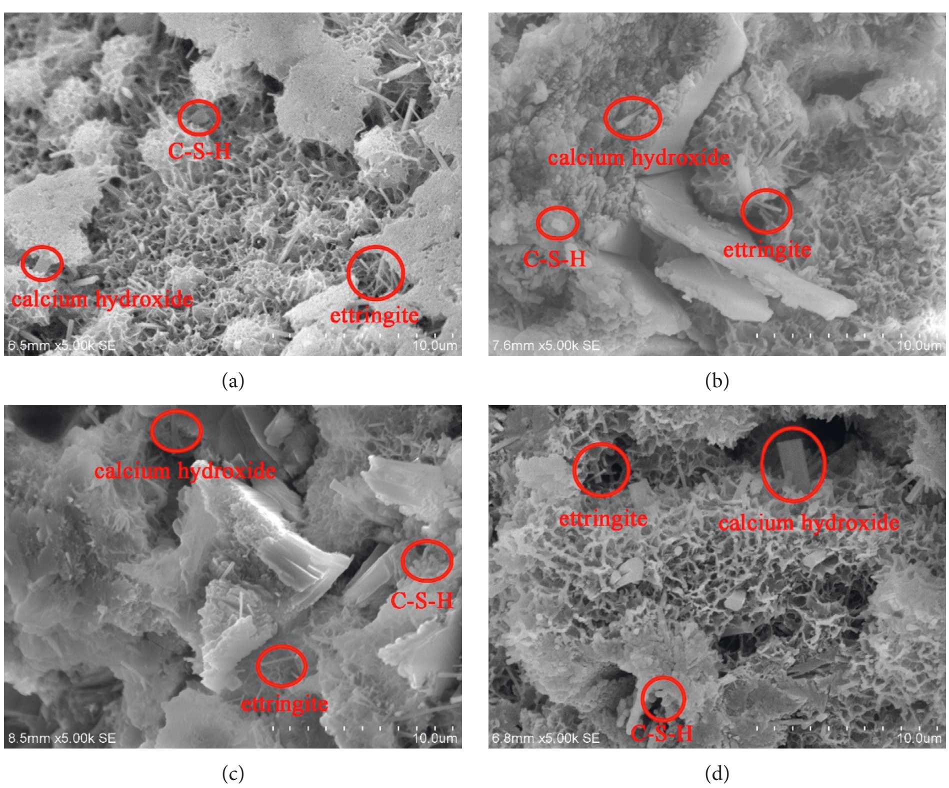

Figure 10: SEM images of FMLSB samples at a 5000x magnification. (a) Level 1 (BT content = 50 kg/m^3). (b) Level 2 (BT content = 100 kg/m^3). (c) Level 3 (BT content = 150 kg/m^3). (d) Level 4 (BT content = 200 kg/m^3).

3.15 MPa, which is 2.75 MPa higher than the strength level 1, which has the highest foam content. Therefore, the foam content has a great influence on the strength. At a high foam volume, bubbles merge, which results in the wide distribution of air-void sizes and low strength [30]. Figure 9(d) shows that there are several closed pores, demonstrating that the FMLSB sample with a BT content of 200 kg/m^3 has a low water absorption.

Figure 10 shows that the main components of the FMLSB samples have different shapes. The cement first reacts with water to release Ca^{2+} ions; then some of the obtained Ca^{2+} ions generate a pozzolanic reaction with kaolinite and other oxides, which are abundant in the BTs, to generate amorphous calcium silicate hydrate (C-S-H), cubic plates of calcium hydroxide crystals, and needle-like ettringite [24]. When the cement and BT contents are low and the foam content is high, the amount of generated products, such as hydrated calcium hydrochloride, is relatively small. These products overlap with each other and form a grid-like hollow structure, which causes the soil volume to rapidly expand and forms new pores, and therefore, the strength decreases (as shown in Figure 10(a)). The higher the contents of cement and BTs, the more the products will be generated. The generated products will fill and embed in the air voids, resulting in the decrease of the porosity [31]. Some of the products and fine soil particles of the BTs contain large amounts of high-viscosity kaolinite, which will bond with each other to form a compact block soil structure (as shown in Figures 10(b)–10(d)).

Therefore, when the cement and BT contents increase and the foam content decreases, FMLSB will have fewer internal pores, and the structure will be dense, thus improving the wet density, the unconfined compressive strength, and the water resistance. This is consistent with the results obtained in Sections 3.2 and 3.3.

4. Range Analyses

The main factors affecting the wet density and unconfined compressive strength of FMLSB include the contents of cement, BTs, and foam. This experiment mainly analysed the variation of the wet density and unconfined compressive strength under four contents with various affecting factors. To further obtain the affecting magnitude of various factors, a range analysis method was adopted to analyse the orthogonal test data, and the results are shown in Table 5. The specific steps used for the range analysis are as follows:

(1) Calculate the B_{ij} value, where B_{ij} is the sum of the corresponding test results for the affecting factor in different levels; j is the serial number of levels of the affecting factor, such as 1, 2, 3, and 4; and i is the serial number of affecting factors, such as 1, 2, 3, and 4

(2) Calculate the b_{ij} value, where $b_{ij} = B_{ij}/4$, $m = 1, 2, 3,$ and 4

(3) Calculate the range value D_i of b_{ij}, where $D_i = \max(b_{ij}) - \min(b_{ij})$

Table 5: Results of the range analysis.

Level parameters	Affecting factor		
	Cement content	BT content	Foam content
Wet density			
b_{i1}	605	730	618
b_{i2}	740	778	740
b_{i3}	840	765	790
b_{i4}	878	790	915
D_i	273	60	297
Sensitivity sequence	Foam > cement > BTs		
Compressive strength			
b_{i1}	0.6	1.49	0.68
b_{i2}	1.25	1.68	1.0
b_{i3}	1.94	1.28	1.78
b_{i4}	1.95	1.3	2.31
D_i	1.35	0.40	1.63
Sensitivity sequence	Foam > cement > BTs		

(4) According to the value of D_i, determine the influence order of the affecting factors

The greater the value of D_i, the larger the influence on the test results, and the more important the affecting factor. As shown by Table 5, the main factor affecting the wet density and unconfined compressive strength is the foam content, followed by the cement content, while the BT content has a relatively small effect. In addition, we can see that, due to the presence of the BTs, the b_{ij} value of the wet density is always lower than 800 kg/m^3, and the b_{ij} value of the unconfined compressive strength is always larger than 1.2 MPa, indicating that FMLSB samples containing BTs are still lightweight and have higher strengths. Therefore, the density and strength are adjusted mainly by controlling the content of foam and cement, and BTs are utilized as much as possible under safe conditions to maximize the replacement rate of cement and the utilization of waste.

5. Optimum Mixture Composition

Based on the intended engineering applications and standard specifications, in general, the optimum FMLSB mixture composition is one that has a low wet density (<1000 kg/m^3) and a high strength (>1 MPa); therefore, the data shown in Tables 4 and 5 should be considered for further analysis.

(1) *Cement*. The unconfined compressive strengths of FMLSB samples with cement contents of 300 kg/m^3, 400 kg/m^3, and 500 kg/m^3 are all greater than 1 MPa. However, as the cement content increases, the corresponding cost increases. As a result, the recommended optimum proportion of cement in the mixture is 300 kg/m^3, and the corresponding wet density also meets the requirement.

(2) *BTs*. FMLSB samples with BT contents of 50 kg/m^3, 100 kg/m^3, 150 kg/m^3, and 200 kg/m^3 all meet the requirements of the wet density and unconfined

compressive strength. To promote the utilization of BTs, a BT content of 200 kg/m^3 is a better choice.

(3) *Foam*. FMLSB samples with foam contents of 300 L/m^3, 450 L/m^3, and 600 L/m^3 all meet the requirements of the wet density and unconfined compressive strength. To decrease the weight of the resulting mixture, a foam content of 600 L/m^3 is a better choice.

6. Conclusions

In this study, the effects of different contents of cement, BTs, and foam on the fluidity, wet density, unconfined compressive strength, water absorption, and microstructure of FMLSB were investigated. Based on the experimental results and the range analyses performed in this investigation, the following conclusions can be made:

(1) The wet density and unconfined compressive strength increase with increasing cement and BT contents but decrease as the foam content increases. It is found that the increase in the unconfined compressive strength as a function of increasing wet density is approximately exponential. In addition, the results of the soaking test show that as the density decreases, the water absorption of the FMLS samples increases and the water resistance decreases.

(2) The SEM observations show that the hydration products of FMLSB are mainly amorphous C-S-H, cubic plates of calcium hydroxide crystals, and needle-like ettringite. More products will be generated as the contents of cement and BTs increase, which will fill and embed in air voids, and therefore, the porosity decreases. As a result, the wet density and unconfined compressive strength increase significantly. It can be seen that BTs act not only as aggregates in FMLSB but also as cementing materials that can be used to replace some cement.

(3) The results of the range analysis show that the factor most affecting the wet density and unconfined compressive strength of FMLSB is the foam content, followed by the cement content. Meanwhile, the BTs can be used to maintain the lightweight and high strength of the FMLSB. The optimum composition of the mixture is determined to be 300 kg/m^3 of cement, 150 kg/m^3 of BTs, and 600 L/m^3 of foam. It is feasible to recycle BTs to produce FMLS.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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