Looking at Fig. 4- Fig. 6 (a), it can be seen that after the lithium slag is compacted and formed, the leaching content of each ion has decreased to within the maximum limit. With the addition of stabilizing materials, even with dosages of only 2%, the leaching contents of various ions have basically stabilized. From Fig. 4- Fig. 6 (b), it can be seen that after the improved lithium slag specimens are crushed to a granular state, the fluctuation of manganese ion leaching content is small, indicating good stabilizing effect. The leaching content of beryllium ions has significantly increased, reaching a maximum of 5.5 μg·L-1, which exceeds the maximum limit. After increasing the dosage of the stabilizing materials to 6%, the leaching content of beryllium ions is basically stable. The leaching content of thallium ions is greatly affected by the stabilizing materials. When the stabilizing material content reaches 10%, the leaching content of thallium ions in the specimen modified with fly ash is four times that of specimens modified with cement and BFS, which is still close to the maximum limit. This indicates that the improvement effect of fly ash on thallium ion is poor.

3.3 CBR

The mechanical strength of the subgrade must be ensured when lithium slag is used as a filling material. Based on previous studies, a mixing ratio of 6% stabilizing material was selected to form the CBR samples. Raw lithium slag was used as a control. The results for each specimen are shown in Fig. 7.

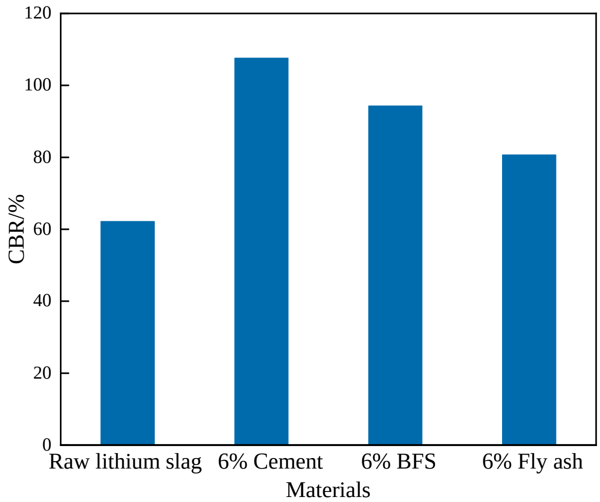
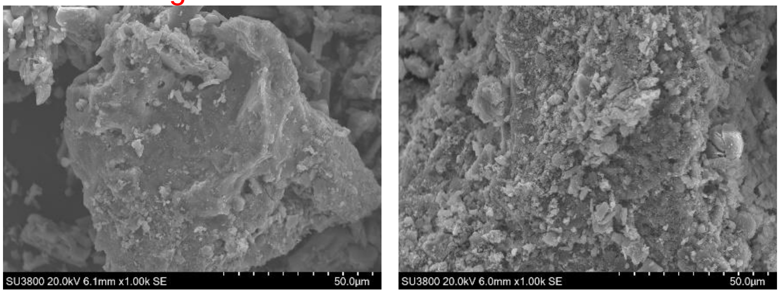


Fig.7 CBR of each specimen

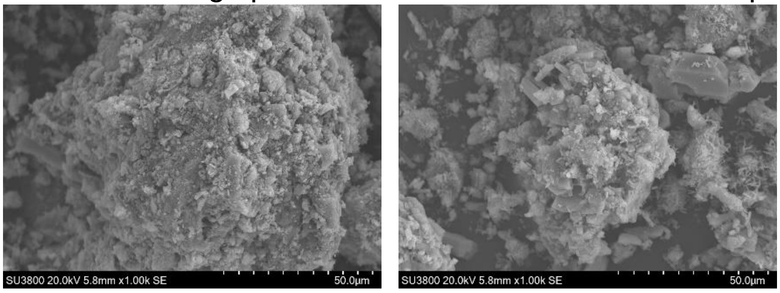
According to the results, the CBR of the lithium slag can reach 62.2%, which is much higher than the technical requirement for highway subgrade filler. The main reason is that lithium slag contains some CaO, which can enhance the strength of materials through hydration and hardening reactions. With the addition of stabilizing materials, the amount of CaO, SiO_2, and Al_2O_3 in the system increases, and the CBR of improved lithium slag will be further increased. Among them, the cement modified specimen increased by 75%, the BFS modified specimen increased by 51.6%, and the fly ash modified specimen increased by 29.7%. The result shows that when lithium slag is used as subgrade filler, it can meet the CBR requirement of each structural layer. After adding stabilizing materials, the CBR of the filler can be further improved.

3.4 Stabilization mechanism

10 mm thick selections of lithium slag from the surface of the CBR specimens were used to prepare scanning electron microscopy (SEM) samples. The microstructure of the samples were then observed and analyzed. The SEM images of the samples are shown in Fig. 8.



（a）Raw lithium slag specimen （b）Cement-modified specimen



（c）BFS-modified specimen （d）Fly ash-modified specimen

Fig. 8 SEM of each specimen

Fig. 8 (a) shows a scanning photo of the lithium slag under 1000× magnification. The surface of lithium slag particles is relatively flat, and there are few gel hydration products. There are a lot of unhydrated particles in the system. Fig. 8 (b), (c), and (d) show scanning photos of lithium slag specimens which have been improved with 8% cement, slag, and fly ash content, respectively, at 1000× magnification. Because there is a large amount of CaO in the stabilizing material, the calcium hydroxide generated after CaO hydration can react with SiO_2 and Al_2O_3 to generate secondary hydration products such as calcium silicate hydrate and calcium aluminosilicate hydrate (refer to Eq. (2) for the reaction process). At this time, the surface of lithium slag is wrapped by a layer of amorphous gel to form clusters, which greatly optimizes the aggregate interface. Meanwhile, due to the mutual bonding between aggregates, the distance between particles is further shortened, resulting in an overall improvement in the density of the material. Compared with the cement-modified specimen, the gel distribution on the surface of the BFS-modified specimen is more uniform, and the stabilizing effect is better. The surface gel of the fly ash-modified specimen is relatively sparse, and some lithium slag had not been wrapped by the gel and was exposed, indicating that the hydration reaction is not complete.

$$Al_2O_3 + 3SiO_2 + Ca(OH)_2 + 2H_2O \rightarrow CaO \cdot Al_2O_3 \cdot 3SiO_2 \cdot 3H_2O \qquad (2)$$

4. VALIDATION

To demonstrate the feasibility of using lithium slag as a subgrade filling material, this study selected 6% BFS-modified lithium slag for engineering verification in a subgrade test section of a highway in Jiangxi Province. The total length of the test section was 220m, the subgrade width was approximately 26m, and the filling height was approximately 25m. A schematic of the test section is presented in Fig. 9. To ensure the safety of the engineering environment, the lithium slag was improved before filling the subgrade, which was used to wrap the improved lithium slag during the filling process. A groundwater monitoring well was installed on the side of the subgrade to track and monitor the surrounding groundwater quality. The on-site construction process is illustrated in Fig. 10.

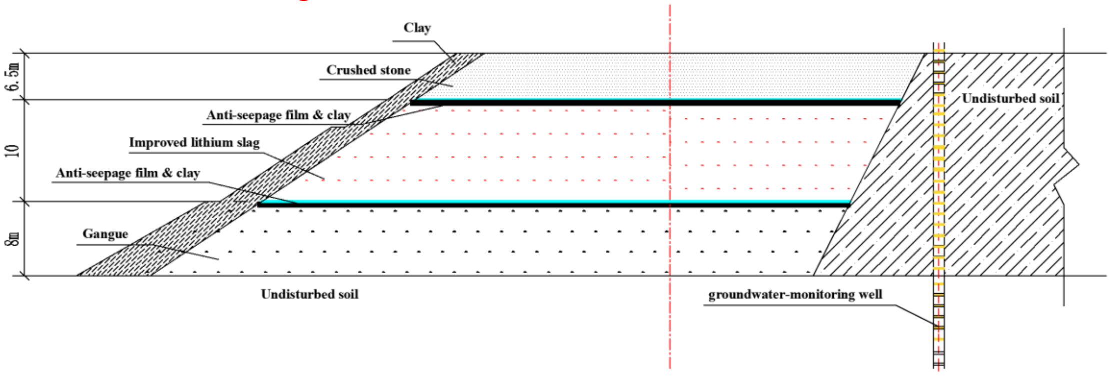
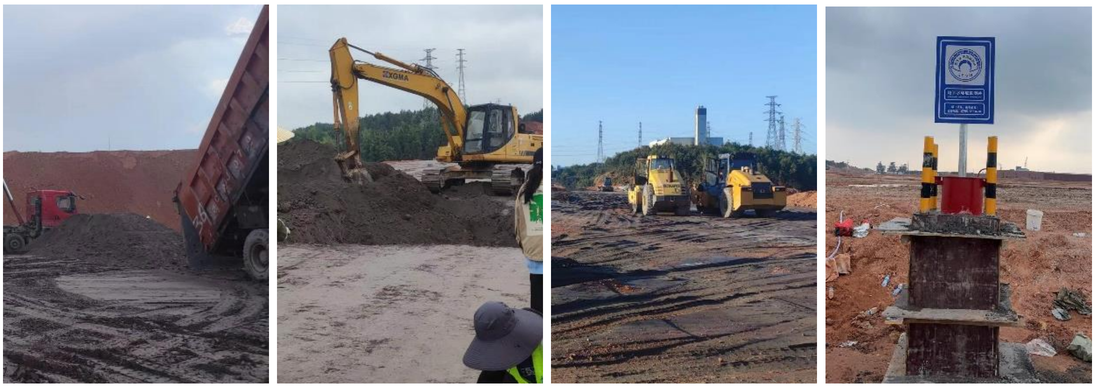


Fig. 9 Schematic of the section of highway used for testing



(a) Transportation (b) Paving (c) Rolling (d) Monitoring

Fig. 10 Construction process of the test section

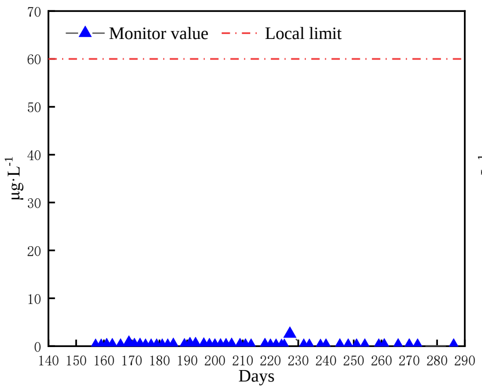
An inspection and evaluation of harmful substance leaching and road performance are carried out on the improved lithium slag filling layer at the construction site according to the integrated wastewater discharge standard (GB 8978-1996) and inspection and evaluation quality standards for highway engineering section 1 civil engineering (JTG F80/1-2017). The results show that the qualification rates of all detection indicators for the improved lithium slag in the experimental section are 100%.

Table 5 Test results of the of improved lithium slag

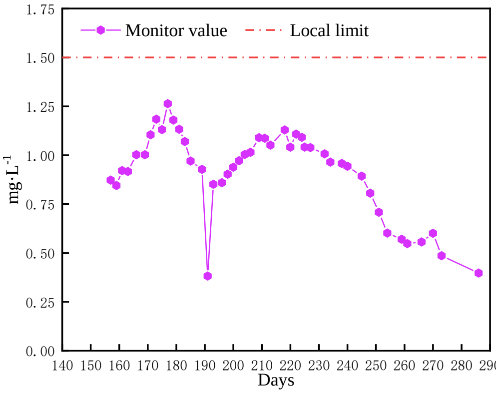
Inspection items	Check points	Qualified point	Pass rate/%
Leaching ions	13	13	100%

Soluble salt	13	13	100%
Degree of compaction	9	9	100%
deflection	84	84	100%

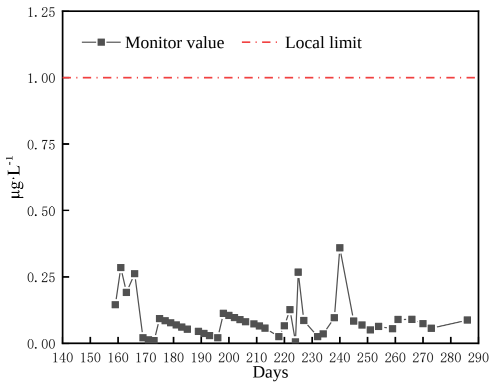
After the construction was completed, the content of harmful substances in the groundwater was tracked and monitored. The long-term monitoring results (Fig. 11) show that the amount of harmful substances can meet the requirements of the standard for groundwater quality (GB/T 14848-2017), indicating that the application of improved lithium slag in the subgrade is feasible.



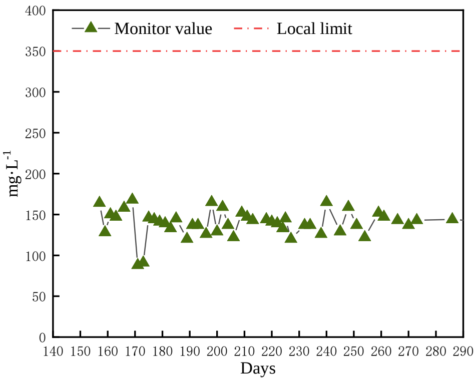
(a) Beryllium content



（b）Manganese content



（c）Thallium content



（d）Soluble salt content

Fig.11 Harmful substance content in groundwater

5. CONCLUSIONS

Cement, BFS, and fly ash have been used as stabilizing materials to improve the performance of lithium slag. The leaching law of harmful substances, road performance, and the stabilization mechanism of the improved lithium slag were analyzed, and the feasibility of using the improved lithium slag as a subgrade filler was experimentally demonstrated. The following conclusions were drawn:

(1) Lithium slag can react with added stabilizing materials to generate gel substances, such as calcium silicate hydrate and calcium aluminosilicate hydrate, on its surface, which can improve the strength and compactness of lithium slag and reduce the leaching content of any harmful substances.

(2) After the lithium slag is compacted and formed, the soluble salt content decreased from 8.79% to 6.29%. After the addition of stabilizing materials, the minimum content was further reduced to 1%. After crushing the formed specimens, the content of each specimen increased by approximately 3%. At this time, the minimum content of the stabilizing material must reach 6% to meet the specification requirements. The relative stabilizing effects of the three materials on salt was in the order of BFS > Cement > Fly ash.

(3) After the lithium slag was compacted and formed, the leaching content of each ion was significantly reduced. Only the addition of 2% stabilizing material met the ion content requirement. After crushing the formed specimens, the manganese still met the requirements; the highest content of beryllium has increased to 5.5 μg·L-1, increasing the content of stabilizing material to 6% can stabilize it; The leaching content of thallium is greatly affected by the stabilizing materials, the leaching content of fly ash modified lithium slag can reach up to 4 times that of cement and BFS modified lithium slag under the same dosage, the improvement effect of fly ash on thallium ions is poor.

(4) The CBR of raw lithium slag reached 62.2%, and after adding 6% cement, BFS, and flay ash, the CBR results increased by 75%, 51.6%, and 29.7% respectively, which fully met the bearing requirements of various subgrade layers.

(5) After verification in the experimental section, the road performance and qualified rate of harmful substance leaching detection reached 100%, and the content of various characteristic harmful substances in the groundwater met the quality requirements of groundwater.

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