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Moisture-induced damage resistance of asphalt mixture entirely composed of gneiss and steel slag

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HIGHLIGHTS

- Gneiss and re-crushed fine steel slag were simultaneously used.
- Gelling of silicate minerals contributed to the solidification of steel slag.
- Nature acidity and layered micro-structure of gneiss caused adverse effect.
- Steel slag powder improved moisture resistance of asphalt mixture.
- Surface status of slag fine aggregate effected moisture stability of mixture.

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ABSTRACT

Gneiss and fine steel slag are seldom used in the construction of asphalt pavement due to their poor performances. Asphalt mixture entirely composed of gneiss (coarse aggregate) and steel slag (fine aggregate and asphalt filler) was proposed in this research in order to promote their wide use. Limestone fine aggregate and filler were functioned as control groups. The inadequacy of using 100% of gneiss to prepare asphalt mixture and the performance deterioration mechanism of fine steel slag were discussed based on some newly revealed material characteristics and previous research results, and corresponding improvement measures were established first. Then four asphalt mixtures (two fine aggregate and two filler) were designed by Superpave procedure. Finally, the moisture stabilities of uncompacted aggregate-mastic system and compacted asphalt mixture were fully investigated, and hot water damage mode and freeze-thaw damage mode were adopted. Results suggested that asphalt mixture entirely composed of coarse gneiss and re-processed fine steel slag possessed satisfactory moisture resistance performance.

1. Introduction

Asphalt mixture, cement concrete and semi-rigid materials are widely used in the construction of infrastructure [1–5], especially in road construction. The road consist of semi-rigid base and asphalt surface course possesses long lifespan and superior service performances (excellent rideability, low noise, high bearing capacity, etc.) simultaneously [2,3]. Hence, the semi-rigid base asphalt pavement is extensively used in the construction of high-grade highways in China. Surface course is paved with asphalt mixture, which mainly composes of aggregate and asphalt mastic (asphalt binder and filler) [6,7]. The aggregate and filler approximately account for 95% of volume of dense-graded asphalt mixture. Therefore, the construction of high-grade pavement consumes a huge amount of natural resources. Especially in China, the annually construction volume is huge because of the large land area. Only the total mileage of expressway has reached 136,500 km by the end of 2017 [8], and more than 90% of which is paved with asphalt mixture [9]. Many methods to reduce the dependence of pavement construction on natural stone resource have been tried. Recycling of solid wastes (demolition waste [10], smelting waste [1,6,7,9,11–16] etc.) and low-grade natural minerals (acid rock[14,17]) in asphalt mixture is a very important strategy to release the supply pressure of superior resources. The future pavement needs to be multifunctional [18–20], resource-saving [14,17,21,22], energy-saving [18,23] and environmentally friendly [19,20,24]. The exploitation of secondary aggregate can contribute to this goal.

Steel slag is a typical smelting waste, generating during steelmaking. Its output accounts for 13% of raw steel [25]. Considering its large output can partly meet the high demand of mineral materials for road construction, the steel slag based asphalt mixture is a

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hot research field in recent years. Previous research results indicated that steel slag coarse aggregate (SSCA) can improve many performances of asphalt mixture such as high-temperature stability [12,15,25,26], fatigue life and fatigue durability [11,27], moisture-induced damage resistance [11,13] and skid resistance [25,26]. While fine steel slag is not as attractive as SSCA because of its poor angularity and substandard surface status [12,14]. What's more, the introduction of the whole gradation of steel slag (coarse and fine aggregate) in asphalt mixture will give a great risk in raising asphalt content. The whole gradation of steel slag is not acceptable. Therefore, the application of fine steel slag is limited.

Gneiss is a typical low-grade natural mineral when referring to asphalt mixture because of its acidity [17]. The bonding performance between acid aggregate and asphalt binder is inferior. The poor bonding behavior would worsen many performance of asphalt mixture such as moisture-induced damage resistance. Therefore, the project decision makers prefer to use more secure natural minerals such as limestone and basalt. The use of gneiss in asphalt pavement requires serious consideration in China at current situation. In order to reduce the consumption of high-grade mineral, utilizing the alternative pavement materials to the greatest extent is anticipated. Therefore, it will have a broad application prospect if the combined use of gneiss and steel slag becomes a reality.

Preparing asphalt mixture entirely composed of coarse gneiss and fine steel slag (fine aggregate and filler) was considered in this research. Based above, the key factor to realize the synchronous utilization of coarse gneiss and fine steel slag is enhancing the bonding performance of asphalt mixture system. The moisture-induced damage resistance of asphalt mixture is very sensitive to the bonding performance. Hence, two main works were conducted: (1) The inadequacy of directly using gneiss and fine steel slag was revealed, and corresponding improvement measures were proposed first. (2) And then the bonding characteristics of uncompacted aggregate-mastic system and compacted asphalt mixture under multiple moisture damage modes were deeply investigated. The research flow chat of this research was shown in Fig. 1. Limestone fine aggregate and filler were functioned as control group.

2. Materials and methods

2.1. Raw materials

In this research, base asphalt binder AH-70 with penetration of 66, ductility of 159 cm (5 cm/min, 15 °C), softening point of 46.1 °C and Styrene-Butadiene-Styrene (SBS) modified asphalt binder with penetration of 68, ductility of 40 cm (5 cm/min, 5 °C) and softening point of 64 °C were used. The used coarse aggregate was gneiss (>2.36 mm), and fine aggregates were steel slag (SSFA) and limestone. Steel slag powder (SSP) and limestone powder (LSP) were also functioned as fillers. The technical properties of aggregate and filler were measured according to Chinese standard methods [28], and the test results were listed in Tables 1 and 2, respectively. Results suggested that all technical properties of used aggregates and fillers met the requirements of Chinese standard [29].

2.2. Experimental methods

2.2.1. Inadequacy analysis

The inadequacy of directly using gneiss and fine steel slag in asphalt mixture were discussed based on their material characteristics. The mineral phase, surface texture and average chemical component of gneiss and steel slag were detected by X-ray diffraction (XRD) and Polarizing Optical Microscopy (POM), Scanning Electron Microscope (SEM) and X-ray fluorescence (XRF), respectively.

2.2.2. Moisture stability evaluation

Aggregate and asphalt mastic are the main components of asphalt mixture. Essentially, moisture damage works on the aggregate-asphalt mastic system. Therefore, the bonding characteristics of uncompacted aggregate-asphalt mastic system were evaluated first, and then the traditional moisture stability indicators of compacted asphalt mixture including Retained Marshall Stability (RMS) and Tensile Strength Ratio (TSR) were measured. Two moisture damage modes were adopted, namely hot water damage and freeze-thaw damage. Four replicates for each test were considered.

2.2.2.1. Uncompacted aggregate-asphalt mastic system.

2.2.2.1.1. Hot water damage mode. The water boiling test is originally developed to investigate the adhesive level between coarse aggregate and pure asphalt binder [30]. The adhesive level was determined based on the stripping percent of asphalt binder from the surface of asphalt coated aggregate particle after suffering water boiling damage for 3 min. While the stripping percent is determined by visual inspection, which is very subjective, and the boiling time of 3 min might not be enough to pick out the winner among different aggregate-mastic systems. Hence, the traditional water boiling test shows some disadvantages.

Some modifications have been made on water boiling test in this research. It was used to evaluate the adhesive level between aggregate (both coarse and fine particles) and asphalt mastic. The volume loss percent of asphalt mastic desquamating from the surface of asphalt mastic coated particle was proposed as a new index to determine the aggregate-mastic system's adhesive level. The maximum boiling water damage time can reach 30 min. The volume loss percent was computed according to Eq. (1):

$$V_l = \frac{\frac{M_{am}-M'_{am}}{\rho_m}}{\frac{M_{am-M_a}}{\rho_m}} \times 100\% = \frac{M_{am}-M'_{am}}{M_{am-M_a}} \times 100\% \tag{1}$$

where V_l is the volume loss percent, %; M_a is the original dry mass of aggregate particle, M_{am} is the dry mass of asphalt mastic coated particle before subjected to boiling water damage, g; M'_{am} is the residual dry mass of mastic coated particle after boiling water damage, g; ρ_m is the density of asphalt mastic, g/cm^3.

The bonding characteristics of coarse aggregate-mastic system under water boiling damage were evaluated first. Two types of asphalt mastic were involved. One consist of asphalt and SSP, and the other one was composed of asphalt and LSP. Therefore, there were two gneiss-mastic systems in this research. Considering the viscosity of modified asphalt is often very large. Base asphalt AH-70 with a much lower viscosity was adopted in order to determine the winner of different aggregate-mastic system efficiently. The water boiling test of coarse aggregate-asphalt mastic system was conducted as following: (1) The approximating cube gneiss coarse particles with size of 19 mm were selected. (2) The suitable blending proportion of asphalt binder and filler (SSP or LSP) was determined based on the distribution uniformity of filler particles in mastic. (3) Hanging the dry gneiss particles into hot asphalt mastic and ensuring the particle surfaces were fully covered, and then moving the mastic coated particles to an oven of 45–60 °C, in which the redundant asphalt mastic naturally dropped down. (4) Finally subjecting the sufficiently cooled mastic coated particles to water boiling damage, and the volume loss percent of asphalt mastic was quantized according to Eq. (1).

There were four fine aggregate-mastic systems (two types of fine aggregate and asphalt mastic) needed to be investigated. Considering the volume of particles in fine aggregate is much smaller, hanging the mastic coated fine particles is not convenient, and the test results of different particles may also fluctuates significantly due to the hard control of particle's geometry. Therefore, the water boiling test of fine aggregate-asphalt mastic system was a little different: (1) 100 g steel slag fine particles with size of 2.36 mm were prepared, and the mass of used limestone fine particles was $100/\rho_{slag} \times \rho_{limestone}$ g in order to keep the volume of steel slag fine particles and limestone fine particles the same. (2) Then they were mixed with the same volume's asphalt mastic, respectively. The dosage of used asphalt mastic can fully coat the surface of fine particles was enough, and ensuring no free asphalt mastic existed. (3) Considering there existed mass loss of asphalt mastic during mixing process, taking the mass of mixed particles moved into the heating container as M_{am}. Water boiling damage was applied and the volume loss percent of asphalt mastic was also measured based on Eq. (1).

2.2.2.1.2. Freeze-thaw cycle damage mode. The standard treatment process of single freeze-thaw damage used in the field of asphalt mixture is that freezing samples at a freeze of -18 °C for 16 h and then thawing them at a hot water bath of 60 °C for 24 h. Considering the asphalt mastic coating on the particle surface may be not strong enough to resist the longtime hot water damage, and the flow of asphalt mastic may happened. Therefore, the freeze-thaw condition has made some modifications. The thaw process was conducted by placing frozen sample at room temperature without water environment to avoid the flow of asphalt mastic. The single freeze-thaw damage process of aggregate-mastic system was conducted as following: (1) The asphalt mastic coated aggregate particles were immersed in room temperature water for more than 15 min in advance. (2) Then the particles were subjected to freeze-haw damage. Freeze-thaw cycle mode was applied until obvious stripping phenomena of surface coating layer can be observed. The freeze-thaw damage was different from hot water damage. The former caused failure by generating volume expansion and shrinkage, and the later caused failure by stripping mastic directly. The freeze-thaw damage may resulted in the loss of loose section on aggregate surface during volume expansion and shrinkage process, especially for slag fine aggregate, which easily generates new components on the surface of slag particles during weathering process. The weight difference of mastic coated particles before and after freeze-thaw damage may not be equal to the mass of stripped mastic. Therefore, measuring the volume loss of mastic coated particles according to Eq. (1) was not suitable. The volume loss was computed as following:

$$V_l = \frac{V_s}{V_{am}} \times 100\% \tag{2}$$