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Effects of phosphorus slag powder and polyester fiber on performance characteristics of asphalt binders and resultant mixtures

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HIGHLIGHTS

- PSP increased the binder viscosity resulting in enhanced mixture rutting resistance.
- PF improved the mixture resistance to low-temperature cracking and moisture damage.
- PSP and PF can be properly recycled together for satisfactory mixture performance.

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ABSTRACT

The objective of this study was to investigate the effect of phosphorus slag powder (PSP) and polyester fiber (PF) on the rheological properties of asphalt binder and performance characteristics of resultant mixtures. It is also of great interest to determine whether the PSP can be used to replace conventional filler (i.e., limestone powder) without negatively affecting the mixture performance. A laboratory experiment was developed which included characterization of PSP and PF, determinations of the optimum content of PF and optimum PSP-binder ratio, and performance evaluation of asphalt mixtures with various combinations of PF, PSP and limestone powder. The PSP behaved effectively as a mineral filler such that it increased the binder viscosity resulting in enhanced mixture rutting resistance. The use of PF significantly improved the mixture resistance to low-temperature cracking and moisture damage as indicated by the flexural strain and tensile strength ratio results. Overall, mixture with 3% PF at the PSP-binder ratio of 1.0 outperformed the others with limestone powder and/or PF, indicating the feasibility of recycling PSP and PF into asphalt mixtures for satisfactory mixture performance.

1. Introduction

Phosphorus slag (PS) is a by-product of yellow phosphorus production using the electrical furnace method. The phosphorus industry in Southwestern China annually results in over 1.6 million tons of PS [1]. This solid waste is in fact a valuable material as it has high content (over 85% by weight) of silicon dioxide (SiO_2) and calcium oxide (CaO). Nevertheless, PS has been routinely used as landfills, which not only occupies the limited space for a landfill, but also results in an environmental problem by creating a highly contaminated liquid called leachate [2].

There have been research efforts on adding phosphorus slag powder (PSP) in cement concrete to maximize the value of its active minerals, i.e., SiO_2 and CaO. Existing studies mainly focus on the mechanical properties of cement concrete with the PSP as a mineral admixture [3–5]. Tang [6] assessed the strength of cement pastes with high PSP content and the PSP admixture was found to effectively lower hydration heat, delay hydration process and consequently result in a low strength of mortars after 3 days of curing. Qi and Peng [7] evaluated the impact of PSP on the pozzolannic effect in concrete, and they concluded that the PSP was beneficial to the development of long-term strength of concrete. Ali and Mostafa [8] further investigated the chemical and mechanical activation induced by adding high PSP content in cement concrete and their testing results confirmed the effectiveness of PSP on enhancing concrete properties. Moreover, the microstructure of cement paste containing PSP was reported to be looser at an early-stage but much denser at late-stage as compared to normal cement paste [9–11]. These observations may explain why cement concrete with PSP normally exhibits low early strength but high long-term strength.

The PS and PSP have also been recycled in asphalt pavement. For example, PS can be used as virgin aggregate, e.g., lightweight

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masonry aggregate and cement kiln feed, in hot-mix asphalt (HMA) mixture [12,13]. The shape and angularity of coarse PS aggregate strengthen the interlocking in the aggregate structure of a given mixture that, in return, improves the mixture's resistance to permanent deformation [14]. Very limited studies, mostly from China, investigated the feasibility of recycling PSP as mineral filler in asphalt mixture. Qian et al. [15] found that PSP increased the stiffness of asphalt binder in a way similar to the conventional agricultural (Ag) lime mineral additive. Later, they introduced PSP into a dense-graded (DG) and a gap-graded stone mastic asphalt (SMA) mixtures and reported the enhanced mixture resistance to rutting and moisture damage. A few other researchers in China also found that PSP can significantly promote the aging resistance of asphalt mixture but slightly degraded the low temperature cracking performance.

Fabric material is another major type of additive that is commonly used in asphalt pavements to improve the mixture tensile properties [16–18]. Button and Hunter [19] performed laboratory and field tests to evaluate different types of chopped synthetic fibers (e.g., polyester and polypropylene fiber) as additives to reduce mixture cracking. Laboratory testing results found that fibers improved the mixture resistance to crack propagation and field pavement performance indicated that the application of polyester fiber (PF) delayed the appearance of reflective cracks for 2–3 years. Chen and Lin [20] investigated the reinforcement effect of cellulose, rock wool and polyester fibers on asphalt binder. They reported that higher fiber concentration resulted in greater tensile strength of the binder-fiber mastics. This observation implied the existence of a desirable adhesion between binder and fibers, which improved the load-carrying ability of binder-fiber mastics.

Whereas tremendous amount of PSP has been collected over the years, its usage in asphalt pavement is still very limited due to a lack of understanding on its effect on performance. In the meantime, adding PF in asphalt mixture has been proven to help mitigate pavement reflective and fatigue cracking, but this PF treatment is typically not considered to be cost-effective [15,21]. Therefore, there is a strong need to investigate the impacts of the PSP and PF on binder rheological properties and determine whether a combined use of PSP and PF can result in both economic and environmental benefits without compromising mixture performance.

2. Objectives and scope

The main objective of this study was to investigate the individual and joint effect of PSP and PF on rheological properties of asphalt binder and performance characteristics of resultant mixtures. It was also of great interest to determine whether PSP can serve as a surrogate to a conventional mineral powder, i.e., limestone powder. To achieve these goals, a laboratory experiment was designed which involved the microstructural characterization of PSP and PF, evaluation of rheological properties of asphalt binder modified with PF, PSP and limestone powder, and finally characterization of rutting, low temperature-cracking and moisture damage resistance of resultant mixtures.

3. Materials and assessment methods

3.1. Materials

The PSP used in this study was finely grinded with less than 0.2% (by weight) above No. 200 (0.075 mm) sieve. Based on the X-ray fluorescence spectrum testing results, the PSP was found to contain approximately 39% SiO_2 and 41% CaO. Table 1 lists some physical and chemical characteristics of the PSP.

Table 1
Characterization of phosphorus slag powder.

Physical properties		Chemical components	
Density	2.885 g cm^{-3}	SiO_2	39.0%
Moisture content	0.10%	CaO	41.0%
PH value	9.7	Al_2O_3	5.0%
>0.075 mm particle content	< 0.2%	Other	15.0%

The PF was mainly composed of mono-fiber, which later required manual dispersion to achieve a uniform distribution in the asphalt binder and mixtures. Table 2 depicts several important physical properties of PF. For example, the melting point of PF must be above 160 °C to withstand the heat during mixture production and its tensile strength must be sufficient to sustain traffic after the paving process. The base binder was an unmodified binder that has been routinely used in China. Table 3 presents penetration, softening point, ductility, flash point, etc., of the base binder.

3.2. Mixture design

The coarse and fine aggregate used was crushed basalt with a density of 2.650 g/cm^3 and 2.768 g/cm^3, respectively. Limestone powder, which is a mineral filler typically used in asphalt mixture in Southern China, was included for purpose of comparison. The particle size range of the limestone powder ranged from 0 to 0.3 mm with 80% (by weight) passing the 0.075 mm sieve. A total of four mixtures with different combination of PF, PSP and limestone powder were designed and evaluated. Table 4 shows four combinations of PF, PSP and limestone powder, and the corresponding asphalt-aggregate ratio of each mixture. It is well known that the overall aggregate gradation has a great impact on mixture performance. Therefore, the gradation was kept constant for all mixtures (Fig. 1), and they were designed following the JTG E20-2011, *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering.*

3.3. Assessment methods

3.3.1. Viscosity test

The Rotational Viscometer test is used to determine the viscosity of asphalt binders in the high temperature range corresponding to manufacturing and construction. It measures the torque required to maintain a constant rotational speed (20 RPM) of a cylindrical spindle while submerged in asphalt binder at a constant temperature. In this study, blends of virgin binder, PSP and PF were tested at various temperatures ranging from 135 °C to 180 °C with an interval of 15 °C. Note that the Superpave specification places a maximum viscosity limit of 3.0 Pa·s for virgin binder.

Table 2
Physical properties of Polyester fiber.

Physical properties	Test results
Fiber length	6 mm
Diameter	20 μm
Relative density	1.317
Melting points	260 °C
Tensile strength	570 Mpa
Oil absorption rate	4.1 times
Moisture absorption rate	2.43%