Research progress of steel slag asphalt concrete

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Abstract. Steel slag asphalt concrete is one of the important components of asphalt concrete. There are some differences between the steel slag asphalt concrete and ordinary asphalt concrete. Based on the research of scholars at home and abroad, this paper systematically introduces the steel slag characteristics and excellent performance of steel slag asphalt concrete, summarizes the problems existing in the practical application of steel slag asphalt concrete, and provides references for its promotion and application.

1 Introduction

Steel slag is a by-product of the steel-making process, it is a composite solid solution formed by adding slag-forming solvents such as lime and fluorite during the steel making process, and belongs to alkaline materials. Approximately 1 tone of stainless steel is generated while producing 3 tones of stainless steel [1]. It should be noticed that fifty million tons per year of steel slag is produced as a by-product in the world.

In China, the current level of production of steel slag is about 20000000 tones per year. However, the utilization level of this steel slag is not high, and the discharge of a large amount of steel slags not only causes waste of resources,but also takes up land and pollutes the environment.Steel slag,due to its high strength and durability,can be used as an aggregate not only in surface layers of the pavement but also in unbound bases and sub-bases. Also, based on high frictional and abrasion resistance, steel slag has gained wide utilization on industrial roads, intersections,and parking areas where high wear resistance is required [2]. In the late 1960s, the United States and Canada jointly constructed a test section of steel slag asphalt concrete, which is the first steel slag asphalt concrete pavement in the world. From 1990 to 1995, the total amount of steel slag asphalt concrete used in New York City reached 250000 tons. Due to the influence of the United States and Canada, steel slag asphalt concrete has been developed and applied in many European countries and has become a high-grade pavement that is popular in Europe. About 50% of steel slag in

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Europe is currently used for road construction [3], the proportion of steel slag used in road construction is up to 98in the UK [4]. The steel slag used in road construction in China is less than 2%, which is far from developed countries.Since the middle of the last century, China has also conducted a lot of research and practical application of steel slag.Based on the research of scholars at home and abroad, this paper systematically introduces the good high temperature stability,moisture susceptibility and low temperature crack resistance of steel slag asphalt concrete, summarizes the reasons for the volume expansion of steel slag concrete，and puts forward some suggestions for the promotion and application of steel slag asphalt concrete.

2 Materials and Methods

2.1 Steel slag characteristics

2.1.1 Physical Properties

Steel slag is a compressed pore structure rich in iron elements, its surface is porous and alkaline, and has good adhesion to asphalt. After a series of crushing, sieving, magnetic separation and other treatments, the particles show an irregular shape and a rough surface. These irregular particles cause a large internal frictional squeezing force inside the steel slag. In addition, the shrinkage of the steel slag is small, and it will not easily cause volume shrinkage due to temperature changes. Asphalt does not fall off even under cold and frosty conditions, ensuring the integrity of the pavement. The physical properties of steel slag are similar to most natural sand and gravel, as shown in Table 1.

Table 1. Main physical properties of steel slag.

Density(g/cm3)	Moisture content (%)	Water absorption (%)	BET (m2/kg)	Pressure resistance (Pa)	Grindability index (Kkm)
3.0-3.6	1.0-1.3	2.5-3.0	370-570	20.4-30.8	0.7-0.9

2.1.2. Chemical Properties

Steel slag is liquid at high temperature, and it is lumpy or powdery after slow cooling, but most of them are irregular in shape. Most steel slag in China are converter steel slags. Due to the different chemical compositions, the appearance and color of the steel slags are quite different [5]. Most steel slags consist primarily of CaO, MgO, SiO_2, Fe_2O_3, Al_2O_3 and so on. The contents of general components are shown in table 2.

Table 2. Main chemical composition of the steel slag w/%.

Mixture type	Stability/KN	Flow /0.1 mm
SAC	17.41	23.0
LAC	10.59	31.7
SGAC	12.60	29.0

2.2 Properties of steel slag asphalt concrete

2.2.1 High temperature stability.

High temperature stability refers to the asphalt concrete under high temperature conditions, after repeated action of vehicle load, with no ruts and waves, no significant permanent deformation, to ensure the smoothnessof the road surface.

Li Jianhua [6] used Marshall stability and dynamic stability tests to evaluate the high-temperature stability of steel slag asphalt concrete (SAC) and coarse steel slag fine gravel asphalt concrete (SGAC), and conducted a comparative study with AC-13 graded limestone asphalt concrete (LAC), the results of which are shown in tables 3 and 4 [6].

Table 3. Asphalt concrete immersion Marshall test.

Mixture type SAC	LAC	SGAC
Dynamic stability （60°C，1h）/ time·mm^{-1}1792	1116	1318

Table 4. Asphalt concrete rutting test.

	CAO	SIO_2	AL_2O_3	MGO	FE_2O_3	MNO	P_2O_5	FEO	F-CAO
Converter slag	40-55	7-18	2-6	6-10	0.2-33	0.6-6	0.2-5	9-17	2-11
Electric furnace steel slag	42-55	17-22	4-9	16-16	1-3	1-4	--	1-2	--

It can be seen from experiment that the SAC has the highest stability and dynamic stability, the LAC has the lowest stability and dynamic stability, and the SGAC is somewhere in between.

Pan Huaibing [7] conducted rutting tests on SMA-5 asphalt mixtures with different amounts of steel slag, and came to the conclusion that as the steel slag content increases, the high-temperature stability of asphalt concrete tends to increase first and then decreases. When the steel slag content is 60%, the asphalt concrete has the best high temperature stability.

Therefore, it can be concluded that the steel slag concrete has good high-temperature stability. This is because:

- The steel slag has good angularity. After tamping and rolling, a tight interlocking effect is formed between the particles, which improves the shear resistance of the steel slag asphalt concrete.
- The surface of the steel slag has a porous structure. The micro porous structure on the surface of the steel slag adsorbs a large amount of resin and oil, and enters the inside of the steel slag along the capillary tube, so that the asphaltene of the steel slag surface layer increases, and the cohesion of the asphalt is increased.

2.2.2 Moisture susceptibility

Moisture susceptibility refers to the ability of the asphalt mixture to resist the peeling of aggregate and asphalt film under the effect of temperature and humidity and vehicle load after being eroded by water. Insufficient moisture susceptibility will cause water damage on asphalt pavement frequently [8]. Water immersion Marshall test and freeze-thaw split test are usually used to investigate the moisture susceptibility performance of asphalt mixtures.

Yang Junlin [9] carried out the water immersion Marshall test and the freeze-thaw split test on the steel slag asphalt mixture and limestone asphalt mixture. The test results are shown in Table 5[9].

Table 5. Immersion Marshall test.

Specimen type	Split strength ratio	Specification value
SAC	88.6	≥75.0
LAC	78.1	≥75.0

It can be seen from table 5 that the residual stability of SAC is higher than that of LAC, which meets the requirements of the specification. However, from the perspective of the failure mechanism, test conditions, and the degree of simulation of actual road water damage, the submerged Marshall test has many shortcomings [10]. The porosity of the mixed specimen in the freeze-thaw split test is relatively large, and considering the influence of water and temperature, the test environment is more in line with the actual situation of the project. It can be seen from Table 6 that the split strength ratio of the steel slag asphalt mixture is higher than that of the limestone asphalt mixture.

Both tests have verified that the steel slag asphalt mixture has good moisture susceptibility, which is because the steel slag is an alkaline material with porous surface. The asphalt absorbed by the internal pores of the steel slag is closely bonded to the steel slag and is not easy to fall off. In addition, Ding Qingjun et al. [11] believed that the excellent moisture susceptibility of steel slag asphalt concrete was also related to the metal cations including Ca^{2+}, Mg^{2+}, Fe^{2+}, Al^{3+} and Mn^{2+} contained in steel slag. Metal cations can react with asphaltic acids and other substances in asphalt to form a chemical adsorption layer on the surface of steel slag, but the strength of chemical interaction is many times more than the molecular force, increasing the bonding force between asphalt and steel slag, so that steel slag concrete has good moisture susceptibility.

2.2.3 Volume stability

Since the steel slag contains active materials such as f-CaO, f-MgO, the hydroxide produced by the hydration of these active materials will cause the volume of the steel slag to expand, as shown in Table 6.

Table 6. Steel slag expansion and crushing.

Influencing f-CaO digestion factors with water	Silicate crystal transformation	Decomposition of Dissolution Fe and Mn of MgO
Volume change		
Increased about 10%0.7 ~ 0.8 times	Increase by about and 35%~40% 1 to 2 times respectively	Increase of Increase by 25%~30%

When the expansion is too large,various diseaseswill appear on the road surface.Therefore, the expansibility of steel slag should be tested before application.At present, the United States mainly uses the autoclave method and the dry and wet alternating method, Germany uses the steam experiment and boiling experiment, while China usually uses the immersion swelling experiment.The experimental principle is to adopt a 90 ° C water bath curing method. After a certain period of time, the f-CaO and f-MgO in the steel slag are digested to produce volume expansion. The stability of the steel slag is evaluated by the volume change rate. The immersion expansion rate of steel slag is calculated according to the formula (1):

$$r = \frac{d_{10} - d_0}{120} \tag{1}$$

Where：r is the water immersion expansion rate, %;120 is the original high degree of the specimen, mm; d_{10} is the final reading of the dial, mm;d_0 is the initial reading of the dial, mm.

To provide the volume stability of the steel slag asphalt mixture, the following aspects can be improved:

- Solvation from the root can cause and improve the steelmaking process.
- To optimize the steel slag treatment process, improve the stability of steel slag by aging and adding modifier.The aging treatment is low in cost, simple and effective, and can not only reduce the content of f-CaO, but also oxidize high valence unstable sulfur ions in the steel slag.However, the aging process takes a long time, generally more than one year, which will affect the progress of the project.At present, the two most commonly used measures are atmospheric steam treatment and pressurized steam treatment.
- Reasonable steel slag blending ratio can also improve the volume stability of steel slag asphalt mixture.

Li Bo [12] uses two types of steel slag blending schemes: one is to use steel slag for coarse and fine aggregates (type I), the other is to use steel slag as coarse aggregate and natural aggregates as fine aggregate (type II).The research found that the volume stability of the steel slag asphalt mixture can be effectively reduced by adopting the type II mixing scheme.

2.3 Low temperature crack resistance

The low-temperature crack resistance of asphalt mixtures was evaluated using a low-temperature trabe cular bending test. Li Jianhua [6] obtained through experiments that the low temperature crack resistance of steel slag asphalt mixture is lower than that of ordinary asphalt mixture, but still meets the requirements of the code. Wang Chao[13] improved the low temperature crack resistance of steel slag asphalt mixture by adding glass fiber. When the content of glass fiber is 0.2%, the low temperature crack resistance of steel slag asphalt mixture is better. When the content of glass fiber is more than 0.2%, it will affect the structure of asphalt mixture, which is not conducive to improving the pavement performance of steel slag asphalt concrete.

2.4 Application status of steel slag asphalt concrete

Western countries have earlier research and application of steel slag. In 1937, Britain used steel slag as the coarse aggregate of asphalt mixture for paving roads. At the end of the 1960s, the United States and Canada jointly built a test section with steel slag asphalt concrete to test the road stability. From the effect of its use, the quality and durability of steel slag asphalt pavement are no problem, and steel slag is better than natural sand and gravel has better skid resistance [14]. Indiana State in the United States applied steel slag to asphalt concrete in 1979 and 1981. When inspecting the pavement conditions in 1988, it was found that polygonal and continuously extending cracks occurred on some pavements, and the base layer did not appear to be damaged. Off-white calcium oxide was found near the cracks. However, these sections did not appear loose, rutting or pushing. From 1980 to 1985, Japan paved steel slag asphalt concrete pavement to resist ruts in tropical areas such as Fukuyama City and Aichi Prefecture, and applied steel slag characteristics to reduce tire wear on asphalt pavement in Sapporo city and Hokkaido.

China started the research of steel slag asphalt concrete relatively late. Wuhan University of Technology was the first to lay steel slag asphalt pavement on the road surface of the WISCORing Factory West Road, the Baoxie section of the Wuhuang overhaul project and the Xiantao Hanjiang Highway Bridge. After about ten years of heavy-duty traffic, all three steel slag asphalt pavements showedexcellent road performance, its anti-sliding performance and durability are better than ordinary asphalt pavements [15]. Beijing Haidian Road and Mentougou's Nanyan Road also paved two steel slag asphalt mixture test roads, and the test roads were observed and tested for three years. From the test results, it can be seen that the friction coefficient of steel slag asphalt pavement at the beginning of use is the same as that of the comparative section, but in the long term use process, the friction coefficient attenuation degree of steel slag asphalt pavement is significantly lower than that of the comparative section.

China has been actively introducing foreign advanced technology and experience. Through a large number of tests and analysis of steel slag, China carried out the standardization of steel slag as a pavement material and compiled the "Steel Slag for Wear-resistant Asphalt Pavements" (GB / T 24765-2009), "Steel Slag for Permeable Asphalt Pavement" (GB / T 24766-2009), and "Steel Slag Stability Test Method" (GB / T 24175-2009) and other national standards. It provided technical specifications and reference basis for the popularization of steel slag in highway engineering.

3 Results and Discussion

With the continuous improvement of China's environmental protection requirements and the shortage of natural ore resources, ordinary asphalt concrete is facing an increasingly severe situation. Experimental research and existing related research results show that the steel slag aggregate particles have good physical properties and adhere well to the asphalt, and the high temperature stability and moisture susceptibility of the steel slag asphalt mixture are better than ordinary asphalt mixtures. This provides a reliable theoretical basis for the research and application of steel slag asphalt concrete.

However, as a by-product of steelmaking, steel slag has certain uncertainties in its chemical and physical properties. In order to ensure the good application of steel slag concrete, systematic research is required from the following aspects:

1. Classification of steel slag. There are some differences in the properties of steel slag due to the different steelmaking processes of steel mills at home and abroad. In the future, a company specializing in the treatment of steel slag should be established to classify steel slag in detail to ensure that various types of steel slag are fully applied.

2.Improving the activity of steel slag. Due to the poor gelling properties of steel slag in the early days, research on new excitant and complex activators is the main direction for future researchers.

3**.** Volume expansion of steel slag. Due to the presence of free calcium oxide and magnesium oxide in the steel slag, the volume expansion of the steel slag asphalt mixture occurs at the later stage. Although there are certain technological means to remove the instability factors in the steel slag, it lacks economic benefits. In the future, research should be conducted from various aspects, such as root treatment and secondary treatment of raw materials, to completely eliminate the instability caused by the volume expansion of steel slag.

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