Journal of Engineering Research and Reports

Volume 26, Issue 11, Page 28-35, 2024; Article no.JERR.124507
ISSN: 2582-2926

Study on the Characteristics of Steel Slag and its Road Performance in Asphalt Mixture

Shuo Chen [a*], Deqing Tang [a] and Zhi Li [a]

[a] School of Civil Engineering and Ttransportation, North China University of Water Resources and Hydropower, Zhengzhou-450045, Henan, China.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jerr/2024/v26i111312

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/124507

Opinion Article

Received: 02/08/2024
Accepted: 05/10/2024
Published: 23/10/2024

ABSTRACT

Based on the characteristics of steel slag, the application progress of steel slag as aggregate in asphalt mixture is summarized. Firstly, the differences in mechanical properties, chemical composition and physical structure of steel slag aggregates treated by different methods are summarized. The surface structure of steel slag is rough and rich in edges and corners, showing good wear resistance and crushing resistance, but there are also problems such as high density, high water absorption and volume instability. Among them, volume instability is the key factor affecting the application of steel slag in asphalt mixture. Then, the effects of steel slag aggregate on the road performance of asphalt mixture, such as water stability, rutting resistance, high temperature stability and low temperature cracking resistance, are summarized in detail. It is found that steel slag instead of coarse aggregate in asphalt mixture can improve the performance of skid resistance, rutting resistance and fatigue resistance. The water damage performance is due to the

**Corresponding author: Email: chenshuocsxx@163.com;*

Cite as: *Chen, Shuo, Deqing Tang, and Zhi Li. 2024. "Study on the Characteristics of Steel Slag and Its Road Performance in Asphalt Mixture". Journal of Engineering Research and Reports 26 (11):28-35. https://doi.org/10.9734/jerr/2024/v26i111312.*

different sources of steel slag, and the uncertainty of the change results is large. On the whole, steel slag instead of aggregate can improve the road performance to a certain extent, but the volume of steel slag aggregate is unstable, which may bring some variability. In the process of road application, targeted regulation should be carried out to ensure the stability of asphalt mixture performance.

Keywords: Steel slag; aggregate; asphalt mixture; physical properties; road performance; summary.

1. INTRODUCTION

Aggregate is one of the main building materials used in road construction and maintenance. With the increase of the volume and scope of highway construction in China, as well as the rapid speed of road construction and maintenance in China, the consumption of sand and gravel aggregate per kilometer is about 40 ~ 60 thousand tons, and the consumption of natural aggregate is large. High-quality aggregate is increasingly lacking. In the context of the continuous implementation of green environmental protection policies, some areas have limited the exploitation of natural sand and gravel, so the aggregates required for highway pavement construction need to be expanded urgently. In order to improve this situation, researchers have actively explored the use of industrial solid waste, such as steel slag, mining waste and construction waste as aggregates for road construction and maintenance. Among them, steel slag has the advantages of high strength, wear resistance, skid resistance, high alkalinity and low cost, and has the potential to replace natural aggregates for road construction and maintenance. In recent years, Chinese scholars have carried out a lot of research on the application of steel slag in asphalt pavement.

Steel slag has the advantages of high strength, wear resistance, skid resistance, high alkalinity and low cost, and has the potential to replace natural aggregates for road construction and maintenance. In recent decades, the increase in steel production has led to an increase in steel slag by-products. At present, China 's annual steel slag production is about 70 million tons, with a cumulative stockpile of more than 1 billion tons, which not only occupies a large amount of land resources, but also causes long-term and difficult to restore harm to the environment. At present, the reutilization rate of steel slag in China is low. Therefore, the popularization and application of steel slag aggregate, saving natural resources, is the only way to realize the sustainable development of road construction and maintenance in China. In this paper, the influence of steel slag content on the performance of asphalt mixture after replacing limestone is studied. Firstly, the basic performance characteristic parameters of steel slag are summarized and analyzed, and the different functions of steel slag aggregate in road asphalt mixture are summarized. Then, the water stability, rutting resistance, high temperature stability and low temperature crack resistance of steel slag asphalt mixture are summarized. The results can provide reference for the application of steel slag in the field of asphalt pavement.

2. BASIC PERFORMANCE CHARACTERISTICS OF STEEL SLAG

2.1 Steel Slag Appearance and Physical and Mechanical Properties

As aggregate, steel slag should have certain physical and mechanical properties to resist the aging of pavement during use. China 's road material specifications stipulate the gradation, stability, wear and crushing strength of aggregates used in road asphalt production. Construction and traffic loads can lead to deterioration of aggregates, so the laboratory usually uses Los Angeles abrasion, crushing and impact tests to evaluate the performance of aggregates.

Table 1. Comparison of characteristic parameters of steel slag and natural aggregate

Aggregate Steel	L.A Abrasion/%	Crushing value/%	water absorption/%	Porosity	Bulk specific gravity(/g·cm^{-3})
Limestone	18.2~39.8	~20.4	0.2~1.1	-	2.57~2.65
Granite	10.5~24.5	-	0.5~1.1	-	2.62~2.68
Basalt	15.4~16.6	~12.7	0.4~0.7	~0.2	2.71~2.76
Steel slag	11.1~13.1	10.3~25.0	0.7~2.2	2.3~5.6	3.02~3.41

Table 1 lists these characteristic indicators of steel slag and commonly used natural aggregates reported in the literature. According to Table 1, it can be found that the Los Angeles wear range of steel slag is between 11.0% and 13.2%, which is better than basalt (15.8% ~ 16.8%), granite (10.3% ~ 25.0%) and limestone (18.4% ~ 40.0 %). This shows that steel slag has higher wear resistance than basalt and limestone. The crushing value of steel slag (12.1% ~ 14.2%) is almost the same as that of basalt (~ 12.7%) and much smaller than that of limestone (~ 20.4%). This shows that steel slag has higher crushing resistance than limestone. Steel slag has excellent wear resistance and crushing resistance, and its crushing value and Los Angeles wear technical requirements can meet the limit value (< 22 %).

Water absorption is an indicator of aggregate durability. It can be seen from Table 1 that the water absorption of steel slag is 0.9% ~ 2.5%, which is more than that of basalt (0.4% ~ 0.7%) and granite (0.5% ~ 1.1 %). This is because steel slag forms a certain amount of vesicular porous structures in the furnace, which can store a part of water. This part may be exposed to the active components in the steel slag, such as free calcium oxide (CaO), magnesium oxide (MgO), etc., resulting in the volume expansion of the asphalt mixture.

The steel slag asphalt mixture has higher stiffness and can replace low-quality and durable aggregates. In addition, the proportion of steel slag is higher than that of natural aggregate, which makes it 20% ~ 30% heavier than the traditional aggregate of the same volume, so the transportation cost is usually higher. The pavement thickness produced by the same quality steel slag is thinner than that of natural aggregate, which may further increase the construction cost. In summary, steel slag has better wear resistance and crushing resistance than natural aggregate, but its water absorption is higher, and the active components in steel slag may undergo hydration reaction, resulting in unstable volume of steel slag asphalt mixture, thus affecting the performance of the mixture. In addition, the proportion of steel slag is higher than that of natural aggregate, which makes the transportation cost of steel slag higher.

2.2 Chemical and Mineral Composition of Steel Slag

The chemical composition and mineral composition of steel slag are affected by factors such as the source of steel slag, the variety of steel, the process of steel making, the treatment process and age of steel slag. Even the composition of steel slag from the same factory is different due to the different dosage of ingredients, the process used and the steel grade produced by the factory. The chemical composition of steel slag generally includes CaO, MgO, SiO_2, FeO, Al2O3, TiO2 and MnO. The content of these components accounted for 88% ~ 90% (Aziz et al., 2014). Understanding the chemical composition of steel slag can help explain the reasons for the change of steel slag in the durability, density and bonding force of asphalt mixture.

Liu Xingcheng et al. (2019) selected steel slag samples from the steel slag stacking site of Yuanli Steel Plant in Quzhou City.After screening, steel slag with a particle size below 0.075 mm was obtained and the steel slag was fully ground. The obtained steel slag samples were detected by X-ray fluorescence spectrometer. The chemical composition contained in the steel slag is mainly composed of CaO, SiO2 and Fe2O3. The composition of steel slag is different from that of natural gravel. At the same time, the steel slag also contains trace amounts of Al, Mn and Mg mineral elements.

Xu Dingbin et al. (2018) tested the chemical composition of Meishan steel slag by X-ray fluorescence spectrometer. According to the test results, Meishan steel slag is mainly composed of Ca, Fe, Mg, Si, Al, Mn and other oxides. The content of CaO, MgO, SiO2 and FeO accounts for about 91% of the total components. According to the calculation formula R = (CaO / (SiO2 + P2O5)) proposed by Mason (1994), the alkalinity of steel slag can be determined, and the activity of steel slag can be judged according to the alkalinity. The higher the alkalinity, the higher the activity of steel slag. Mason 's method is used to define the basicity of steel slag in China, and steel slag is divided into three kinds of low basicity slag (M2.5) according to the basicity. The basicity of the steel slag measured by the author reached 2.86, which belongs to the high basicity steel slag and belongs to the category of alkaline aggregate. It is the common result of chemical adsorption and physical adsorption that asphalt can adhere to the surface of aggregate. Asphalt contains surface active substances such as asphaltic acid and anhydride. When it contacts with alkaline aggregate, it will produce strong chemical adsorption. In addition, the high alkalinity of steel slag, its high surface roughness and porous characteristics make steel slag and asphalt have good adhesion.

2.3 Thermal Stability of Steel Slag

The thermal stability of aggregate plays an important role in transportation. Studying the exothermic stability characteristics of steel slag aggregate is helpful to judge the transportation distance and construction rolling time of steel slag asphalt mixture.

Due to the porosity of the steel slag aggregate, the air volume inside the steel slag aggregate particles is more, and the gas thermal conductivity is less than that of the general solid, which can reduce the heating rate of the steel slag aggregate. Compared with natural aggregate, the heat conduction speed of clean steel slag is faster and the specific heat capacity is smaller, but the heat absorption of steel slag containing impurities increases, and the heating speed of steel slag is significantly slower than that of natural aggregate, which is due to the fact that impurities absorb part of the energy. One of the test methods for evaluating the high temperature stability of steel slag is to use thermogravimetric and differential scanning calorimetry (TG-DSC).

Zhang (2022) tested the thermal stability of steel slag by comprehensive thermal analysis. The results show that the properties of steel slag in the whole asphalt mixture preparation and pavement paving can be stable at the drying temperature of about 180 °C and the mixing temperature of asphalt mixture. Therefore, steel slag can have good thermal stability in the application of asphalt mixture pavement engineering. This thermal stability characteristic makes the temperature loss rate of steel slag asphalt mixture slow in the process of transportation, laying and compaction, which ensures the construction quality of the pavement.

2.4 Expansion Analysis

Steel slag has expansibility. If steel slag with greater expansibility is used in the road, it will cause greater internal stress in the steel slag asphalt mixture pavement, resulting in diseases such as bulges and cracks (Xu et al. 2006). Therefore, in the application of steel slag, it is necessary to focus on effectively reducing the expansion of steel slag. According to the test of the volume immersion rate of steel slag, it can be concluded that the immersion expansion rates of the two particle sizes of coarse steel slag and fine steel slag have different changes. The test results show that the swelling rate of coarse steel slag is small, while the swelling rate of fine steel slag is large. On the one hand, due to the small particle size of fine steel slag, it has a higher specific surface area, so the active components on the surface of steel slag participate in more chemical reactions, the reaction speed is faster, and the expansion rate is greater. On the other hand, the structure of fine steel slag is compact after being compacted in the mold, which reduces the volume expansion relief space of steel slag in the mold. Steel slag will produce volume expansion under the action of water, so it must be pretreated before its application, such as aging, etc., to reduce its volume expansion rate and reduce the possibility of cracking in road engineering applications. In view of the expansion characteristics of steel slag, corresponding treatment measures should be taken according to the specific requirements of road engineering.

3. PERFORMANCE ANALYSIS OF STEEL SLAG ASPHALT MIXTURE

3.1 Water Stability

Water stability refers to the ability of asphalt mixture to resist water erosion. Rainfall can lead to the moisture of asphalt pavement and even water accumulation. Water will enter the interior of asphalt pavement with the gap of asphalt pavement, or with the action of automobile load, water will be pressed into the interior of asphalt pavement by automobile, and tires will also suck water from the interior of asphalt pavement, forming a cycle, which is also called dynamic water erosion. Under the action of dynamic water erosion, water will produce pressure on the internal structure of asphalt mixture, destroy the internal structure, lead to the decrease of adhesion between asphalt and aggregate, resulting in the decrease of strength of asphalt mixture and loose condition. Under the action of vehicle load for a long time, the road surface is crowded, damaged, pits and other damage (Wang et al., 2018).

In order to evaluate the water stability of steel slag asphalt mixture, the researchers used immersion Marshall test and freeze-thaw splitting test to evaluate the water stability of steel slag asphalt mixture. Wang Chao and others (Wang et al., 2020) made Marshall specimens for four kinds of asphalt mixtures: hot stuffy steel slag asphalt mixture, cold abandoned slag asphalt mixture, limestone asphalt mixture (both coarse and fine aggregates are limestone) and steel slag limestone asphalt mixture, and then carried out immersion Marshall test and freeze-thaw splitting test to evaluate its water stability. The test results show that the water stability of different types of steel slag asphalt mixture is higher than that of limestone asphalt mixture. With the increase of soaking time, the residual stability of limestone asphalt mixture decreases continuously, while the residual stability of cold discarded slag asphalt mixture, hot stuffy steel slag asphalt mixture and steel slag limestone mixture increases continuously.

Zhang Xiaohan (2022) carried out immersion Marshall test and freeze-thaw splitting test on asphalt mixture mixed with natural aggregate and 54% coarse and fine steel slag, and compared it with 54% coarse steel slag and 54% fine steel slag mixture. The results show that compared with natural aggregate, the incorporation of coarse steel slag makes the residual stability of the mixture increase, while the incorporation of fine steel slag makes the water stability of the mixture decrease significantly, and the water stability of the asphalt mixture mixed with steel slag is between the two, which is lower than that of natural aggregate asphalt mixture. The splitting tensile strength of fine steel slag asphalt mixture is significantly lower than that of natural aggregate asphalt mixture, but the incorporation of coarse steel slag improves the splitting tensile strength of the mixture before and after freezing and thawing. The coarse and fine mixed steel slag improves the splitting tensile strength of the mixture before freezing and thawing, and does not change the splitting tensile strength after freezing and thawing.

Goli et al. (2017) found that when electric furnace steel slag is used to replace limestone (coarse aggregate, fine aggregate or both) in asphalt mixture, the elastic modulus, indirect tensile strength and fracture energy of the mixture will increase, which will have an adverse effect on water stability. The limestone asphalt mixture without steel slag replacement has better water stability.

3.2 Anti-Rutting Performance

Li Jianxin et al. (2024) conducted a rutting test on asphalt mixture mixed with RAP and steel slag. The results show that adding a certain proportion of RAP and steel slag to the asphalt mixture can still meet the requirements of high temperature stability of asphalt pavement design in China. In addition, compared with ordinary basalt mixture, the addition of steel slag can greatly improve the dynamic stability of asphalt mixture. Arabani et al. (2012) used steel slag instead of dacite aggregate to test the performance of the mixture. The results show that compared with the control mixture and 100 % steel slag instead of fine aggregate, the steel slag can improve the anti-rutting performance after replacing the coarse aggregate of the control mixture.

Pasetto et al. (2011) studied the rutting performance of limestone asphalt mixture with different proportions of electric furnace steel slag. The test carried out multiple axial load tests at 40 °C, and studied the performance of 0 %, 30 %, 60 % and 90 % electric furnace steel slag in the limestone wear layer asphalt mixture. The results show that the increase of steel slag percentage leads to the decrease of perm

Amelian et al. (2018) used cyclic axial load and Hamburg rutting test to compare the rutting performance of 12.5 mm NMAS limestone asphalt mixture and steel slag limestone mixture. The results show that the anti-rutting performance of the mixture with converter steel slag instead of limestone coarse aggregate is better than that of limestone asphalt mixture.

Most of the literature shows that using steel slag instead of coarse aggregate can improve the rutting resistance of asphalt mixture. The reason is that the steel slag has a larger density and better angularity, and the steel slag has a honeycomb porous structure, a larger angle, a lower sphericity and a higher texture, which can significantly improve the adhesion and mechanical properties of the recycled asphalt mixture, and provide a better skeleton strength for the mixture. At the same time, the larger surface roughness of steel slag also forms a good interface strength with asphalt, so it means that the steel slag as the original aggregate mining can significantly improve the rutting resistance of asphalt mixture.anent deformation, which indicates that the rutting resistance is improved.

3.3 High Temperature Stability

Cao Yang et al. (2023) verified the high temperature performance of steel slag, coarse steel fine stone, 50 % coarse steel fine stone, coarse stone fine steel and whole limestone, combined with high modulus asphalt and SBS modified asphalt. It is found that the high temperature stability of asphalt mixture can be improved by using steel slag and high modulus asphalt at the same time, which is about 2 times that of ordinary limestone asphalt mixture. The high temperature stability of asphalt mixture can be improved by adding steel slag coarse aggregate alone, and the high temperature performance of asphalt mixture with steel slag fine aggregate alone is also improved, but the improvement is not obvious, which shows that coarse aggregate and asphalt have a great influence on the high temperature performance of mixture. Fine aggregate also has an effect on the high temperature performance of asphalt mixture, but the effect is small. Both coarse aggregate and fine aggregate use steel slag, which is better than the high temperature stability obtained by replacing coarse aggregate (or fine aggregate) alone.

Ning Wuqiang et al. (2024) used five different proportions of steel slag asphalt mixture to test high temperature stability. The results show that the dynamic stability changes obviously with the increase of steel slag content, which increases first and then decreases. When the mass content of steel slag is 38%, the dynamic stability of steel slag modified asphalt mixture decreases obviously, and the difference of dynamic stability of steel slag modified asphalt mixture under 55 % and 72% is small. The main reason is that the ability of steel slag to adsorb asphalt is strong, thus improving the high temperature performance of steel slag modified asphalt mixture. However, with the increase of steel slag content, the amount of asphalt per unit volume also increases. When the adsorption is less, the interface strength of asphalt-aggregate can be stabilized, while the ' side effects ' of excess asphalt under high temperature are more obvious, thus reducing the high temperature performance of steel slag asphalt mixture.

3.4 Low Temperature Crack Resistance

In the low temperature environment, the asphalt mixture will ' harden and become brittle ', that is, with the decrease of temperature, the stiffness of the mixture itself will gradually increase, and the brittleness will also increase. The asphalt mixture will easily be cracked under the action of vehicle load or temperature stress, resulting in cracks in the asphalt pavement, causing pavement damage. Therefore, in the performance requirements of asphalt mixture, it is not only required that the asphalt mixture has good high temperature stability to meet the performance under high temperature environment, but also has certain low temperature crack resistance to meet the use under low temperature environment.

Fan Jianfeng et al. (2024) showed the performance test data of different types of modified asphalt mixture and steel slag recycled asphalt mixture under low temperature conditions, including maximum load, flexural tensile strength and tensile strain. The results show that the comprehensive performance of steel slag recycled asphalt mixture is the best, and the steel slag recycled asphalt mixture is better than the modified asphalt mixture. The rough surface and irregular shape of steel slag help to intertwine and lock particles of different particle sizes and shapes in the mixture to form a compact skeleton. This structure can better disperse and transfer loads and improve the overall stability and crack resistance of the mixture.

Niu Zhe et al. (2016) prepared and cut the trabecular specimens of AC-13 steel slag mixture and basalt mixture, SMA steel slag mixture and basalt mixture according to the standard method, and carried out the trabecular bending test to test its low temperature performance. The results show that the maximum flexural tensile stress of the steel slag mixture is larger than that of the control group, indicating that the strength of the steel slag mixture is greater. The introduction of steel slag slightly reduces the modulus of the mixture and increases the fracture energy of the mixture. The low temperature performance of asphalt mixture has a great relationship with asphalt binder, and the addition of steel slag increases the asphalt content, which is the main reason for the improvement of the low temperature performance of steel slag asphalt mixture. In addition, the surface characteristics of steel slag determine that the adhesion between aggregate and asphalt binder is enhanced after steel slag is mixed with asphalt mixture. However, there is no surplus asphalt at low temperature as in high temperature environment, so the low temperature performance of steel slag modified asphalt mixture is improved comprehensively.

4. CONCLUSION

Steel slag is an industrial by-product produced in the process of steel production. Based on the characteristic parameters of steel slag, this paper summarizes the influence of steel slag on the performance of asphalt mixture after replacing natural aggregate with steel slag in road construction and maintenance. Steel slag has good wear resistance and crushing resistance. Using steel slag instead of coarse aggregate in asphalt mixture can improve water stability, rutting resistance, high temperature stability and low temperature crack resistance. The indicators meet the requirements of most standards. The increase of steel slag percentage in asphalt mixture usually leads to the increase of design asphalt content, aggregate gap rate, Marshall stability and density. However, after the steel slag replaces the fine aggregate, it may also cause some performance of the asphalt mixture to deteriorate. The free CaO and MgO in steel slag form an alkaline environment, which improves the chemical bonding force between aggregate and asphalt. However, CaO and MgO in the free state of steel slag also lead to large volume instability, which may lead to in-situ expansion of steel slag aggregate, resulting in random surface cracks on the pavement. In addition, the hydration of steel slag will reduce its alkalinity, and may also form a weak layer of calcium carbonate deposition on the steel slag, resulting in a decrease in the adhesion of the asphalt mixture.Even steel slag obtained from the same source may have different properties. Therefore, it should be more cautious to use it to replace natural aggregates. Therefore, it is suggested that when different batches of steel slag are used, various indicators should be tested many times, focusing on volume stability, establishing an application quality control system, and designing a reasonable mix ratio to monitor the pavement performance changes throughout the life cycle for a long time, so as to promote the wide application of steel slag aggregate in road construction and maintenance.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Amelian, S., Manian, M., Abtahi, S., et al. (2018). Moisture sensitivity and mechanical performance assessment of warm mix asphalt containing by-product steel slag. *Journal of Cleaner Production*, 176, 329-337.

Arabani, M., & Azarhoosh, A. (2012). The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures. *Construction and Building Materials*, 35, 1-7.

Aziz, M. M. A., Hainin, M. R., Yaacob, H., et al. (2014). Characterisation and utilization of steel slag for the construction of roads and highways. *Materials Research Innovations*, 18(S6), S6-255-S6-259.

Cao, Y. (2023). *High modulus steel slag asphalt mixture design and road performance research* [Doctoral dissertation, Shandong Jianzhu University]. Instructor: Wang, L., & Wang, G.

Fan, J., Wu, L., Wu, S., Liu, Q., & Yang, X. (2024). Study on the enhancement mechanism of steel slag on the pavement performance of recycled asphalt mixture. *Journal of Wuhan University of Technology*, 46(03), 1-8.

Goli, H., Hesami, S., & Ameri, M. (2017). Laboratory evaluation of damage behavior of warm mix asphalt containing steel slag aggregates. *Journal of Materials in Civil Engineering*, 29(6).

Li, J. (2024). Road performance of steel slag asphalt mixture. *Heilongjiang Transportation Technology*, 47(06), 38-41.

Liu, X. (2019). *Study on the performance of OGFC-13 asphalt mixture with different steel slag content* [Doctoral dissertation, Chang'an University].

Mason, B. (1994). The constitution of some open-heart slag. *Journal of Iron and Steel Institute*, (11), 69-80.

Ning, W., & Lan, J. (2024). Steel slag modified asphalt mixture road performance research. *Western Transportation Technology*, (02), 19-21 + 58.

Niu, Z. (2016). *Preparation and performance of steel slag asphalt mixture* [Doctoral dissertation, Southeast University].

Pasetto, M., & Baldo, N. (2011). Mix design and performance analysis of asphalt concretes with electric arc furnace slag. *Construction and Building Materials*, 25(8), 3458-3468.

Wang, C. (2020). *Steel slag asphalt mixture performance research* [Doctoral dissertation, Hebei University of Technology]. Tutor: Zhang, C.

Wang, L., & Zeng, D. (2018). Performance evaluation of recycled asphalt mixture. *Hunan Transportation Science and Technology*, 44(04), 59-61.

Xu, D. (2018). *Research on material and performance of steel slag asphalt mixture* [Doctoral dissertation, Southeast University]. Tutor: Wang, V.

Xu, H., Fu, G., et al. (2006). Expansive experiment of steel slag. *Environmental Engineering*, (06), 62-64.

Zhang, X. (2022). *Research on the application of steel slag in asphalt mixture* [Doctoral dissertation, Suzhou University of Science and Technology]. Tutor: Song, X., & Sun, B.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/124507