Physical and Mechanical Properties of Foamed Mixture Lightweight Soil Doped With Bauxite Tailings Slurry

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Abstract. In order to make better use of the BTs slurry with high water content stored in tailings ponds by wet method, foamed mixture lightweight soil (FMLSB) at four wet density were prepared using dry BTs and BTs slurry with different water contents. Their wet density, fluidity, unconfined compressive strength and water absorption were tested through indoor test, and the experimental results were analyzed by microstructure analysis. The results show that the performance of FMLSB improves as the wet density and water content of BTs slurry increase. FMLSB prepared by BTs slurry with 60% water content is poorly fluidity. That means at lower wet density due to the connected internal pores, its strength is significantly reduced and water absorption is significantly increased compared to the dry BTs group. However, with the increase of wet density, the above adverse effects of FMLSB caused by BTs slurry with low water content will decrease; and with the increase in water content of BTs slurry, its internal pore structure is significantly improved, the same as its unconfined compressive strength. When the water content is 100%, its performance is no different from that of dry BTs group. With the increase of wet density, the C-S-H produced by hydration reaction of FMLSB increases, forming a dense skeleton structure together with BTs particles and the unconfined compressive strength increases exponentially. The research results can provide a scientific basis for the direct utilization of high water content BTs slurry in tailings pond.

1. Introduction
Foamed mixture lightweight soil (FMLS) has the advantages of lightweight, regulatory of strength and density, fire-resistance, being environmentally-friendly and economical. At present, it has been widely used in the field of thermal insulation materials, highway widening, soft foundation treatment, underground pipe and cavity filling and others [1-3]. Many scholars have carried out a series of experimental studies on the physical properties, mechanical properties and durability of FMLS [4-6]. In addition, in order to reduce the cement content, some scholars usually add mineral admixtures commonly used in concrete such as slag, fly ash and silica fume to FMLS [7-8], while others use fiber to improve the performance of FMLS [9-10]. Although the performance of FMLS modified by the
above-mentioned materials has been improved, there is still a problem of poor economic benefits in preparing FMLS for filling materials.

China is the largest alumina producer and consumer in the world with the aluminum industry occupying an important position in China’s industry. However, although China's bauxite resources are abundant, the grade is poor. Therefore, the flotation-bayer process is the main method to produce alumina from low-grade bauxite in China. The bauxite tailings (BTs) produced in the alumina production process have the characteristics of fine particle, low strength, high water content and innoxious [11]. There are 14 large-scale BTs ponds currently in Guangxi. But they take up a large amount of land resources, and the high water content BTs slurry stored in the tailings pond for a long time is also a dangerous source of artificial debris flow with high potential energy, which threatens the security of the region seriously [12-13]. To cope with these issues, scholars have conducted extensive research. Wang et al. [14] proposed that the BTs be prepared into adsorption materials for wastewater treatment, according to the characteristics of high water absorption of BTs; Zhang et al. [15] prepared a series of CaO based CO$_2$ adsorbents with aluminum nitrate and BTs as admixture and lime mud as calcium source. The results of the research show that the adsorption stability of carbon dioxide is improved by adding BTs. However, the above methods can not be used for large-scale utilization of BTs. The research on the application of BTs in construction materials is beneficial to its resource utilization, but there are also some problems. For example, when preparing ceramics and Al-Si alloy, the energy consumption would inevitably increase [16-17], and when used as mortar admixture and synthetic geopolymer it would also cause a significant reduction in performance [18-19]. For this reason, Peng et al. [20] prepared a kind of foamed mixture lightweight soil mixed with BTs (FMLSB) by using dried and crushed BTs, which can meet the requirement of cavity filling and has high economic benefits. However, the BTs in the tailings pond not only has a too high water content but also is not easy to solidify, which is obviously not conducive to the efficient application of BTs, if it needs to be dried and crushed before it can be utilized. Therefore, it is of great significance to study the direct utilization of high water content BTs in the tailings pond.

In this paper, dry BTs and BTs slurry with different water content are used to prepare FMLSB. Then the wet density, fluidity, unconfined compressive strength and volume water absorption of each of them are compared and analyzed from the microscopic view. The research results will not only provide a scientific basis for the direct utilization of high water content BTs slurry, but also bring great social and economic benefits to the development of western Guangxi and related industries.

2. Experimental details

2.1. Materials
FMLSB is prepared from cementitious material, BTs, water and foaming agent. The cementitious material is P.O42.5 ordinary Portland cement produced by Xinning Conch Brand Cement Co., Ltd., Fusui County. BTs is used as fine aggregate, selected from the 1# Tailings Pond Depression Center of China Aluminum Co., Ltd., Guangxi, and its formation process is shown in figure 1. The particle size distribution curve is shown in figure 2, presenting that the fine particles of BTs cover a big percentage, and the proportion of the particles of less than 1 mm is nearly 90%. The BTs for research need to be dried and crushed, and the BTs slurry is prepared by fully mixing the dry BTs with water according to its devised content. The chemical composition and mineralogical composition of BTs, obtained by testing six sets of specimens using XRD diffractometer and Rietveld full-spectrum fitting analysis, are shown in Table 1. The foaming agent used in this test is animal protein foaming agent produced by Linyi Ketai Energy-saving Building Materials Co., Ltd. Through the performance test of foaming agent, the best performance index is obtained when the dilution ratio of foaming agent is 1:30.
Figure 1. Formation process of BTs.

Figure 2. Particle size distribution curve of BTs.

Table 1. Chemical composition and mineral composition of BTs.

| Chemical composition         | Content / % | Mineral composition         | Content / % |
|------------------------------|-------------|-----------------------------|-------------|
| Silicon dioxide (SiO₂)       | 38.75       | Kaolinite (H₄Al₂Si₂O₉)      | 38.75       |
| Alumina (Al₂O₃)              | 21.32       | Diaspore (HAIO₂)            | 21.32       |
| Ferric oxide (Fe₂O₃)         | 20.25       | Lepidolite (HFE₂O₅)         | 20.25       |
| Calcium oxide (CaO)          | 10.73       | Gibbsite (Al(OH)₃)          | 10.73       |
| Titania (TiO₂)               | 7.73        | Quartz (SiO₂)               | 7.73        |
| Potassium oxide (K₂O)        | 1.68        | Anatase (TiO₂)              | 1.68        |
|                             |             | Zeolite (Al₀.₈Si₁₀₂O₂₁.₆)   | 0.55        |

2.2. Mix proportions
Generally the water content of BTs slurry in the tailings pond is not a fixed value. When BTs slurry directly pumped out from the tailings pond is used to prepare FMLSB, the BTs content of FMLSB will be too high or too low consequently, which will adversely affect the performance. Through the previous drainage consolidation test for BTs slurry, we found that the BTs slurry with high water content tend to form the "mud skin" with low permeability in the process of self-weight consolidation, and it is difficult to continue to decrease after the water content is reduced to roughly 60%; besides, through the indoor
deposition test of BTs, the average water content of the sedimented mud formed after mud-water stratification of BTs slurry is normally about 80% [21-22]; Therefore, it can be considered to take drainage measures for rapid consolidation or set up a sedimentation tank for mud-water stratification in the preparation process of FMLSB for cavity backfill projects. Based on this, this experiment is designed with BTs slurry groups with 60% and 80% water content (WA60, WA80) and an additional group with 100% water content (WA100) to determine which water content in BTs slurry is suitable for the preparation of FMLSB. In addition, a control group (DA) using dry BTs is also set up.

Referring to the “Technical specification for foamed mixture lightweight soil filling engineering” CJJ/T 177-2012 (Hereinafter referred to as “CJJ / T 177-2012 Standard”) [23], four grades of wet density were devised for this test, and the ratio of each material is shown in Table 2.

### Table 2 Constituent proportions of FMLSB.

| Serial number | Designed wet density / (kg·m⁻³) | Cement / (kg·m⁻³) | BTs / (kg·m⁻³) | Foam / (L·m⁻³) | W/B |
|---------------|---------------------------------|-------------------|----------------|----------------|-----|
| 1             | D437.5                           | 200               | 50             | 750            | 0.6 |
| 2             | D670                             | 300               | 100            | 600            | 0.6 |
| 3             | D902.5                           | 400               | 150            | 450            | 0.6 |
| 4             | D1170                            | 500               | 200            | 300            | 0.6 |

2.3. Sample preparation and curing
The preparation process of FMLSB sample is listed as follows:

- Preparing cement-BTs mixed slurry and foam: Firstly, cement, BTs and water are weighed according to the proportion in Table 2, and then mixed them and stirred evenly. The animal protein foaming agent diluted by a ratio of 1:30 is transported to the mini-foaming machine to prepare foam.
- Mixing and pouring: The cement-BTs mixed slurry and foam was respectively transferred to the concrete mixer and stirred evenly for 2 minutes to produce the FMLSB slurry. The FMLSB slurry is poured into the 10 cm × 10 cm × 10 cm concrete cube mould for molding.
- Sample curing: After curing 24 hours, the poured samples are demoulded and sealed with plastic bags. Then, the samples are then cured for 28 days for testing.

For WA60, WA80 and WA100 groups using BTs slurry, the water content in BTs slurry should be deducted when calculating the water consumption of FMLSB, and the other preparation process is the same as the above.

2.4. Testing method
Guangxi Province is characterized by typical Karst landscape, so FMLSB is considered to be used to fill cavities in Karst areas. Referring to CJI / T 177-2012 Standard [23], the main design indexes of FMLSB are wet density, fluidity and unconfined compressive strength.

- Wet density and fluidity: The wet density should be measured 3 times with a 1L measuring cup, and the arithmetic mean is taken. The fluidity is tested with a cylinder with an internal diameter of 80 mm and a height of 80 mm. Pouring the prepared FMLSB into the cylinder, slowly lifting it up, letting it stand still for 1 minute and then using the vernier caliper to measure the maximum radius. Repeat the measurement for 3 times and take the arithmetic mean, with fluidity controlled within 160 ~ 200 mm.
- Unconfined compressive strength: Testing instrument is Hualong WAW-600 microcomputer controlled electro-hydraulic servo universal testing machine, and the displacement control method is used for loading, with the loading rate of 5 mm · min⁻¹. The unconfined compressive strength of FMLSB is calculated from the arithmetic mean value of the measured values of three samples.

- Micro-analysis: The middle part of the FMLSB sample is cut into SEM samples of 4 mm × 8 mm × 4 mm and its natural structure surface is taken as the observation surface. Then the Hitachi S-3400N scanning electron microscope (SEM) is used to observe the pore and skeleton structure between the pore
of the FMLSB.

Water absorption: Three samples of each group cured for 28 days are soaked in distilled water at 20 °C, and their weight is measured at 0, 1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 25, 30, 40, 50 and 60 days. Finally, the volumetric water absorption is calculated according to the following formula, so the variation law of volumetric water absorption of FMLSB with soaking time under each design wet density is obtained.

\[
VA = \frac{m_i - m_0}{\rho_w V_0} \times 100\% \tag{1}
\]

Information: 
VA = Volumetric absorption of water of FMLSB; 
\(V_0\) = Initial volume of FMLSB (m³); 
\(m_i\) = Weight of FMLSB samples immediately after ith days of soaking (kg); 
\(m_0\) = Initial weight of FMLSB (kg); 
\(\rho_w\) = Density of water, take 1000 kg·m⁻³.

3. Test results and discussion

3.1. Wet density and fluidity

Table 3 shows the wet density and fluidity of FMLSB in each group. It can be seen that the difference between the measured wet density and the designed wet density is within a reasonable range, indicating that the foam produced by the foaming agent has good stability. The results of fluidity test for the DA group (hereinafter referred to as the control group) shows that the FMLSB prepared with dry BTs has good fluidity at a water-cement ratio of 0.6, while the test results of the WA60 group shows that the FMLSB prepared with BTs slurry with 60% water content has poor fluidity, which is 8 ~ 18 mm different from the requirements of the CJJ / T 177-2012 Standard [23].

Table 3. Test results of FMLSB in each group.

| Serial number | Measured wet density / (kg·m⁻³) | Fluidity / mm | 28d compressive strength / MPa |
|---------------|---------------------------------|---------------|-------------------------------|
| DA            | 437                             | 176           | 0.47                          |
|               | 703                             | 175           | 1.46                          |
|               | 870                             | 183           | 2.35                          |
|               | 1193                            | 188           | 4.51                          |
|               | 487                             | 143           | 0.36                          |
|               | 693                             | 142           | 1.13                          |
|               | 913                             | 153           | 2.27                          |
|               | 1165                            | 152           | 4.33                          |
| WA60          | 449                             | 168           | 0.45                          |
|               | 686                             | 169           | 1.37                          |
|               | 894                             | 172           | 2.41                          |
|               | 1140                            | 171           | 4.37                          |
|               | 460                             | 175           | 0.48                          |
| WA80          | 700                             | 177           | 1.44                          |
|               | 860                             | 185           | 2.29                          |
|               | 1120                            | 183           | 4.26                          |

The reason for the difference in fluidity between the above two groups of FMLSB is that the water absorption process of dry BTs particles, especially the pore water absorption process between the mineral layers of BTs, is relatively slow [18], and in the preparation process of cement and BTs mixed slurry, BTs particles can not absorb water completely during the mixing process due to the relatively short mixing time, so the free water content in the slurry is high, and the fluidity of the prepared FMLSB is also high. While the particles in the BTs slurry with 60% water content are able to absorb water saturation under the condition of long-time water absorption, coupled with the strong water retention
capacity of BTs itself, a considerable portion of water is endowed in the BTs particles, leading to a high inter-particle adhesion of the 60% water content of the slurry, which makes it unable to dispersed completely in the mixing process. Therefore, when the mixing time and actual water consumption are the same as those of control group, the FMLSB slurry prepared by BTs slurry with 60% water content is not only more viscous, but also less uniform and has less fluidity.

In addition, the fluidity of FMLSB also increases with the increase in water content of BTs slurry. As shown in figure 3(b) and (d), the BTs slurry with 80% water content has shown a certain degree of fluidity, and some free water would precipitate after standing for a period of time, with still some adhesion between the BTs particles. Therefore, the fluidity of FMLSB at each wet density grade in WA80 group is still smaller than that in the control group shown in Table 4, but it has reached 168–172 mm, all of which meet the requirements of the CJJ / T 177-2012 Standard [23]. By contrast, the BTs slurry with 100% water content shown in figure 3(c) and (e) presents a flow state completely, and the solid-liquid stratification phenomenon is obvious after standing for a period of time. At this time, the fluidity of FMLSB at each wet density level further increases, and the fluidity measured in the test is 175 ~ 185 mm, which is close to that of the control group and meet the requirements of the CJJ / T 177-2012 Standard [23].

Figure 3. Status of BTs with different water content. (a) water content 60%; (b) water content 80%; (c) water content 100%; (d) water content 80% BTs stratification state; (e) water content 100% BTs stratification state.

3.2. Unconfined compressive strength

3.2.1. Effect of water content of BTs on compressive strength
Due to the difference of the measured wet density between each group, the specific strength (i.e. the ratio of compressive strength to measured wet density) is used to analyze the influence of water content of BTs on compressive strength. The ratio of the 28 d compressive strength to the measured wet density is taken to obtain the specific strength of each group as shown in figure 4. The pore structure of the control group and BTs slurry group (WA60, WA80, WA100) under the scanning electron microscope is shown in figure 5. (Because of the limited length of this article, only the wet density grades at D437.5
and D902.5 are taken for analysis.

It can be seen from figure 4, that when the design wet density is D437.5 and D670, the specific strength of WA60 group is significantly different from that of the control group, only 68.73% and 78.51% of the control group. The reason may be related to the poor fluidity of WA60 group. It is also known from subsection 3.1 that the fluidity of FMLSB in WA60 group at design wet density of D437.5 and D670 group is less than 145 mm, and the lower fluidity is not conducive to the dispersion of foam during the mixing process, which in turn leads to the rupture of pore and the formation of connecting pores. The SEM images in figure 5 also confirm the above analysis. It can be seen from figure 5(b) and (d) that most of the pores in the WA60 group are connected pores and have a larger size, while in the control group shown in figure 5 (a) and (c), the connection between the pores is less and the pore size is smaller. In addition, with the increase in design wet density, the difference of specific strength between WA60 group and the control group shows a decreasing trend. When the designed wet density is D902.5 and D1170, the specific strength of WA60 group increased to 92.01% and 97.64% of the control group respectively. This may be due to the increase in wet density and the corresponding increase in the content of cementitious materials in FMLSB and the corresponding decrease of the foam content. At this time, the skeleton structure plays a leading role in the strength and the influence of the pore factor on the strength is weakened.

Figure 4. Specific strength of FMLSB cured for 28 days.

![Figure 4](image-url)
Figure 5. The 50× SEM image of FMLSB. (a) DA-437.5; (b) WA60-437.5; (c) DA-902.5; (d) WA60-902.5; (e) WA80-902.5; (f) WA100-902.5.

In addition, it can also be seen from figure 4 that with the increase in water content of BTs, the difference of specific strength between BTs slurry group and control group also decreases significantly. The specific strength of WA80 and WA100 groups reaches 93.11% and 96.95% of the control group at D437.5 level respectively, and the specific strength of WA80 and WA100 groups is even higher than that of the control group at D902.5 and D1170. As mentioned in subsection 2.1, BTs has a certain fluidity when the water content is more than 80%, and the fluidity of the corresponding FMLSB slurry is good, so the probability of pore rupture is reduced and the number of pores connected is less. Figure 5 (e) and (f) also confirmed this view. At D902.5 grade, the connected pores of FMLSB in WA80 and WA100 groups are significantly less than those in WA60, and their pore is more similar to that of the control group. Therefore, it can be considered that when the water content is greater than or equal to 80%, the mechanical properties of FMLSB prepared by BTs slurry are almost the same as those of FMLSB prepared by dry BTs.

3.2.2. Wet density and compressive strength.

The research in 3.2.1 subsection shows that FMLSB prepared with BTs slurry has good mechanical properties, so the relationship between wet density and unconfined compressive strength is established according to the test data in Table 3. The measured wet density and 28d unconfined compressive strength of the control group DA, WA80 and WA100 are fitted, as shown in figure 6. The data fitting results show that the wet density and unconfined compressive strength of FMLSB change exponentially in the four designed wet density ranges, that is, the 28d unconfined compressive strength of each test group increases exponentially with the increase in wet density. It is likely that the strength of FMLSB is closely related to its internal skeleton structure. Usually while the wet density is low, the foam content of FMLSB is high and the content of cementitious material is low. Therefore, the pores tend to expand to form the large diameter pores shown in figure 5, and the skeleton structure between the pores is also weak. With the increase in wet density, the content of cementitious material also increases accordingly, which not only limits the expansion and connectivity of pores, but also makes the skeleton structure of FMLSB thicker. Thus the strength is improved.
Taking the WA80 Group as an example, the relationship between wet density and unconfined compressive strength is further analyzed from the microscopic images of SEM. Figure 7 shows the 1000-fold SEM image of the WA80 group FMLSB at four wet density. As shown in figure 7, the skeleton structure of FMLSB mainly contains hydrated calcium silicate (C-S-H), calcium alumina (AFt) and calcium hydroxide (CH) generated by the hydration of Portland cement, and the morphology of hydration products shows gel-like, flake-like, and needle and rod-like, respectively. In addition, SiO₂ and Al₂O₃ contained in BTs can react with cement to form calcium aluminate hydrate (CaO·Al₂O₃·H₂O) and C-S-H [21], and BTs not involved in the reaction can also play a filling role in the skeleton due to its small particles. At the wet density of D437.5, the hydration products of FMLSB shown in figure 7(a) are mainly hexagonal lamellar CH, while the lamellar CH cannot be closely stacked with each other, which leads to more voids in the skeleton structure of FMLSB with lower density, coupled with the poor strength of CH itself, often the weak link in the skeleton structure; on the other hand, only a small amount of C-S-H and AFt are generated in its hydration products, which cannot wrap the unreacted BTs particle. This is one of the reasons why the strength of the FMLSB with smaller density is more affected by the characteristics of the pores. In contrast, it is difficult to observe hexagonal lamellar CH in FMLSB with wet density of D902.5 and D1170, indicating that the cementitious material reacts to produce a large number of C-S-H with higher strength, which makes the skeleton structure of FMLSB more dense, and C-S-H is also considered as the main source of strength of FMLSB skeleton [24]. This is another reason for the exponentially varying relationship between the wet density of FMLSB and the unconfined compressive strength.
3.3. Water absorption

Figure 8 shows the curve of water absorption of FMLSB with soaking time. It is worth noting that the growth rate and maximum value of water absorption of WA60-437.5 and WA60-670 groups are significantly greater than other groups at the initial stage of soaking. The water absorption of WA60-437.5 and WA60-670 groups reaches 14.79% and 7.13% respectively after soaking for one day, and then reaches the maximum after soaking for 30 days, while the control group and the other groups need to soak for 40 days (as shown in figure 8 (a) and (b)). It is likely that when the wet density is low, the pore diameter of FMLSB prepared with 60% BTs water content is larger, with only the surface pore absorbing water at the initial stage of soaking, so the larger the pore diameter is, the greater the water absorption is. In addition, when the wet density is low, the internal pores of the FMLSB in the WA60 group are connected with each other and the wall of the pore is cracked, which makes the water not only exist in the gap with the skeleton, but also enter into the pore through the pore wall break, and eventually absorb more water. In contrast, the other groups not only have less connected pores, but also have more complete pore walls. As a result, the water absorption of WA60-437.5 and WA60-670 increase rapidly in the early stage, and the maximum value is higher. And with the increase in wet density, the difference between the water absorption of WA60-902.5 shown in figure 8(c) and the other groups decrease. However, it is still at the maximum value because there are still some connecting holes in WA60-902.5; while WA60-1170 shown in figure 8(d) has almost the same water absorption as the other groups due to the high degree of skeleton compactness, the dense skeleton slows down the water infiltration rate and reaches the maximum value only at 50 days.

In summary, it can be found that BTs with 60% water content only has a great effect on the water absorption of FMLSB with lower wet density. When the water content of BTs is above 80%, the variation law and maximum value of water absorption of FMLSB are almost the same as those of the control group, which is also consistent with the rule in 3.2.1 subsection.
Figure 8. The variation of the volumetric water absorption rate of FMLSB with time. (a) D437.5 level; (b) D670 level; (c) D902.5 level; (d) D1170 level.

4. Conclusions
This article compares and analyzes the wet density, fluidity, unconfined compressive strength and water absorption of FMLSB prepared by dry BTs and BTs slurry through indoor test and SEM analysis methods, with the conclusions drawn following:

- The performance of FMLSB is improved with the increase in wet density and water content of BTs slurry. The fluidity of FMLSB prepared by using BTs with 60% water content is low, with its internal pores interconnected. When the wet density is small, the strength decreases obviously, the water absorption becomes higher and water resistance is poor, but this adverse effect weakens when the wet density is high; and with the increase in water content of BTs, the fluidity, pore structure and strength are improved. For example, the fluidity of FMLSB prepared by using BTs slurry with more than 80% water content meets the requirements, and the mechanical properties and water resistance of FMLSB prepared by BTs slurry are no different from those prepared by dry BTs. This indicates that it is feasible to prepare FMLSB with BTs slurry.

- The strength of FMLSB mainly comes from C-S-H produced by cement hydration, and BTs also participates in the reaction, but mainly plays the role of filling and compaction. SEM images show that the main hydration products of FMLSB with different wet density are distinctive. When the wet density is small, the hydration products of the skeleton of FMLSB are mainly sheet-like calcium hydroxide with poor strength; but with the increase in wet density, a large amount of hydrated calcium silicate and ettringite generated by the hydration reaction fills the voids of the skeleton, with the skeleton gradually denser and the strength increasing significantly which shows an exponential increasing trend.

- FMLSB is a new type of green environmental protection material. The use of BTs slurry to prepare foamed mixture lightweight soil not only eliminates the curing and drying process of BTs, but also has high economic and environmental benefits. However, when used for filling works, in order to obtain the best fluidity and compressive strength, BTs slurry with water content of 80% or more should be used.

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