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Effects of nano-particles on improvement in wear resistance and drying shrinkage of road fly ash concrete

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HIGHLIGHTS

- We prepared nano-modified fly ash cement mortar and concrete specimens.
- We studied the effect of the nano-particles on wear resistance of fly ash concrete.
- We studied the effect of the nano-particles on drying shrinkage of fly ash concrete.
- We analyzed those improving mechanism.

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ABSTRACT

Nano-materials have been widely applied in cement-based materials due to its excellent performance. Two types of nano-particles, namely nano-SiO_2 (NS) and nano-SiC (NC), were employed to prepare nano-modified fly ash cement mortar and road fly ash concrete specimens respectively, and the effects of the nano-particles content on wear resistance and drying shrinkage were studied on the basis of strength test, the mechanisms were then analyzed theoretically. The results indicated that nano-particles could improve the wear resistance of road fly ash concrete, but increase the drying shrinkage. The optimum added dosage of NS for single-doping NS concrete was 2%, and that for NC was 3%. The superior wear resistance of nano double-doped concrete could be found with 2% NS and 2% NC, and meanwhile, the wear loss was only 0.64 kg/m^2, with a decrease by 75%; the drying shrinkage rate of the concrete containing 2% NS and 2% NC at 28 d was increased by 124.8% and 85.8%, respectively, compared to the reference concrete. Therefore, it is concluded that due to its surface effect, pozzolanic reaction and microscopic aggregate filling effect, nano-particles have larger surface energy, to change the orientation degree of calcium hydroxide crystals in the interface transition zone and fill pores among cementitious materials, thereby improving the wear resistance and drying shrinkage of fly ash concrete. These results would provide guidance on the design of the high wear resistance and low drying shrinkage fly ash concrete.

1. Introduction

As an emerging special material, nano-materials have been widely used as an excellent modified admixture to optimize a range of performance of concrete because of its very large specific surface areas and other unique properties, such as the surface and interface effect, the pozzolanic reaction, the quantum size effect, and the macroscopic quantum tunnel effect. Therefore, to improve performance of road concrete, using nano-materials has also been considered by several researchers. There is several reason to believe that nano-materials can be applied to road materials and prepare nano-modified concrete, which has broad application prospects to improve the mechanical properties and prevent drying shrinkage with remarkable benefits in terms of long-term service life of the pavement in the near future [1–3].

Numerous researches indicated that the addition of nano-SiO_2, nano-modified mineral admixture and basalt fiber could enhance not only the mechanical properties, but improved the frost resistance, impermeability, carbonation resistance and wear resistance [4–8]. While the addition of nano-SiO_2 and nano-TiO_2 could significantly improve not only the flexural fatigue of concrete, but also enhance its theoretic fatigue lives in different extent [9]. Some researches have been devoted to explore the influence of nano-

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SiO_2 and silica fume on consistency and setting time of fresh cement paste, it has been found that the nano-SiO_2 can make cement paste thicker and accelerate the hydration process cement paste. Meanwhile, the increase of the rate of bond strength is more than that of its compressive strength when the nano-SiO_2 content increases [10]. Some scholars also found that the mechanical properties of the ultra-high performance concrete doped nano-materials were increased with the increase in strain rate and the added amount of nano-materials [11,12].

An early study found that the drying shrinkage of concrete was influenced by many factors, and the addition of a certain amount of ultra-fine fly ash in highway concrete could reduce the concrete shrinkage at different ages [13]. There is, however, strong evidence that the drying shrinkage of concrete is related to aggregate content and particle size. When the water binder ratio remains constant, the shrinkage of concrete increases with the increasing dosage of slag powder, but the increasing range is related to the water binder ratio [14–18]. The investigation results showed that the early drying shrinkage rate of steel fiber reinforced concrete was higher than that of the ordinary concrete, because of the higher its porosity [19]. Nano-SiO_2 is favorable for inhibiting the drying shrinkage, and the reason for this is attributed to the improvement in the microstructure of hardened cement paste and the promotion in the hydration product, which would reduce the content of free water. As reported, the drying shrinkage was decreased by 7.5%, when nano-SiO_2 is doped into the palm oil fuel ash (POFA) cement mortars [20].

According to the previous research, nano-particles are attracting more attention as an alternative component used for the improvement of the road concrete. It is well known that the wear resistance and drying shrinkage are the key performance indicators of the road concrete, but currently, few research about the effect of the different nano-particles on the wear resistance and drying shrinkage of road fly ash concrete have been found. Therefore, in this study, the ultra-fine fly ash of meso-scale and the nano-particles of micro scale were used to prepare the nano-modified road fly ash concrete, and the mechanical properties, wear resistance and drying shrinkage were investigated. Finally the mechanisms were analyzed with microscopy scanning electron microscope analysis. It is anticipated that the results would provide guidance on the design of the road concrete.

2. Experiments

2.1. Raw materials

2.1.1. Cement

An ordinary Portland cement (C), produced in Hunan Pingtang South Cement Co. Ltd., was used. The specific surface area is 330 m^2/kg; the 28 d compressive strength is 47.3 MPa; the flexural strength is 7.9 MPa, and its chemical compositions are shown in Table 1.

2.1.2. Ultra-fine fly ash

Ultra-fine Fly Ash (UFA), produced by Hunan Yueyang power plant. The specific surface area is 550 m^2/kg, whose chemical compositions are shown in Table 1.

2.1.3. Nano-materials

Nano-SiO_2 (Nano Silica, NS), produced by Chengdu Kaxihua Chemical Co. Ltd; Nano-SiC (Nano Silicon Carbide, NC), produced by Xuzhou Hongwu nanometer material Co. Ltd, the chemical compositions and properties of nano-particles are shown in Table 2.

2.1.4. Aggregates

(1) Coarse aggregate
Macadam maximum size: 26.5 mm, coarse aggregate parameters are shown in Table 3.

(2) Fine aggregate
Continuous grading river sand from Xiangjiang of Hunan Province, fine aggregate parameters are shown in Table 4.

2.2. Admixture

High efficient naphthalene water reducing agent, which is brown yellow powder, Cl^- content <0.1%, water reducing ratio is 25%.

2.3. Experimental methods

Fly ash cement mortar and road fly ash concrete were prepared by using 18% UFA equivalent replaced cement. Afterwards, nano-modified fly ash cement mortar and road fly ash concrete were prepared using nano-materials with 1%, 2% and 3% of cementitious materials totaling content, respectively.

The strength test of cement mortar was done at the age of 28 days in accordance with Chinese standard "JTG/E30-2005" [21] using 40 mm × 40 mm × 160 mm prismatic specimen, the flexural strength and compressive strength were measured after 28 days standard curing in constant temperature chamber at 20 ± 1 °C, relative humidity >90%.

The wear resistance of cement concrete was done at the age of 28 days in accordance with Chinese standard "JTG/E30-2005" using 150 mm × 150 mm × 150 mm cube specimen, the 28 d wear loss were measured.

The drying shrinkage of cement mortar was done at the age of 7, 14, 21 and 28 days in accordance with Chinese standard "JTG/E30-2005" using 25 mm × 25 mm × 280 mm mortar bar with sand to binder ratio of 0.5. The shrinkage test was performed after 28 days standard curing in constant temperature chamber at 20 ± 3 °C, 50 ± 4% relative humidity.

The drying shrinkage of cement concrete was done at the age of 1, 3, 7, 14, 21 and 28 days in accordance with Chinese standard "JTG/E30-2005" using 100 mm × 100 mm × 400 mm prismatic specimen. The drying shrinkage test was carried out after standard curing in constant temperature chamber at 20 ± 2 °C, 60 ± 5% relative humidity.

3. Results and discussion

3.1. Preparation of fly ash cement mortar doped with nano-particles

The wear resistance of road concrete mainly depends on the wear resistance of cement mortar. Therefore, the optimal content range of nano-materials was determined based on the results from the cement mortar strength test. And then, three types of nano-modified concrete (NS concrete, NC concrete and nano double-doped concrete) were prepared by replacing the cement with equal mass nano-materials. The mechanical properties of cement mortar were tested. The details of the mix proportions of cement mortar test investigated in this study are given in Table 5.

3.2. Strength test results of fly ash cement mortar

Strength test results of cement mortar doped single nano-materials (groups 0–6) were synthetically summarized in Fig. 1. It can be found that the nano-materials have a positive effect on the strength of cement mortar, with an enhancement of the flexural strength and compressive strength. When nano-materials content is in the range of 0–3%, with the increasing content of NS, the flexural strength and compressive strength of cement mortar increases firstly and then slightly decreases, indicating that the optimum content of NS is 2%; while for NC cement mortar, the flexural strength and compressive strength show an increasing trend

Table 1
Chemical components of cementitious materials (mass/%).

Materials	SO_3	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O
C	2.41	23.30	2.77	5.41	61.16	2.65	0.68	0.07
UFA	0.42	50.25	5.35	34.20	4.50	1.50	1.20	0.80