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Characteristics of dry shrinkage and temperature shrinkage of cement-stabilized steel slag

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HIGHLIGHTS

- Paper presents characteristics of dry shrinkage and temperature shrinkage of CSS and CSM.
- The cement content and gradation types affect the dry shrinkage and temperature shrinkage deformation of CSS and CSM.
- The hydration of CSS is more obvious than that of CSM.
- Using CSS instead of CSM as base course materials can effectively reduce the shrinkage deformation.

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ABSTRACT

The objective of the present study was to investigate the characteristics of dry shrinkage and temperature shrinkage of cement-stabilized steel slag (CSS). The steel slag was intended to be utilized to replace the macadam in cement-stabilized base course to reduce dry shrinkage and temperature shrinkage of semi-rigid base materials. Dry shrinkage and temperature shrinkage tests were performed to analyze the water loss rate, dry shrinkage strain, dry shrinkage coefficient and temperature shrinkage strain of CSS and cement-stabilized macadam (CSM) as functions of time, cement content and gradation types of the material. The water loss rate of CSS increased with the rise in time, and then tended to be flat on about 10th days. The hygroscopicity of coarse gradation CSS was larger than those of intermediate gradation and fine gradation CSS. With the same gradation, the more the cement content was, the greater the water loss rate was. It was suggested that the cement content of CSS should not be more than 4%, which can obviously reduce the dry shrinkage strain. Compared with CSM, CSS with rational adjustment of gradation owned a smaller dry shrinkage strain and would not produce a larger temperature shrinkage strain. It is feasible to replace the base macadam with waste steel slag, which is beneficial to improve the characteristics of dry shrinkage and temperature shrinkage of semi-rigid base material and utilization of waste steel slag. This paper aims to provide a solid theoretical foundation to popularize the wide utilization of CSS in engineering applications.

1. Introduction

As a basic construction material, cement-stabilized macadam (CSM) is currently used in pavement for public roads, in municipal construction applications, and mining areas [1]. CSM is a composite material composed of aggregates with proper gradation, 3%~8% cement of the aggregates weight, and water at optimum content [2,3]. The cement can significantly induce the incensement of stiffness and strength of unbound aggregates because of its hydration and hardening [4,5]. CSM has a better bearing capacity and can reduce the tensile strain of the bottom of hot mix asphalt layer [6,7]. Thus, CSM is widely used as base course materials to improve the load bearing capacity of asphalt pavement structure in many countries [8]. However, CSM is easily cracked [9,10], and the dry shrinkage and temperature contraction of cement paste lead to inevitable cracking in CSM base course [11], which seriously decreases its structural strength and affects the quality of roads. Consequently, the characteristics of dry shrinkage and temperature shrinkage of CSM needs to be further investigation to propose reasonable and practical measures to reduce cracking, which is a problem that needs to be urgently resolved.

The past studies that focused on reducing the dry shrinkage and temperature cracks of base course materials are summarized as follows. Zhang et al. [12] studied the cracking mechanism of semi-rigid base asphalt pavement, and proposed some measures

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to reduce cracks. Li et al. [13] analyzed the influence of base course modulus on the mechanical property of asphalt pavement. Yang [14] studied the expansion rules of semi-rigid base asphalt pavement reflection cracks and temperature fatigue cracks, and proposed the application of a stress absorption band to minimize cracking. Yang et al. [15] analyzed the effect and mechanism of conventional treatment technologies to reflective cracking of asphalt pavement with semi-rigid base. Zhang et al. [16] studied the dry shrinkage and temperature shrinkage performances of low activity fly-ash base course. Their results showed that the low activity fly-ash could be used as the base course of asphalt pavement and it had better anti-crack performance. France and Holland [17] developed a new road base material (semi-flexible base materials) with the capacity of effectively prevent the reflect cracks. Liao et al. [18] studied the basic principles underlying the effects of the supporting layer on cracks resulted in the CSM base. They noticed that the shrinkage cracks resulted from water loss during the early stage of CSM engineering projects. Simultaneously, their results showed that the base was also affected by the content of the cement, which caused differences in late-occurring cracks. Li et al. [1,19] investigated the role of waste asphalt concrete fibers in enhancing crack resistance in CSM. They showed that water loss from the blended materials effectively decreases if the cement content was set to a suitable level. As a result, the resistance to shrinkage cracks is changed.

In addition, China is a big country of steelmaking and steel output has ranked first in the world for many years. According to the relevant data, every ton of steel production will produce about 0.13 ton of steel slag, and the annual output reaches 100 million tons. By the end of 2014, accumulated steel slag was more than 1 billion tons, however the comprehensive utilization of steel slag was only 10%. It causes huge pollution to the environment, and some scholars had done a lot of research on the basic mechanical properties of waste steel slag [20–22]. Steel slag contains many kinds of oxides and minerals, which is similar to physical and chemical components of Portland cement clinker, which shows stable performance, high strength, uniform particles in a certain environment (water, temperature, medium) after electrolytic hydration. With characteristics of wear resistance, small crushing value and large porosity, steel slag aggregate shows better adhesion than macadam when uses together with gelled material such as cement and lime. Meanwhile, traditional CSM base course need a lot of stone, which go against the protection of environment. Therefore, the way that use steel slag to replace macadam as the main material in road construction, it will save resources, protect the environment, and also achieve its utilization scientifically.

The present study aims to use steel slag to replace macadam as the main materials in road construction, and to investigate the characteristics of dry shrinkage and temperature shrinkage of cement-stabilized steel slag (CSS). Furthermore, the fitting equations of CSS and CSM had been obtained and the results had been compared. This paper may provide a theoretical foundation for the practical application of CSS so that it can be widely applied in road construction.

2. Experimental procedures

2.1. Materials

Raw materials used in this experiment mainly include steel slag, cement and macadam. According to the requirements of Chinese test procedures [23], the physical and mechanical properties of steel slag were investigated and provided in Table 1.

The chemical compositions of steel slag may change with the different composition of the raw ore and manufacturing process.

Table 1
Physical and mechanical properties of steel slag.

Serial number	Test items	Standard	Test result
1	Crushing value/%	⩽26	16.7
2	Apparent relative density	⩾2.60	3.31
3	Water absorption/%	⩽2	2.3
4	Soft stone content/%	⩽3	2.6
5	Asphalt adhesion/level	⩾4	4.2
6	Needle and flake content/%	⩽15	5.7
7	Wear loss in Los Angeles	⩽28	21.5
8	Polished stone value(PSV)	⩾42	47
9	Free-calcium oxide(f-CaO)/%	⩽3	0.14
10	Immersion expansion rate/%	⩽2	0.43
11	Impact value/%	⩽25	13

According to statistical results of the Waste Steel Slag Association of Japan, its main chemical compositions are CaO, SiO_2, T-Fe, MgO and Al_2O_3. It also has a strong hydraulic. Due to the impact of CaO, the PH value of waste steel slag can reach 10–12 when reacts with water. Therefore, using waste steel slag as semi-rigid base material can improve bearing capacity of the subgrade, and also achieve the purpose of corrosion protection.

Cement is a hydraulic cementitious material of semi-rigid base course. Its main chemical compositions contain $3CaO{\cdot}SiO_2$, $2CaO{\cdot}SiO_2$, $3CaO{\cdot}Al_2O_3$ and $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$. It can be better hardened when meet with water, and maintain and develop its strength. Ordinary portland cement (P.O32.5) was employed in the research, according to China's national standards and Chinese pavement specification [24], its main technical indexes and test results are summarized in Table 2.

2.2. Gradation design

According to the specification of China (JTJ 034-2000) [2], the upper, middle and lower limits of gradation range are selected as three kinds of gradations of CSS aggregates and CSM aggregates. It is noteworthy that the grading curve of CSS and CSM had been artificially prepared to be same to ensure the comparable performance between CSS and CSM. The coarse grading of CSS aggregates is corresponding to the skeleton-pore of CSM aggregates, the intermediate grading of CSS aggregates is corresponding to the skeleton-dense of CSM aggregates, and the fine grading of CSS aggregates is corresponding to the suspended-dense of CSM aggregates. The pass rate of CSS and CSM aggregates under different screen apertures are provided in Table 3, and the corresponding gradation curves are shown in Figs. 1and 2.

2.3. Mix proportions

The mix proportions of CSS aggregates and CSM aggregates are shown in Tables 4 and 5. According to the specification of China (JTG F10-2006) [25], compaction test was performed to determine the optimal water content and maximum dry density of CSS and CSM. Meanwhile, according to the specification of China (JTG D50-2006) [26], Portland cement P.O32.5 with the content of 3%, 4%, 5% was added to stabilize the three kinds of gradations of CSS and CSM.

2.4. Specimen preparation

The size of the test specimen is $50mm \times 50mm \times 240mm$. The specimens were compacted and molded by compression machine to achieve the compaction degree(K) of 98%, and then the specimens were cured under a moisture condition for 7 days, as shown in Fig. 3. According to the different content of cement, there were 6 groups of specimens for each gradation of semi-rigid material, and