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Research Article

Performance and Environmental Evaluation of Stabilized Base Material with Strontium Slag in Low-Volume Road in China

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Strontium slag, a by-product of the strontium carbonate refining industry, has been produced at million tons per year in China. The use of strontium slag in the roads could reduce the demand of virgin materials and help solve the environmental problems caused by strontium slag. However, it is necessary to evaluate its environmental effect and the performance of the pavement with strontium slag before it could be used in roads. In this study, two test sections with strontium slag base layer were paved in low-volume roads in China to investigate its performance and environmental impact: (1) cement-treated base (CTB) section (5 cm asphalt surface over 20 cm CTB containing strontium slag) and (2) lime-treated base (LTB) section (3 cm asphalt surface over 20 cm LTB with strontium slag). The performance of the test sections was evaluated through laboratory and field experiments. The cost and environmental effect of strontium slag were investigated using production cost analysis and life-cycle assessment, respectively. Results of this study indicate that the CTB section exhibited a better performance compared to the LTB section, and the strontium slag decreased the material cost and the emissions during production.

1. Introduction

Low-volume roads (LVRs) can be defined as paved or unpaved roads with average daily traffic of fewer than 500 vehicles per day [1]. Recently, more and more unpaved LVRs have been paved to improve the transportation quality in China. The new LVR construction needs more materials such as aggregates, asphalt binder, and cement. Obtaining the road materials is becoming difficult for some locations in China as local aggregates available are not enough. On the other hand, more and more waste materials, including recycled asphalt pavement (RAP), ground tire rubber (GTR), waste concrete and brick, fly ash, and slag, were produced with the development of society. Strontium slag, a by-product of the strontium carbonate refining industry, has been produced at nearly 5 million tons per year in China [2]. The disposal of strontium slag can create significant environmental concerns and damage to landfills when disposed in the land. Cement-treated and lime-treated base materials are widely used in LVRs in China as they can offer a strong foundation for the pavement. Using strontium slag in the stabilized base layer in LVRs could reduce the demand of virgin materials and help solve the problems caused by strontium slag.

Plenty of research efforts have been conducted on the impact of some waste materials (e.g., RAP, GTR, and waste concrete and brick) on the performance of the roads through laboratory and field tests. For example, the researchers reported that RAP improved the rutting resistance [3–8] and GTR improved the resistance to permanent deformation and cracking of the asphalt mixtures [9–13]. Jia et al. [14] presented the use of construction and demolition wastes in LVRs and indicated using them in the base and subbase is feasible for low-volume roads if the mix design is appropriate. However, few researchers investigated the effect of strontium slag on the pavement performance. Thus, it is necessary to evaluate its environmental effect of strontium slag and the performance of the pavement with it before it is used widely in LVRs in China.

2. Objective and Scope

The objectives of this research are to (1) explore the performance of the pavement with strontium slag by laboratory and field experiments and (2) evaluate the environmental effect of strontium slag used in the roads. To obtain the objectives, two field test sections of the asphalt pavement with strontium slag base layer were paved in low-volume roads in Chongqing, China: (1) cement-treated base (CTB) section (5 cm asphalt surface over 20 cm CTB containing strontium slag) and (2) lime-treated base (LTB) section (3 cm asphalt surface over 20 cm LTB with strontium slag).

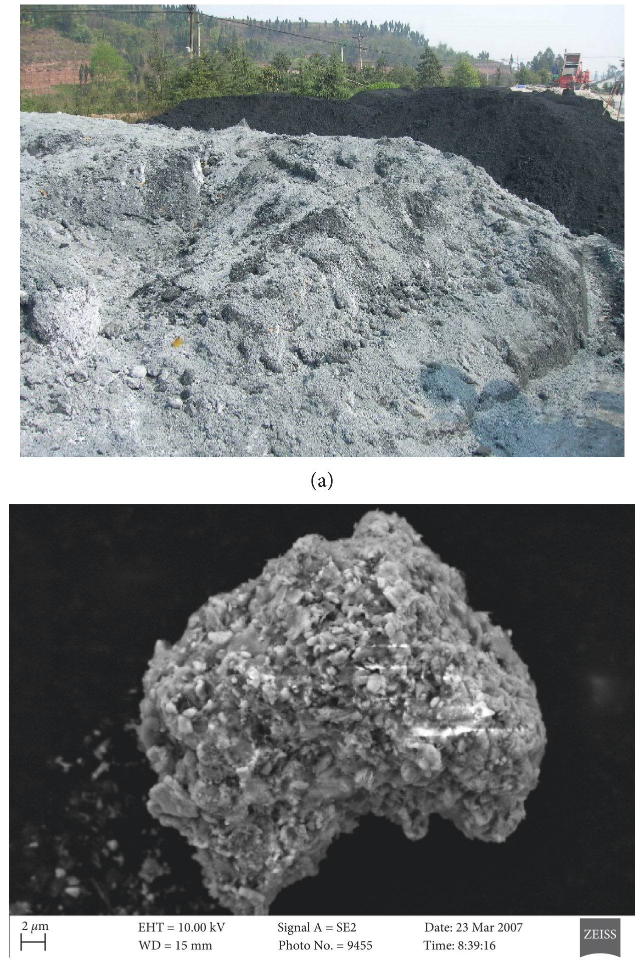
In the following sections, the materials and laboratory performance are first presented. Secondly, the construction of test sections is described. Thirdly, the field testing and investigation are shown. Fourthly, the cost analysis and environmental impact are discussed. Finally, key findings are offered.

3. Materials

3.1. Strontium Slag. Strontium slag used in this study was produced by a strontium factory in Chongqing, China. Figure 1 shows the raw condition and the scanning electron microscopy (SEM) image of the strontium slag. It was observed that the strontium slag was fine powder and had a porous microstructure. Table 1 shows the physical properties of strontium slag, indicating the slag had a higher moisture content of 11.8%. Figure 2 shows its gradation, and its particle sizes were mostly between 0.15 and 2.36 mm. The main chemical components of strontium slag are shown in Table 2. For comparison purposes, the chemical components of local fly ash are also listed in Table 2. As shown in Table 2, more CaO and SiO_2 were in the strontium slag when compared to Fe_2O_3, Al_2O_3, and MgO. Compared to the local fly ash, strontium slag had higher CaO content while much lower Al_2O_3 and SiO_2, which could result in the pozzolanic activity and self-hardening. Thus, it is expected that strontium slag could have a lower pozzolanic activity. Additionally, it was also observed that strontium slag had the similar loss on ignition to the local fly ash.

3.2. Portland Cement and Lime. In the study, Portland cement and lime were used in the two base layers as a stabilizing agent, respectively. Table 3 shows the setting time and cubic compressive strength of the cement which were measured in accordance with the specification of Ministry of Transport of China (JTG E30-2005) [15]. The percentage of CaO and MgO and particle size distribution of the lime are shown in Table 3.

3.3. Aggregate. Three different sizes of limestone aggregates, including 5–10 mm, 10–20 mm, and 20–40 mm, were used in both cement- and lime-treated base materials. Three virgin aggregates were preblended based on the mix design before they were mixed with slag and cement/lime. The properties of the aggregate blend are shown in Table 3.



(a)

(b)

Figure 1: Strontium slag pile (a) and 2 μm slag SEM image (b).

Table 1: Physical properties of strontium slag.

Properties	Value
Apparent specific gravity	2.34
Bulk density (g/cm^3)	1.17
Moisture content (%)	11.8

4. Laboratory Testing Results

In this section, the optimum moisture contents (OMC) and maximum dry density (MDD) of cement- and lime-treated base materials were determined using the Proctor tests, and then, the effect of slag contents on the performance of stabilized base materials was investigated. The mix performance tests included the compressive strength (UCS), indirect tensile (IDT) strength, and dry shrinkage. Finally, the appropriate slag contents were determined based on the mix performance.

To investigate the impact of slag contents on the properties of CTB material, 27, 32, and 39% slag contents were selected. Table 4 shows the mix gradation for three slag contents. It can be seen that the mix with 39% slag had the finest gradation while the mix with 27% slag showed the coarsest gradation. The specification of Ministry of Transport of China recommends that the appropriate cement content for the base layer

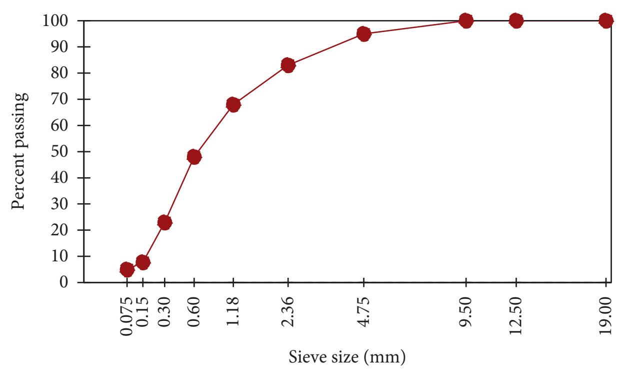


Figure 2: Gradation of strontium slag.

Table 2: Chemical composition of strontium slag and fly ash.

Component	SO_3	CaO	Fe_2O_3	Al_2O_3	SiO_2	MgO	Loss on ignition
Strontium slag (%)	4.7	26.7	4.2	4.9	24.6	7.0	3.6
Fly ash (%)	0.2	16.0	4.7	24.4	48.8	1.1	4.0

Table 3: Properties of Portland cement, lime, and aggregate blend.

Material	Test item		Values
Portland cement	Setting time (min)	Initial	176
		Final	433
	Compression strength (MPa)	3 days	20.3
		28 days	38.9
	Flexural strength (MPa)	3 days	4.6
		28 days	9.8
Lime	Composition (%)	CaO	75.7
		MgO	6.9
	Percent retained on	0.125 mm	11.5
		0.71 mm	0.3
Aggregate blend	Apparent specific gravity		2.72
	Flat and elongated >3 : 1 (%)		16.7
	Aggregate crushing value (%)		25.6

Table 4: Aggregate gradation of CTB.

Sieve size (mm)	Slag content (%) 27	32	39
	% passing		
37.5	100.0	100.0	100.0
31.5	94.2	94.6	95.1
19	62.8	65.3	68.9
9.5	47.4	51.0	56.1
4.75	44.1	47.6	52.5
2.36	37.8	41.0	45.3
1.18	30.1	32.7	36.4
0.6	21.7	23.6	26.1
0.3	6.3	7.5	9.1
0.15	2.1	2.5	3.0

mix is about 4–6%. The cement content of 5% was selected in the study based on this recommendation. The cement content in CTB material was fixed to 5% in all the tests.

For the lime-treated base material, 24%, 32%, and 40% slag contents were selected to determine an appropriate slag content for LTB mixes. Table 5 shows the aggregate gradations of the mixes with different slag contents. It was observed that the aggregate gradations of the mixes were finer with the increasing slag contents as the slag was the fine powder aggregate. The ratio of lime to slag was kept at the same value of 1 : 4 for all the LTB material tests based on the previous construction experience.

Table 5: Aggregate gradation of LTB.

Sieve size (mm)	Slag content (%) 24	32	40
	% passing		
37.5	100.0	100.0	100.0
31.5	98.5	98.7	98.9
19	82.9	85.0	87.2
9.5	55.3	60.9	66.7
4.75	37.8	45.0	52.5
2.36	27.3	34.2	41.5
1.18	20.4	26.3	32.5
0.6	14.5	18.7	23.0
0.3	7.4	9.4	11.5
0.15	2.7	3.3	4.0

4.1. Specimen Preparation. For USC and IDT strength tests, the following processes were followed to prepare the specimens: firstly, the dry aggregates and slag were blended with the optimum amount of water and cement/lime, and then, the specific mass of the blended materials was transferred to a compaction mold with a diameter of 150 mm; secondly, the blended materials were compressed statically to a target compaction degree of 95% and a target height of 150 mm; finally, the specimens were sealed in the plastic bags and cured for the specific number of days after the extraction from the compaction molds.

For the dry shrinkage test, the rectangular specimens with a length of 240 mm, a width of 50 mm, and a thickness of 50 mm were prepared using the rectangular molds. The target compaction degree of the rectangular specimens was about 97%. The specimens were cured for 7 days in sealed bags at 20°C before the dry shrinkage testing.

4.2. Moisture-Density Characteristics. The Proctor test was conducted in accordance with the specification of the Ministry of Transport of China (T 0804, JTJ 57–94) [16] to explore the moisture-density property of stabilized base mixes. In this test, a 4.5 kg rammer dropped from a height of 450 mm to compact the material in the mold. The base material with a specific water content was placed in three layers into a mold with a volume of 2,177 cm^3, with each layer compacted by 98 blows.

Figures 3 and 4 show the effect of slag contents on the moisture-density characteristics. It was observed that OMC increased and MDD decreased as the slag content increased, regardless of CTB or LTB. It is likely because the slag had lower specific gravity and higher water absorption. Additionally, LTB materials exhibited lower MDD and higher OMC when compared to CTB materials. This is expected since more quicklime was used in LTB materials, and it could absorb more water when compared to the cement in CTB.

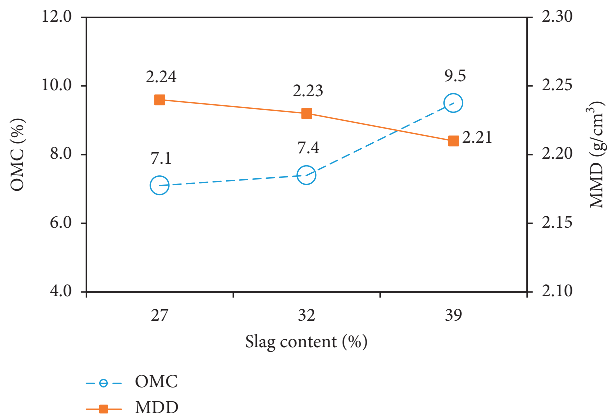


Figure 3: Moisture-density characteristics of CTB.

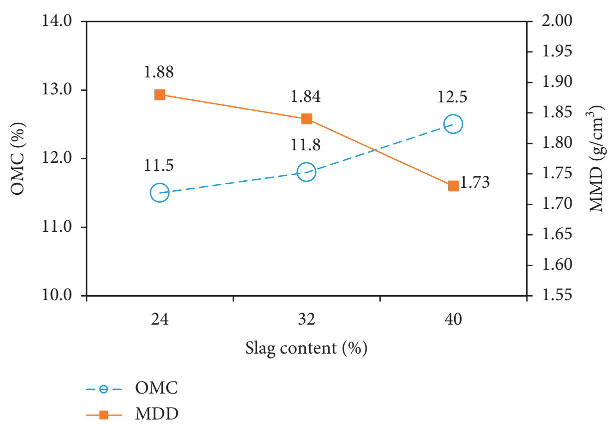


Figure 4: Moisture-density characteristics of LTB.

4.3. Compression Strength and Moisture Susceptibility. The unconfined compressive strength (UCS) represents the bearing capacity of the materials. A higher UCS value means a higher bearing capacity. The UCS testing was performed in accordance with the specification of the Ministry of Transport of China (T 0805, JTJ 57–94) [16] to investigate the compression strength performance of base mixes. Specimens with a height of 150 mm and a diameter of 150 mm were used. To investigate the moisture susceptibility of materials, two sets of twelve specimens were tested: unconditioned and conditioned sets. The unconditioned set of six specimens was tested directly after curing, and the conditioned set of six specimens was tested after soaking under water. Table 6 shows the details of curing conditions for two sets. In this study, the curing was conducted for 7, 28, and 60 days at 20°C. UCS test was performed on the specimen at a displacement rate of 1 mm/min until failure (see Figure 5). The UCS ratio of the conditioned and unconditioned samples was used to evaluate mix moisture susceptibility. The UCS value was calculated based on Equation (1), which is the stress in the vertical direction that corresponds to the peak load:

$$\text{unconfined compressive strength} = \frac{P}{A}, \qquad (1)$$

where P is the maximum applied load on the specimen A is the area of the specimen cross section.

Figure 6 shows the UCS results for CTB materials. The UCS values increased with the increase of slag content and curing time. The reason for the UCS increase with the increase of slag content could be that more pozzolanic activity occurred when more slag content was used. The mix containing 39% slag always exhibited the highest UCS while 27% slag mix showed the lowest UCS. Figure 7 shows the UCS ratio results for CTB materials. A higher UCS ratio value means a higher resistance to moisture damage. As shown in Figure 6, the base mix with 32% slag exhibited better moisture resistance than the other two mixes in most cases. The base mix with 39% slag showed the lowest UCS ratio after 7-day and 28-day curing time. This trend is opposite to the UCS results. It means that the mix with 39% slag could have lower moisture resistance at one month after construction. It is likely because more slag in this base mix could absorb more water which could result in more moisture damage.

Figure 8 shows the UCS results for LTB mixes after 7-day curing. It can be seen that the mix containing 32% slag exhibited the highest UCS, regardless of unconditioned or conditioned situations. Note that the LTB specimens with 40% slag broke after submerging in the water, suggesting that 40% slag mix could have a worse resistance to moisture damage. Based on this observation, a longer-time curing was conducted only on the mixes with 24% and 32% slag. Figure 9 shows the unconditioned and conditioned UCS results for LTB mixes with 24% and 32% slag. Figure 10 shows the UCS ratio results for these two mixes. Figures 9 and 10 indicated that 32% slag LTB mix showed a higher UCS, regardless of unconditioned or conditioned situations, suggesting this mix could have a better resistance to moisture damage compared to 24% slag LTB material. Additionally, LTB materials always had significantly lower UCS than CTB materials. It is expected since the lime material generally has much lower strength than the cement material after the curing.

4.4. Tensile Strength. The indirect tensile (IDT) strength represents a potential capacity of resisting cracking. The IDT testing was performed on the unconditioned specimens in accordance with the specification of the Ministry of Transport of China (T 0806, JTJ 57–94) [16] to investigate the tensile strength performance of base mixes. The geometry of the cylindrical specimens used in this study was 150 mm in diameter and 150 mm in thickness. The compressive load was applied on the specimens along the vertical diametrical plane through two 18.75 mm wide steel strips (Figure 11). The compressive load indirectly produces a tensile load in the horizontal direction of the sample, causing a tensile failure in the specimens. A loading rate of 1 mm/minute was adopted. IDT strength is the maximum tensile stress at the center of specimen, which was calculated using Equation (2) according to the specification of the Ministry of Transport of China. A higher tensile strength corresponds to a stronger cracking resistance:

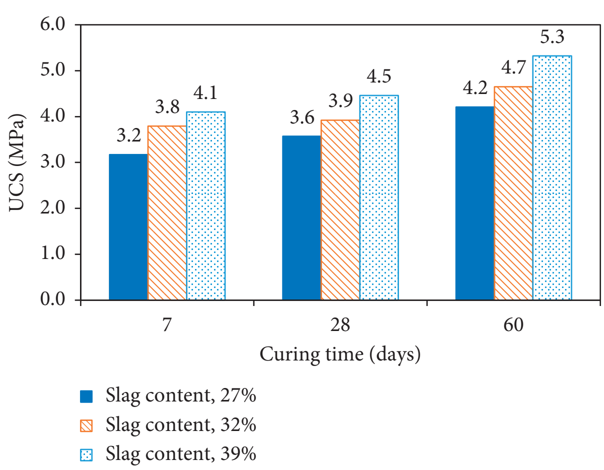
Table 6: Curing condition.

	Curing time		
	7 days	28 days	60 days
Unconditioned set	7-day curing at 20°C in plastic bag sealed	28-day curing at 20°C in plastic bag sealed	60-day curing at 20°C in plastic bag sealed
Conditioned set	6-day curing at 20°C in plastic bag sealed, and then submerged in water for one day at 20°C	27-day curing at 20°C in plastic bag sealed, and then submerged in water for one day at 20°C	59-day curing at 20°C in plastic bag sealed, and then submerged in water for one day at 20°C

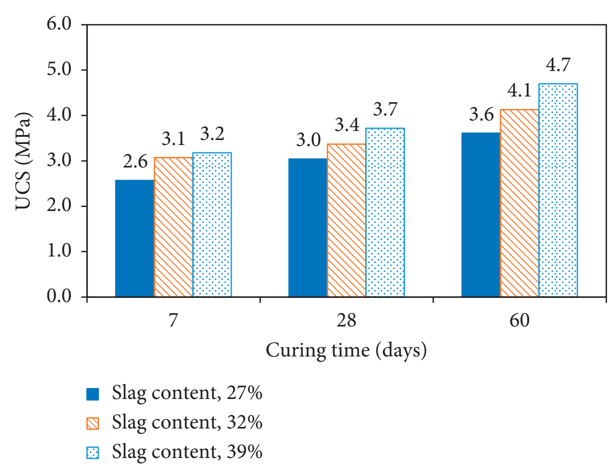
(a)

(b)

Figure 5: Setup of UCS test.



(a)



(b)

Figure 6: Unconfined compressive strength results for CTB. (a) Unconditioned set. (b) Conditioned set.

$$\text{Indirect tensile strength} = 0.004178\frac{P}{h}, \quad (2)$$

where P is the maximum applied load on the specimen and h is the thickness of the specimen.

Figures 12 and 13 show the IDT strength results for CTB and LTB mixes, respectively. Note that all IDT specimens were cured in the sealed bags and no water submersion was applied on the specimens. In addition, IDT specimens of CTB were cured for different lengths of time, while LTB specimens were cured only for 7 days as the similar trend was found in other curing time. As shown in Figures 12 and 13, IDT strength values of base layer mixes increased as the slag content and curing time increased. Furthermore, LTB mixes always showed similar IDT strength to CTB mixes after 7-day curing.

4.5. Dry Shrinkage Property. Cracking caused by dry shrinkage is a big concern for CTB and LTB materials. It is important to evaluate the dry shrinkage property of CTB and LTB mixes. The dry shrinkage test was performed according to the specification of the Ministry of Transport of China

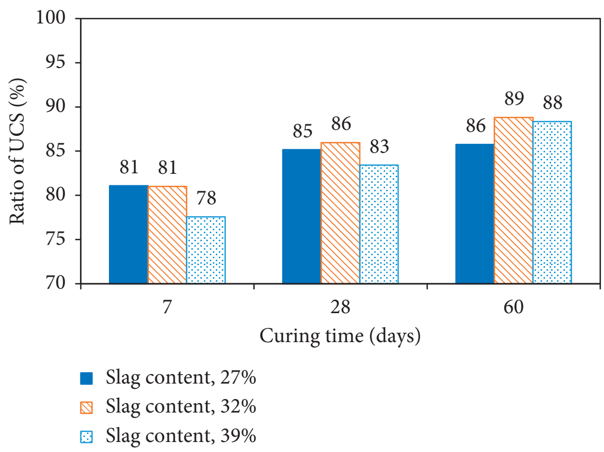


FIGURE 7: Ratio of unconfined compressive strength for CTB.

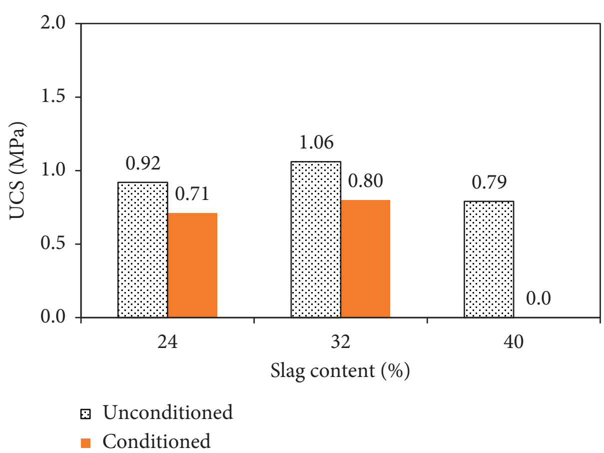


FIGURE 8: Compression strength results after 7-day curing for LTB.

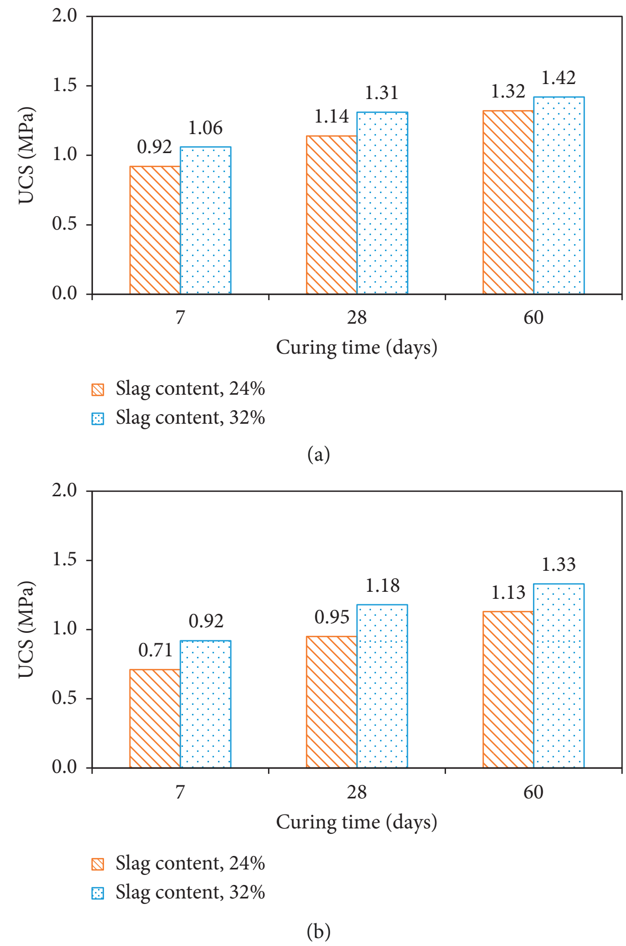


FIGURE 9: Unconfined compression strength results for LTB. (a) Unconditioned set. (b) Conditioned set.

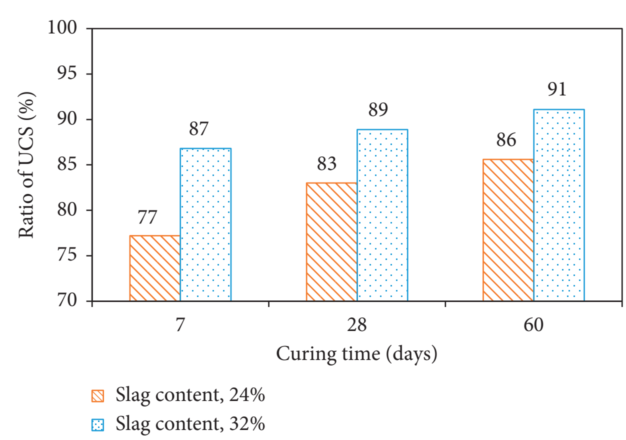


FIGURE 10: UCS ratio results for LTB.

(T 0854, JTJ 57–94) [16]. In this test, metal gauge studs were glued onto the ends of the samples with epoxy to facilitate shrinkage measurements over the following specific days. The length change of each specimen was monitored by a dial gauge with a resolution of 0.001 mm (see Figure 14). The dry shrinkage tests were conducted in an environmental chamber at 20°C and a relative humility of 60%. The dry shrinkage strain was calculated by the following equation:

$$E = \frac{\Delta L}{L}, \tag{3}$$

where E is the dry shrinkage strain; ΔL is the change of the specimen length in the test (mm); L is the length of the specimen before the test (mm)

Figures 15 and 16 show the dry shrinkage strain for CTB and LTB mixes, respectively. It was observed that dry shrinkage strain values of both base layer mixes increased with the increase of slag content in most cases. For CTB mixes, the mix with 32% slag had a little bit higher dry shrinkage strain than that with 27% slag, while the mix with 39% slag exhibited a significantly higher dry shrinkage strain compared to other two mixes. For LTB mixes, the mix with 32% slag had a little bit higher dry shrinkage strain than that with 24% slag. This trend is expected since a higher slag content resulted in a higher optimum moisture content (Figures 3 and 4) which could lead to a higher dry shrinkage. Additionally, it was observed that most of the dry shrinkage happened during the early testing time. This is reasonable as most of the moisture generally lost at that period.

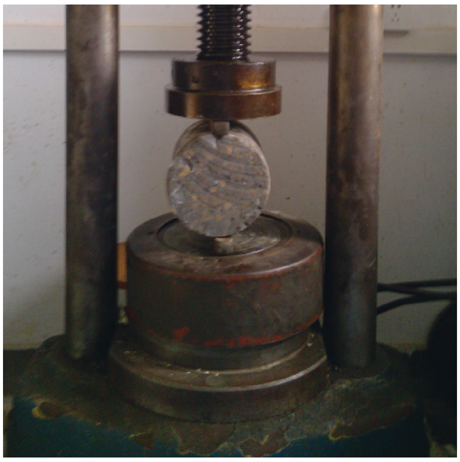


Figure 11: Setup of IDT test.

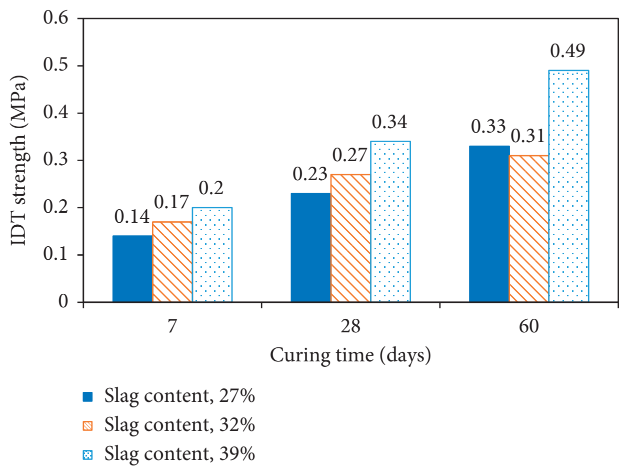


Figure 12: IDT strength results for CTB.

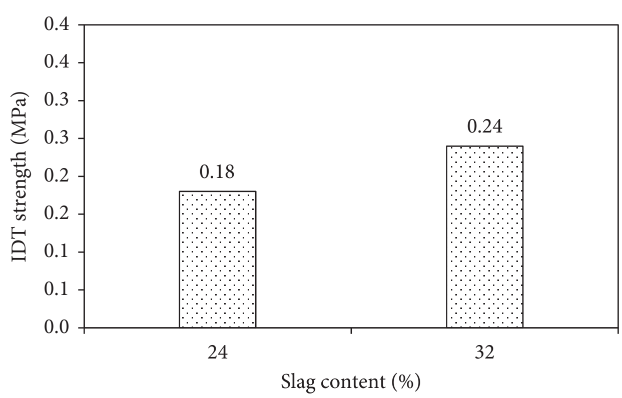


Figure 13: IDT strength results after 7-day curing for LTB.

Figure 14: Setup of dry shrinkage test.

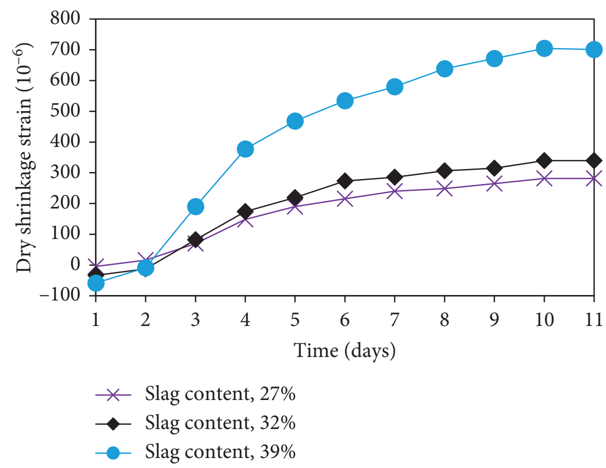


Figure 15: Dry shrinkage strain for CTB.

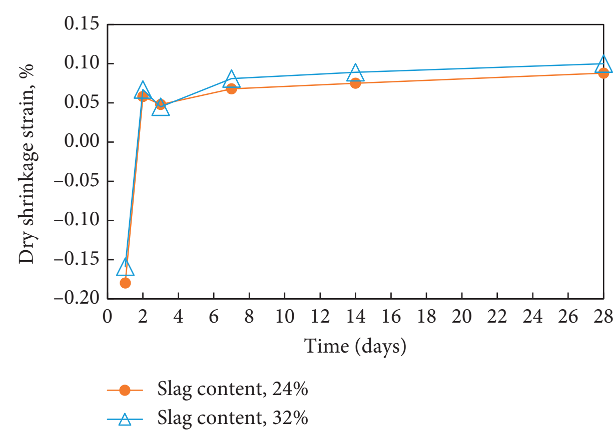


Figure 16: Dry shrinkage strain for LTB.

In addition, both LTB mixes showed much higher dry shrinkage strain than all the CTB mixes. This is expected as LTB mixes had higher moisture contents than CTB mixes in terms of the testing results in Figures 3 and 4. It was also noted that all the CTB and LTB samples exhibited the expansion on the first day. It is likely because SO_3 in the slag reacted with CaO-Al_2O_3-H_2O (C-A-H) and then produced $3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$ (AFt), which may cause the expansion of the materials.

4.6. Determination of Slag Content. Based on the above experimental results, two things were concluded in this section. Firstly, the CTB and LTB mixes with 32% slag had a better resistance to moisture damage compared to those with other contents of slag. Secondly, the CTB and LTB mixes with 32% slag exhibited a little bit higher dry shrinkage strain than those with lower slag content, while the CTB mix with 32% slag had significantly lower dry shrinkage strain than that with higher slag content. Moisture damage in the

(a) (b)

Figure 17: Cement-treated mixture mixing (a). Lime-treated mixture mixing (b).

(a) (b)

Figure 18: Base layer paving.

(a) (b)

Figure 19: Base layer compaction (a) and after compaction (b).

asphalt pavement is a big concern in Chongqing, China, as there is plenty of rainfall in there. Therefore, 32% slag was selected for both CTB and LTB test sections.

5. Construction

The CTB and LTB mixes were placed on the two sections in Chongqing, China, in 2007. Both test sections were about 15 km long, 5.5 m wide, and 20 cm thick. A 5 cm and 3 cm asphalt layer was paved on the CTB and LTB test sections, respectively. The compulsory mixer was used for producing the CTB mixture, and the loader was employed to mix the LTB mixture. The mixing time was controlled to ensure the slag distributed in the mixture uniformly. Figures 17 and 18 show the pictures of the mix production and paving, respectively. Both mixes were delivered using dump trucks and then leveled by the loader. The mixes with optimum moisture were compacted using the 12 ton roller. The breakdown rolling pattern was two static passes. The intermediate rolling pattern was five vibratory passes. The finishing pattern was one static pass. Figure 19 shows a picture of the mix compaction. After construction, the base

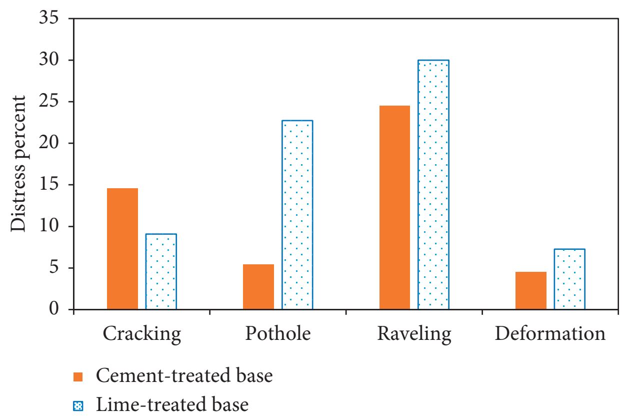


Figure 20: Field performance results.

(a)

(b)

Figure 21: Cement-treated (a) and lime-treated (b) test sections after 10-year traffic.

mixes were cured for 7 days and then covered by the asphalt surface mixture.

6. Field Performance

6.1. Structural Performance after Construction. The structural performance of test sections was investigated using

Figure 22: Typical cracking in test section in May 2017.

Figure 23: Typical pothole in test section in May 2017.

Figure 24: Typical ravelling in test section in May 2017.

the layer deflection. A lower surface defection means a better structural performance. In this study, the Benkelman beam deflectometer was used to measure the deflection of CTB and LTB layers. The Benkelman beam deflection was measured by a loaded truck of 100 kN on a single axle at dual tire pressure of 700 kPa. Average deflection values for CTB and LTB layers were 0.73 mm and 0.53 mm, respectively. Both the deflections met the specification requirement of 1.15 mm. The reason why the

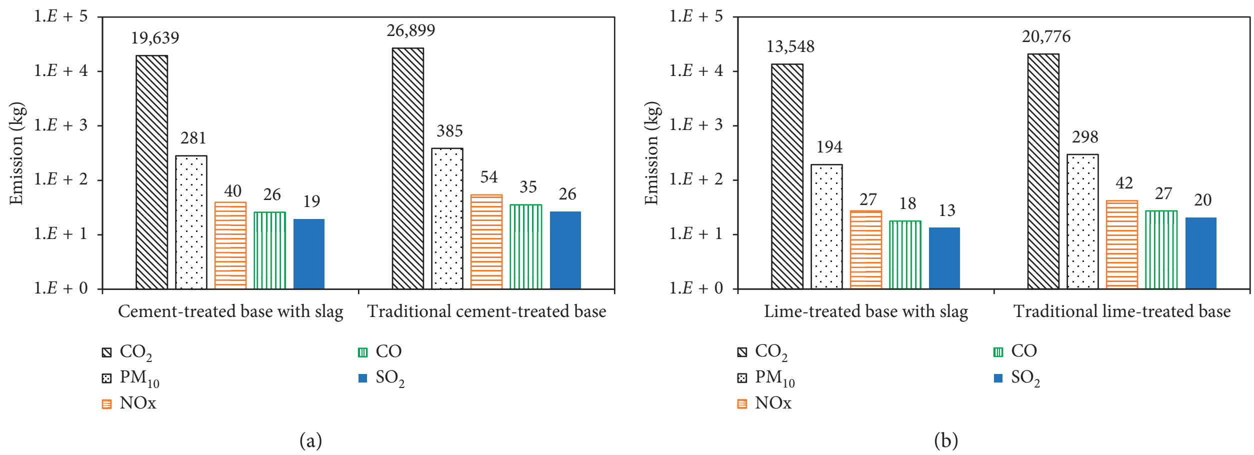


Figure 25: Emission comparison for aggregate production. (a) Cement-treated base. (b) Lime-treated base.

Table 7: Material cost comparison.

Material	Material price, \$ per ton	Cost per ton of mix (USD)		
		CTB without slag	CTB with slag	LTB with slag
Cement	45	2.25	2.25	—
Lime	50	—	—	4.00
Slag	2	—	0.54	0.64
Aggregate	9.5	9.03	6.46	5.70
Material cost		11.28	9.25	10.34
Percent savings		—	18.0	8.3

CTB layer had higher deflection than LTB is likely because the subgrade in the CTB section was softer than that in the LTB section.

6.2. Long-Term Field Performance. A field performance evaluation was conducted on two test sections in May 2017 after 10-year traffic. Field data were collected on the test sections based on the distress identification methods in China (JTJ 073–2001) [17]. Figure 20 shows the field performance results for the test sections. It was seen that both the test sections showed plenty of ravelling. It is likely because the asphalt surface had the severe weathering and/or the asphalt binders in the surface had the issue of bonding to aggregates. Additionally, the LTB section exhibited more potholes, ravelling, and deformation than CTB. This indicates that the CTB material used in this study may have a better bearing capacity and higher resistance to moisture damage than LTB, which was consistent to the laboratory USC results. The following reasons could result in the field performance differences between CTB and LTB: (1) the LTB mix had a lower USC values and worse resistance to moisture damage when compared to CTB and (2) the LTB section had a thin asphalt layer than the CTB section. Figures 21–24 show the typical distresses in the test sections.

7. Material Cost and Life-Cycle Assessment

Based on the mixture constituents and local material price, a material cost comparison was conducted on CTB and LTB test sections with slag. For comparison purposes, the cost for CTB without slag was also calculated. The material cost comparison is shown in Table 7. Table 7 indicates that the material cost of CTB and LTB can save 18.0% and 8.3%, respectively. Also, CTB with the slag could result in a greater reduction on the material cost compared to the LTB material.

The environmental impact of the slag was performed through the Palate program developed by the Consortium on Green Design and the University of California, Berkeley. Palate is an Excel-based life-cycle assessment tool, which can investigate energy consumption, emissions, and leachate information. Figure 25 shows the emissions for 1,000 meter test section. Note that the emissions in Figure 25 were only for material production. It indicates that CO_2 was the greatest emission in each section, followed by PM10, NOx, CO, and SO_2. The use of the slag significantly decreased the emissions and protected the environment.

8. Conclusions

This study investigated the performance of the pavement with strontium slag through laboratory and field experiments and evaluated the environmental effect of strontium slag used in the roads. Two test sections with strontium slag were paved in low-volume roads in Chongqing, China. Laboratory performance tests and field investigation were conducted on both the test sections. The cost analysis and environmental impact were also compared on the sections. The findings of this study are summarized as follows:

(i) Compressive strength, indirect tensile strength, and dry shrinkage values of CTB and LTB mixes increased with the increase of strontium slag content and curing time. CTB and LTB mixing with 32% strontium slag had the highest resistance to moisture damage in terms of the compressive strength ratio results.

(ii) After 10-year traffic, both field test sections with the strontium slag showed plenty of ravelling. LTB sections exhibited more potholes, ravelling, and deformation than CTB.

(iii) The use of the slag in the base layer decreased the material cost and the emissions. CTB with the strontium slag could result in a greater reduction on the material cost compared to the LTB material.

(iv) Based on the laboratory testing, field performance, and material cost analysis, CTB with the strontium slag exhibited a better performance and less material cost compared to LTB with the strontium slag.

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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