Study on the Effect of Steel Slag Fine Aggregate on the Road Performance of Cement Stabilised Sandstone Subgrade

Liu Yang[1*], Changxi Tang[2]

[1]Xi'an University of Posts & Telecommunications, Xian, Shanxi 710061
[2]Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, Kunming, Yunnan 650500

*Corresponding author Email: 2279399834@qq.com;
Changxi Tang's e-mail: 1401048524@qq.com

Abstract. The application of steel slag in pavement subgrade can not only improve the comprehensive utilization of steel slag, but also help to reduce the consumption of natural sand and gravel materials. In order to analyze the influence of steel slag fine aggregate on the road performance of cement-stabilized sandstone base layer (CSSB), this paper compares and analyzes the compressive strength, splitting strength and shrinkage of CSSB under different conditions of replacing limestone fine aggregate with steel slag fine aggregate, and uses SEM combined with energy spectroscopy to reveal the influence of steel slag fine aggregate on the microstructure of CSSB. The results show that: steel slag fine aggregate can effectively improve the late strength of CSSB, in which the 60 d strength of CSSB with 100% (mass fraction) steel slag fine aggregate replacement rate increased by 18.7% compared with the undoped steel slag samples, but there is a certain negative effect on the early strength of CSSB; steel slag fine aggregate can improve the shrinkage performance of CSSB, and the higher the doping, the more obvious the improved performance; although steel slag fine aggregate can improve the shrinkage performance, the higher the doping, the more obvious the improved performance. Compared with the unadulterated steel slag samples, at the age of 28 d, the m(Ca)/m(Si) mass ratio of CSSB interfacial transition zone was reduced by 62.95% at 100% steel slag fine aggregate replacement rate, and the C-S-H gel increased significantly, and the structure was denser. The study shows that steel slag fine aggregate can be used as a substitute for traditional sand and gravel fine aggregate by controlling the reasonable dosage, and has good application prospects in pavement subgrade.

Keywords: road engineering; steel slag; sandstone; pavement base; shrinkage properties; water stability

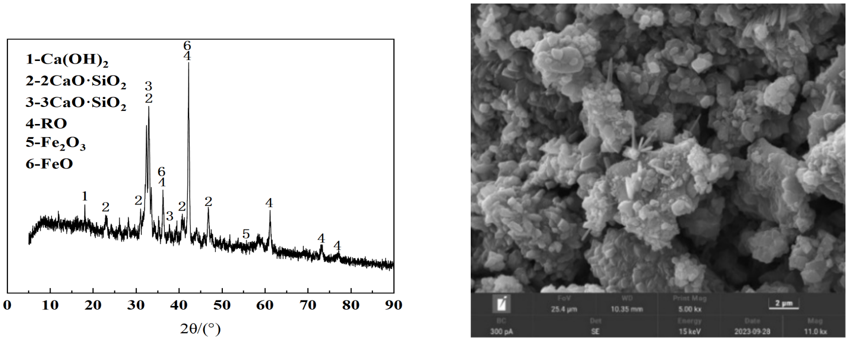
1 Introduction

Steel slag is one of the by-products produced in the steelmaking process, according to

G. Zhao et al. (eds.), *Proceedings of the 2024 7th International Symposium on Traffic Transportation and Civil Architecture (ISTTCA 2024)*, Advances in Engineering Research 241,
https://doi.org/10.2991/978-94-6463-514-0_61

statistics, the annual global crude steel production of 1,878.5 million tonnes in 2022, of which, only China's crude steel production reached 1,013 million tonnes [1], in accordance with the current iron and steel production efficiency in China, the steel slag generation rate of crude steel production of 8% to 15%, so the steel slag production of about 0.8 to 150 million tonnes, a large number of steel slag needs to be properly treated. The United States, Japan and other industrialised countries applied steel slag earlier, and the current utilisation rate of steel slag can reach 98%, while the utilisation rate of steel slag in China is only about 29.5% [2], most of which is piled up or transported as rubbish to landfills for disposal, which not only occupies land resources, but also may cause environmental pollution. At the same time, with the rapid development of China's transport construction, the lack of sand and gravel materials is becoming increasingly serious, many areas of sand and gravel materials are scarce, so it is urgent to find a new sand and gravel alternative resources. Steel slag has good physical and mechanical properties, high strength, rough surface, good compatibility, and has a certain cementing properties [3] If used properly, steel slag can partially or completely replace the aggregate in the mixture, not only to alleviate the problem of scarcity of gravel, but also to save engineering costs and reduce the damage to the environment[5-6].

At present, there have been several studies on the application of steel slag as a pavement material in road engineering [7]. Gao [8] analysed the mechanism of steel slag on the water stability of asphalt mixture from the chemical composition and microstructure of steel slag, and found that the steel slag indicates alkaline, porous surface, which increases the effective contact area between the steel slag and asphalt, and can significantly improve the water stability of asphalt mixture. Therefore, this paper carries out a systematic research on mixing steel slag fine aggregate in cement stabilised sandstone base layer. Five cement stabilised gravel mixtures with 0%, 25%, 50%, 75% and 100% steel slag fine aggregate were designed to study the mechanical properties, shrinkage properties and water stability of cement stabilised gravel mixtures with different steel slag fine aggregate dosages [9]. The results of the study can provide reference for the application of steel slag in semi-rigid base layer.



(a) XRD map of steel slag (b) microscopic images of steel slag

Fig. 1. Raw material XRD and microscopic morphology

Table 1. Main chemical composition of steel slag

Type	CaO	Fe_2O_3	SiO_2	MgO	TiO_2	MnO	Al_2O_3	V_2O_5	K_2O
Content/%	39.66	21.02	16.10	3.37	2.75	5.75	3.46	1.541	0.063

1.1 Proportioning Design

The main chemical components of steel slag were determined by X-ray fluorescence spectrometry (XRF) and the surface morphology of steel slag specimens was characterized by a Czech Tescan MIRA LMS scanning electron microscope (SEM), and the results are shown in Figure 1 and Table 1.In order to investigate the effects of different steel slag fine aggregate replacement rates on the strength characteristics and water stability of cement stabilised sandstone mixes, the cement stabilised gravel mix ratios were carried out according to the Technical Rules for the Construction of Highway Pavement Base Levels (JTG/T F20-2015) [10] and Test Procedures for Stabilising Materials for Inorganic Cement Stabilised Gravel Mixtures for Highway Engineering (JTG E51-2009) [11].

Table 2. Experimental mixing ratio

Mixture Number	Mass Fraction of the Material (wt/%)						
	Sandstone				Limestone	Steel slag	Cement
	19-26.5	16-19	9.5-16	4.75-9.5	0-4.75	0-4.75	
LS-0	17	6	20	16	36	0	5
LS-25	17	6	20	16	27	9	5
LS-50	17	6	20	16	18	18	5
LS-75	17	6	20	16	9	27	5
LS-100	17	6	20	16	0	36	5
LS1	17	6	20	16	36	0	4.5
LS2	17	6	20	16	36	0	5.5

1.2 Test Methods

Strength Test.

Standard cylindrical specimens were molded under standard conditions according to the ratios in Table 2, and cured under standard curing conditions until the experimental age and the specimen was soaked in water for 24h one day before the determination of unconfined compressive strength and splitting strength. The YES305-5000 digital pressure tester was used (Jinan Tester Group Co., Ltd.), and the specimen was tested in accordance with The compressive strength and splitting strength tests were carried out by YES305-5000 digital display pressure testing machine (Jinan Testing Group Co, Ltd.) in accordance with the Test Procedure for Stabilisation Materials of Inorganic Binding Material for Highway Engineering (JTG E51-2009) [12], and the loading rate was 1 mm/min.

Shrinkage Performance Test.

The three groups of ratios numbered 1, 3 and 5 were selected in accordance with the "Highway Engineering Inorganic Combined Material Stability. Material test procedure" (JTG E51-2009) of the forming method in the best moisture content and maximum dry density of forming contraction test with the middle beam specimen, size 100mm × 100mm × 400mm, the same proportion of the mixture of six for a group, three specimens to determine the shrinkage deformation of the material, and in addition to reserve three standard specimens for the measurement of the material's contraction of the water loss rate. The test was carried out when the material was maintained to 7d according to the standard method of maintenance.

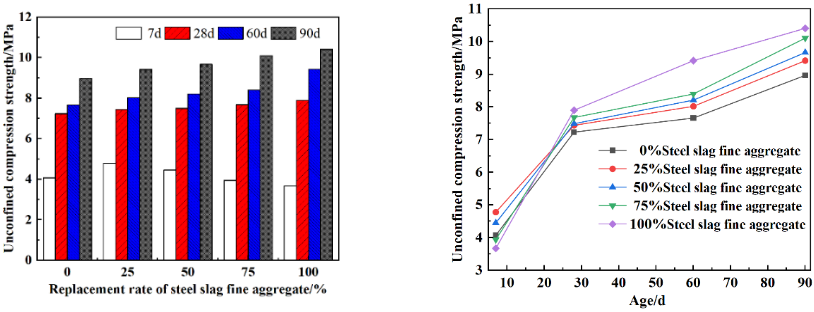
Microscopic Property Test (SEM-EDS).

In order to clarify the effect of steel slag on the microstructure of CSSB, a scanning electron microscope was used to test the microstructure of CSSB

2 Results and Discussion

2.1 Unconfined Compressive Strength Test

The unconfined compressive strength is the most direct and critical index for evaluating the performance of cement stabilised aggregates [13], in order to study the influence of different steel slag fine aggregate replacement rate and maintenance age on the strength of cement stabilised aggregates, the unconfined compressive strength test was carried out on 5 different ratios of cement stabilised aggregates for 7d, 28d, 60d and 90d. The relationship between the unconfined compressive strength of specimens and the replacement rate of steel slag fine aggregate and the age of maintenance is shown in Figures 2.



(a) Replacement ratio

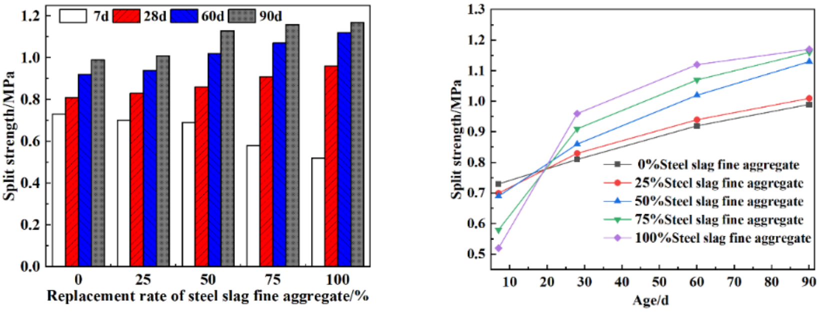
(b) Age

Fig. 2. Effect of different factors on the unconfined compressive strength of CSSB

The strength of cement-stabilised aggregates is mainly composed of two parts: the adhesive force of hydrates produced by the hydration reaction of cement and the friction between coarse and fine aggregates [14-15]. As can be seen from Figure 2, under the same replacement rate, the unconfined compressive strength of the mix increases with the growth of age, in which the long-term strength of the mix increases significantly with the increase in the replacement rate of steel slag fine aggregate, and the 60d strength of the mix with 50% steel slag fine aggregate replacement rate reaches 8.21 MPa, which is 7.2% higher than that of the mix with unadulterated steel slag fine aggregate.

2.2 Splitting Strength Test

As an important structural layer in the pavement, the base layer will be subjected to tensile stress in addition to compressive stress, the splitting strength reflects the cracking resistance of cement stabilised aggregates to a certain extent [16-17], and the specimens were subjected to the splitting strength test, and the test results are shown in Fig. 3.



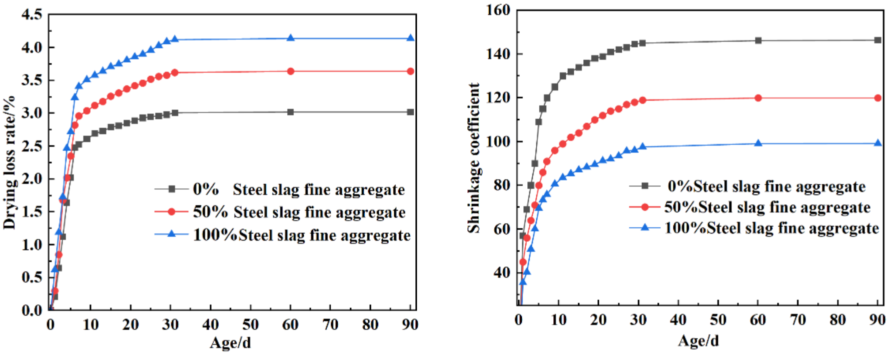
(a) Replacement ratio (b) Age

Fig. 3. Effect of different factors on the splitting strength of CSSB

Splitting tensile strength mainly reflects the cementation capacity of cement stabilised aggregate within the aggregate, which mainly depends on the cohesion between aggregates [18]. As can be seen from Figure 3(a), at the same replacement rate of steel slag fine aggregate, the splitting strength of the specimen increases with the growth of the age of maintenance, and the longer the age of maintenance, the more obvious the increase. As can be seen from Figure 3(b), at different ages, the split strength of the mixture is similar to the law of strong compressive strength, the split strength at the age of 7 d decreases with the increase of the replacement rate of steel slag fine aggregate, and the split strength at the ages of 28d, 60d and 90d all increase with the increase of the replacement rate of steel slag fine aggregate.

2.3 Analysis of the Effect of Steel Slag Fine Aggregate on Shrinkage Properties

Shrinkage cracks will occur when cement stabilised materials are used as pavement base layers undergoing a certain degree of dry and wet cycling [19], so in addition to strength, the influence of the material on the shrinkage properties of the mix needs to be considered [20]. Since steel slag fine aggregate contains a certain amount of f-CaO, it will have a positive effect on the shrinkage properties of the mix. The cumulative moisture loss rate and shrinkage coefficient of the mixes with different steel slag fine aggregate replacement rates were calculated according to the standardize, and the results are shown in Fig. 4(a). It can be seen that the moisture loss rate is faster in the first few days of the test, which is mainly due to evaporation of free water in the specimen. The moisture loss of the specimen with 50 per cent steel slag fine aggregate replacement rate in the pre-conditioning period is much higher than that of the specimen without steel slag, which is due to the fact that the steel slag fine aggregate This is due to the fact that steel slag fine aggregate has a higher water absorption rate than limestone fine aggregate, and the water loss in the initial period is also greater. 30d later, the water loss rate of the three mixes tends to stabilise, and basically no longer changes.



(a) Dry Water Loss (b) Shrinkage factor

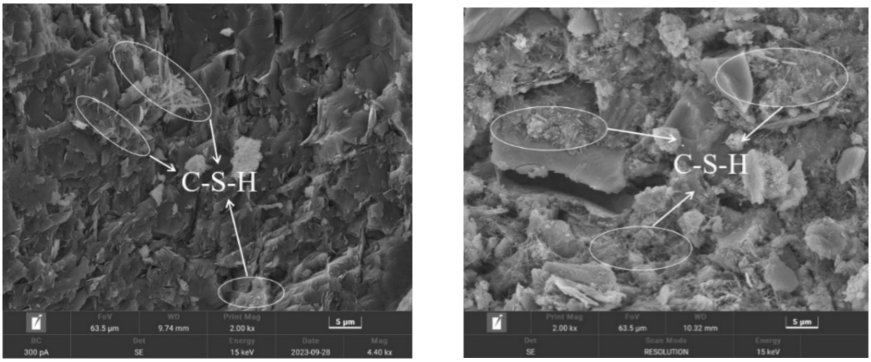
Fig. 4. Effect of different steel slag fine aggregate replacement rates on CSSB

As an important structural layer in the pavement, the base layer will be subject to tensile stress in addition to compressive stress, the splitting strength reflects the cracking resistance of cement stabilised aggregates to a certain extent, and the specimens were subjected to the splitting strength test, and the test results are shown in Fig. 4(b).

Fig. 4(b) shows the shrinkage coefficient of mixes with age change rule of three kinds of steel slag fine aggregate replacement rate, it can be found that the steel slag fine aggregate has a good inhibition effect on drying shrinkage, the higher the replacement rate of steel slag fine aggregate, the more obvious the reduction of the shrinkage coefficient, at the end of the age of maintenance, compared with the unadulterated steel slag specimens, the shrinkage coefficient of the specimens of the 50% steel slag fine aggregate replacement rate and the 100% steel slag fine aggregate replacement rate were reduced by 18.03%, 32.24%, the reason is that steel slag microexpansion can offset some of the volume shrinkage, which is similar to the findings of Huang [20].

2.4 Microstructure Testing Result

From Fig.5(a), it can be seen that the CSSB without steel slag fine aggregate generated fewer C-S-H gels with sparse distribution, while a small amount of acicular calcareous alumina and flaky Ca(OH)2 appeared, whereas in Fig. 5(b), it can be clearly seen that a large number of fibrous interspersed C-S-H gels were generated in the internal part of the CSSB with the incorporation of steel slag to form a dense structure.



(a) 0% (b) 100%

Fig. 5. Effect of different steel slag replacement rates on microstructure

3 Conclusion

(1) The surface of steel slag is rough and porous, with high water absorption rate and high density, which has good engineering mechanical properties; with the increase of the replacement rate of steel slag fine aggregate, the optimum water content and maximum dry density of the mix are increased.

(2) The inclusion of steel slag fine aggregate will reduce the early mechanical properties of the mixture to a certain extent (including unconfined compressive strength and splitting strength), but can improve the long-term strength of the mixture, based on the results of this paper, the reasonable mixing amount of steel slag fine aggregate in 25%~75%, to meet the use of general road pavement grass-roots level requirements.

(3) The incorporation of steel slag fine aggregate will significantly improve the shrinkage properties of the mixture, and the improvement effect increases with the replacement rate. Compared with the unadulterated steel slag fine aggregate samples, the shrinkage coefficient of 100% steel slag fine aggregate replacement rate samples is reduced by 32.24%, and the shrinkage performance is greatly improved.

References

1. World Steel Statistics [DB/OL], 2023. https://worldsteel.org/.
2. Huang You,LIU Zhaohui,LIU Li et al. Performance and environmental impact test of steel

slag-cement stabilized gravel[J]. Journal of Chang'an University (Natural Science Edition), 2021,41(05):43-53. (in Chinese).

3. Wan Tianbao. Mechanical Characteristics and Microanalysis of Cement-Stabilized Steel Slag Aggregate Subgrade[J]. Chinese and foreign highway,2023,43(03):248-252. (in Chinese).
4. Feng Qunying. Research on the application of steel slag in highway roadbed pavement engineering [D]. Chongqing Jiaotong University,2013. (in Chinese).
5. Huang Wei, QIU Peng, TANG Gang et al. Research on the preparation and performance of steel slag mixed soil base material[J]. *Silicate Bulletin*, 2019, 38(10):3237-3242+3265. (in Chinese).
6. Xiao J, LONG C J, HE J G et al. Performance and Micro Characteristics of Cement StabilizedMacadam with a Large Amount of Activated Steel Slag Powder [J]. *China J. Highw. T ransp,* 2021, 34(10): 204-215. (in Chinese).
7. Ma S J, ZHOU Z D, ZHANG Z C et al. Environmental Impact and Economic Benefit Analysis of Cement Stabilized Steel Slag Macadam Mixture [J]. *HIGHWAY*, 2023, 68(01): 368-377. (in Chinese).
8. Gao Zhen-Xin, SHEN Ai-Qin, ZHAI Chao-Wei et al. Determination of volumetric parameters of steel slag asphalt mixtures and the mechanism of water stability[J]. J*ournal of Transportation Engineering*, 2018,18(02):1-10. (in Chinese).
9. Xin D J, LIU Z Q, JI X et al. Study on the characteristics of cement-stabilized steelslag and gravel base in dry and cold region [J]. Journal of Xi’an University of Science and Technology, 2022, 42(1): 116－124, (in Chinese).
10. Ministry of Transportation and Communications of the People's Republic of China. Aggregate Testing Procedure for Highway Works: JTG E42—2005[S]. Beijing: China Communications Press, 2005 (in Chinese).
11. Ministry of Transportation and Communications of the People's Republic of China. Technical details of road pavement subgrade construction: JTG/TF20—2015[S]. Beijing: China Communications Press, 2015 (in Chinese).
12. Ministry of Transportation of the People's Republic of China. JTG E51-2009, Test Specification for Stabilizing Materials of Inorganic Binding Material for Highway Engineering [S]. Beijing: People's Transportation Press, 2009.
13. Pateriya, D.J. Robert, K. Dharavath, S.K. Soni, Stabilization of marble wastes using cement and nano materials for subgrade applications, Construction and Building Materials, Volume 326, 2022, 126865, ISSN 0950-0618,
14. Zou Guilian, WANG Huaxin, FANG Shuai. Research on road performance of cement stabilized recycled aggregates [J]. Highway Engineering.2018,43(05):28-32.
15. Tian Xiaoge, YU Shui, LI Guangyao et al. Effects of different measures on the properties of cement stabilized aggregates[J]. Silicates Bulletin, 2022,41(07):2235-2243.
16. Cai Deming. Neutrally activated steel slag micropowder and its application in cement stabilized aggregates [D]. Changsha University of Science and Technology, 2020.
17. Guan, J.; Lu, M.; Yao, X.; Wang, Q.; Wang, D.; Yang, B.; Liu, H. An Experimental Study of the Road Performance of Cement Stabilized Coal Gangue. Crystals 2021, 11, 993.
18. Hou, Y.Q.; Ji, X.P.; Liu, L.Q. Study on Mechanical and Influencing Factors of Cement Stabilised Recycled Aggregate. J. Highw. Transp. Res. Dev. 2016, 33, 56–61.
19. Lei Lei,JIANG Hui,GU Wan et al. Experimental study on regenerated cement stabilized gravel base material improved by external dopant[J]. Highway, 2022, 67(02):31-37.
20. Huang Guiping, HAN Zuli, TAN Yi. Experimental study on road performance of cement stabilized gravel mix with steel slag fine aggregate[J]. Western Transportation Science and Technology. 2022(10):7-12. DOI: 10.13282/j.cnki.wccst.2022.10.003.