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Wear 260 (2006) 1262–1266

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Abrasion resistance of concrete containing nano-particles for pavement

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Received 14 December 2004; received in revised form 15 August 2005; accepted 23 August 2005
Available online 10 October 2005

Abstract

The abrasion resistance of concrete containing nano-particles for pavement is experimentally studied. Both nano-TiO_2 and nano-SiO_2 are, respectively, employed to be as the additives. For comparison, the abrasion resistance of plain concrete and the concrete containing polypropylene (PP) fibers is also experimentally studied in this work. The test results indicate that the abrasion resistance of concretes containing nano-particles and PP fibers is significantly improved. However, the indices of abrasion resistance of concrete containing nano-particles are much larger than that of concrete containing PP fibers. The abrasion resistance of concrete containing nano-TiO_2 is better than that containing the same amount of nano-SiO_2. The enhanced extent of the abrasion resistance of concrete decreases with increasing content of nano-particles. Finally, the relationship between the indices of abrasion resistance and compressive strength of concrete is obtained, which indicates that the abrasion resistance of concrete increases with increasing compressive strength.

Keywords: Abrasion resistance; Pavement concrete; Nano-particles; Polypropylene (PP) fiber

1. Introduction

Pavement concrete is mostly used for road surfaces, bridge decks, airfield runways and parking lots. Pavement concrete endures dynamical loads and subjects to rigorous environment. High-performance of pavement concrete requires good durability as well as strength. Durability of pavement concrete includes abrasion resistance, impact resistance, permeability and freeze-thaw cycles. The abrasion resistance is one of the key considerations.

Numerous studies on the abrasion resistance of concrete have been carried out. The results showed that the abrasion resistance of concrete was strongly influenced by compressive strength, surface finishing techniques, curing types, aggregate properties and testing conditions, i.e. dry or wet [1,2].

There are two views on the relationship between compressive strength and abrasion resistance of concrete. One of them is that compressive strength is the most important factor governing the abrasion resistance of concrete [3], and the abrasion resistance of concrete increases with increasing compressive strength [1,2,4,5]. For example, Naik et al. [1] and Gjorv et al. [4] indicated that the relationship between compressive strength and abrasion resistance of concrete was linear, however, Cengiz [2] pointed out that the relation was hyperbolic. While the other view is that the abrasion resistance of concrete is independent on compressive strength [6,7].

Many investigations have shown that both surface finishing techniques and curing types have a strong influence on the abrasion resistance of concrete [3]. In general, proper finishing and curing practices are known to enhance the abrasion resistance of concrete considerably. Sadegzadeh et al. [8] studied the relationship between surface microstructure and abrasion resistance of concrete. The results indicated that different surface finishing techniques produced distinct pore structures and hardnesses within a surface zone of a few millimeters, and the abrasion resistance of concrete was largely dependent on the pore structure and microhardness of the surface zone.

A number of studies have shown that the addition of PP fibers can improve the abrasion resistance of concrete. Most of the test results indicated that the abrasion resistance of concrete containing PP fibres could increase by 20–60% according to different contents of PP fibres and different researchers [9,10]. The result of simulant abrasion test carried out by the National Highway Laboratory of Norway showed that the abrasion resistance of concrete containing PP fibers increased by 52% [11]. However, the result tested by the U.S. Army Corps of Engineers using

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doi:10.1016/j.wear.2005.08.006

CRD-C52-54 method indicated that the abrasion resistance of concrete containing PP fibers could increase by 105% [11].

The abrasion resistance of concrete containing nano-particles (TiO_2 and SiO_2) for pavement is experimentally studied. For comparison, the abrasion resistance of plain concrete and the concrete containing PP fibers is also experimentally studied in this work. The test results indicate that the abrasion resistance of concretes containing nano-particles and PP fibers is significantly improved. However, the indices of abrasion resistance of concrete containing nano-particles are much larger than that of concrete containing PP fibers. If the concrete containing nano-particles is used for pavement, the service life of pavement can be prolonged.

2. Experiment

2.1. Materials and mixture proportions

The cement used is Portland cement (P.O42.5). Fine aggregate is natural river sand with a fineness modulus of 2.4. The coarse aggregate used is crushed diabase with diameter of 5–25 mm. UNF water-reducing agent (one kind of β-naphthalene sulfonic acid and formaldehyde condensates, China) is employed to aid the dispersion of nano-particles in concrete and achieve good workability of concrete. The defoamer, tributyl phosphate (made in China) is used to decrease the amount of air bubbles.

The nano-particles are purchased from Zhoushan Mingri Nano-phase Material Co. (Zhejiang, China) and their properties are shown in Table 1. The modified PP fibers are obtained from Zhangjiagang Synthetic Fiber Co. (Jiangsu, China) and their properties are shown in Table 2.

The water-to-binder (the sum of cement and nano-particles) ratio used for all mixtures is 0.42. Sand ratio is 34%. The mixture proportions for cubic meter of concrete are given in Table 3. Herein, PC denotes plain concrete. PPC1and PPC2 denote the concrete containing PP fibers in the content of 0.6 and 0.9 kg/m^3, respectively. NSC1 and NSC3 denote the concrete containing nano-SiO_2 in the amount of 1 and 3% by weight of binder, respectively. And NTC1, NTC3 and NTC5 denote the concrete containing nano-TiO_2 in the amount of 1, 3 and 5% by weight of binder, respectively.

2.2. Specimen fabrication

To fabricate the concrete containing nano-particles, water-reducing agent is firstly mixed into water in a mortar mixer, and then nano-particles are added and stirred at a high speed for 5 min. Defoamer is added as stirring. Cement, sand and coarse aggregate are mixed at a low speed for 2 min in a concrete centrifugal blender, and then the mixture of water, water-reducing agent, nano-particles and defoamer is slowly poured in and stirred at a low speed for another 2 min to achieve good workability.

To fabricate plain concrete and the concrete containing PP fibers, water-reducing agent is firstly dissolved in water. After cement, sand, coarse aggregate and PP fibers (if used) are mixed uniformly in a concrete centrifugal blender, the mixture of water and water-reducing agent is poured in and stirred for several minutes.

Finally, the fresh concrete is poured into oiled molds to form cubes of size 100 mm × 100 mm × 100 mm that are used for compressive testing, prisms of size 100 mm × 100 mm × 400 mm for flexural testing and cubes of size 150 mm × 150 mm × 150 mm for abrasion testing. After pouring, an external vibrator is used to facilitate compaction and decrease the amount of air bubbles. The specimens are de-molded at 24 h and then cured in a standard moist room at a temperature of 20 ± 3 °C.

2.3. Test methods

Both compressive and flexural tests are performed in accordance with JTJ 053-94 (testing methods of concrete for highway engineering, China). Abrasion testing is conducted according to GB/T16925-1997 (test method for abrasion resistance of concrete and its products, China), testing equipment is ball bearing abrasion machine.

Firstly, the abraded face of specimen is put upward. The abrasion head is put on the abraded face. The machine rotates the abrasion head rubbing the abraded face. The abraded face is flushed by water in order to clean the dust from the abraded face as the machine rotates. The abrasion head abrades a circular groove with diameter of 75 mm on the abraded face of specimen. The depth of abrasion groove is measured to be as the initial depth when abrading 30 revolutions. Henceforth, the machine stops once time when rotating per 1000 revolutions,

Table 1
The properties of nano-particles

Item	Diameter (nm)	Specific surface area (m^2/g)	Density (g/cm^3)	Purity (%)	Phase
SiO_2	10 ± 5	640 ± 50	<0.12	99.9	–
TiO_2	15	240 ± 50	0.04–0.06	99.7	Anatase

Table 2
The properties of PP fibers

Item	Elongation (%)	Fiber number (D)	Diameter (μm)	Length (mm)
Target	40 ± 3	11 ± 0.5	84–92	15 ± 1

Table 3
Mix proportions of specimens (kg/m^3)

Mixture no.	Water	Cement	Sand	Coarse aggregate	PP fiber	Nano-SiO_2	Nano-TiO_2	UNF	Defoamer	Slump (cm)
PC	151	360	650	1260	–	–	–	5.4	–	5–6
PPC1	151	360	650	1260	0.6	–	–	5.4	–	3–4
PPC2	151	360	650	1260	0.9	–	–	5.4	–	2–3
NSC1	151	356.4	650	1260	–	3.6	–	5.4	0.216	2–3
NSC3	151	349.2	650	1260	–	10.8	–	7.2	0.288	1–2
NTC1	151	356.4	650	1260	–	–	3.6	5.4	0.216	2–3
NTC3	151	349.2	650	1260	–	–	10.8	7.2	0.288	2–3
NTC5	151	342	650	1260	–	–	18	7.2	0.288	1–2

and the depth of abrasion groove is measured. When the revolutions of abrasion head reach 5000 revolutions or the depth of abrasion groove exceeds 1.5 mm, the testing can be stopped. The revolutions of abrasion head are recorded and the final depth of abrasion groove is measured.

Then the index of abrasion resistance is defined as

$$I_a = \frac{\sqrt{R}}{P} \quad (1)$$

where, I_a is the index of abrasion resistance; R is the revolutions of abrasion head (kilo revolution); P is the depth of abrasion groove (mm), which is the difference between the final depth and initial depth of abrasion groove.

The index obtained from the test that takes the molded face of specimen as the abraded face is called surface index of abrasion resistance, and that taking the side of specimen as the abraded face is called side index of abrasion resistance. The surface index is slightly discreter than the side index of abrasion resistance, but it is more in agreement with the actual circumstance of pavement concrete.

The larger the value of the index of abrasion resistance is, the stronger the abrasion resistance of concrete is. Generally, when surface index of abrasion resistance is larger than 1.60, the abrasion resistance of concrete pavement can be ensured.

3. Test results and discussions

3.1. Compressive and flexural strengths

Table 4 shows the compressive and flexural strengths of all specimens at the 28th day. It can be seen that, when nano-particles in a small amount are added, both the compressive and flexural strengths of concrete can be enhanced. However, when nano-particles in a large amount are added, the flexural strength of concrete is lower than plain concrete although the compressive strength is still a little enhanced. The effectiveness of nano-TiO_2 in increasing the compressive and flexure strengths increases in the order: NTC5 < NTC3 < NTC1 (with the decrease on nano-TiO_2 content) and the similar results can be observed in Table 4 for the concrete containing nano-SiO_2. When the content of PP fibers increases from 0.6 to 0.9 kg/m^3, compressive strength of the concrete containing PP fibers enhances only a little, but its flexural strength improves markedly.

Table 4
Compressive and flexural strengths of specimens

Mixture no.	Flexural strength		Compressive strength	
	Target (MPa)	Enhanced extent (%)	Target (MPa)	Enhanced extent (%)
PC	5.46	0	59.08	0
PPC1	5.99	9.81	61.02	3.28
PPC2	6.60	20.87	63.29	7.12
NSC1	5.69	4.21	66.36	12.31
NSC3	5.36	−1.87	61.16	3.51
NTC1	6.02	10.28	69.73	18.03
NTC3	5.62	3.04	66.62	12.76
NTC5	5.28	−3.27	60.00	1.55

If concrete is perfect and has no flaws, its compressive and flexural strengths should be enhanced synchronously. But in practice, the enhanced extent of compressive strength of concrete is greatly larger than that of flexural strength. This is primarily attributed to the presence of micro-cracks with different scales in concrete, and the effect of micro-cracks on flexural strength of concrete is greater than on compressive strength [9]. However, with the addition of PP fibers, the formation and propagation of micro-cracks are inhibited, and the scales of micro-cracks are reduced, so the enhanced extent of flexural strength of the concrete containing PP fibers is higher than that of compressive strength. When the content of nano-particles is larger, such as the concretes containing 3% nano-SiO_2 and 5% nano-TiO_2, the workability of concrete is worse, and the number of micro-cracks in concrete increases, which results in the decrease of flexural strength of concrete. In addition, because nano-particles are more difficult to uniformly disperse when the contents are large, and the weak zone in concrete increases, which also causes the decrease of flexural strength of concrete.

3.2. Abrasion resistance

Table 5 shows the results of abrasion resistance of all specimens at the 28th day. It can be seen that the abrasion resistance of concretes containing nano-particles and PP fibers is remarkably improved, in particular the abrasion resistance of concrete containing nano-particles. The enhanced extent of the abrasion resistance of concrete containing nano-particles is much higher than that of concrete containing PP fibers. The side indices of abrasion resistance of all concretes are larger than their surface indices of abrasion resistance.

Table 5
The results of abrasion resistance of specimens

Mixture no.	Surface index of abrasion resistance		Side index of abrasion resistance	
	Target	Enhanced extent (%)	Target	Enhanced extent (%)
PC	1.19	0	1.55	0
PPC1	1.42	19.1	2.42	55.9
PPC2	1.60	34.4	2.62	69.2
NSC1	3.06	157.0	3.71	139.4
NSC3	2.39	100.8	2.93	89.0
NTC1	3.34	180.7	4.24	173.3
NTC3	2.95	147.7	3.72	140.2
NTC5	2.27	90.4	2.88	86.0

The effectiveness of nano-TiO_2 in enhancing abrasion resistance increases in the order: NTC5 < NTC3 < NTC1 (with the decrease on nano-TiO_2 content). The abrasion resistance of concrete containing nano-TiO_2 in the amount of 1% by weight of binder increases by 180.7% for the surface index and 173.3% for the side index. Even for the concrete containing nano-TiO_2 in the amount of 5% by weight of binder, the abrasion resistance increases by 90.4% for the surface index and 86% for the side index. The similar results can be found for the concrete containing nano-SiO_2.

The index of abrasion resistance of concrete containing PP fibers increases with increasing fibers content. The enhanced extent is almost the same as that presented in the related literatures.

The addition of nano-particles is much more favorable to the abrasion resistance of concrete than that of PP fibers.

The mechanism of nano-particles improving the abrasion resistance of concrete can be interpreted as follows. Supposed that nano-particles are uniformly dispersed and each particle is contained in a cube pattern, the distance between nano-particles can be specified. After hydration begins, hydrate products diffuse and envelop nano-particles as kernel. If the content of nano-particles and the distance between them are appropriate, the crystallization will be controlled to be a suitable state through restricting the growth of $Ca(OH)_2$ crystal by nano-particles. This makes the cement matrix more homogeneous and compact. As a consequence, the abrasion resistance and strength are improved evidently such as the concrete containing 1% nano-TiO_2. With increasing content of nano-particles, the distance between nano-particles decreases, $Ca(OH)_2$ crystal can not grow up enough, which leads to the ratio of crystal to C–S–H gel small and the microstructure of cement matrix is loose. The abrasion resistance and strength of concrete decrease relatively.

In addition, because cement content and water content in this study are small, the slump of fresh concrete, especially the concrete containing nano-particles is less than 60 mm, which leads to a thin mortar layer on the surface of concrete forming. The thin mortar layer is favorable to the improvement of abrasion resistance of concrete.

However, the abrasion resistance and strength of concrete are decreased with increasing content of nano-particles. Studies have shown that the content of nano-particles has a strong influence on the water demand of cement paste [12]. The larger the content of nano-particles is, the more the water demand of cement paste is. If the mixture proportions of concrete are the same, the workability of concrete will decrease remarkably with increasing content of nano-particles, which consequently decreases the abrasion resistance and strength of concrete. In addition, the uniform dispersion of nano-particles in cement paste is difficult with increasing content of nano-particles, which also decreases the strength and abrasion resistance of concrete.

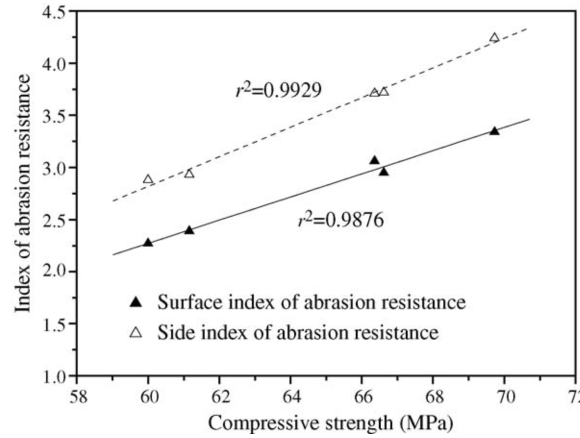

Fig. 1. The relationship between the index of abrasion resistance and compressive strength of concrete containing nano-particles.

The abrasion resistance of concrete containing modified PP fibers is improved, which is mostly attributed to the crack-arresting effect and crack-thinning effect of PP fibers [9], and the bridge effect of PP fibers on cracks and diversion effect of PP fibers on separated cement blocks [13]. The larger the content of PP fibers is, the stronger these effects are. In addition, friction work is consumed when PP fibers are pulled out from concrete [13].

3.3. The relationship between abrasion resistance and compressive strength of concrete

As mentioned in introduction, there are different views on the relationship between abrasion resistance and compressive strength of concrete at present. The relationship between abrasion resistance and compressive strength of concrete is obtained from this test, and shown in Figs. 1 and 2, respectively.

It can be seen from Fig. 1 that the indices of abrasion resistance of concrete containing nano-particles increase with increasing compressive strength. The relationship appears to be linear, and the correlation coefficient is close to 1.0. The correlation of side index of abrasion resistance is slightly larger than that of surface index.

Fig. 2 shows the total relationship between the indices of abrasion resistance and compressive strength for plain concrete, the concrete containing nano-particles and the concrete containing PP fibers. It can be seen that the curves approach hyperbola basically, which confirms that compressive strength is a critical factor affecting the abrasion resistance of concrete.

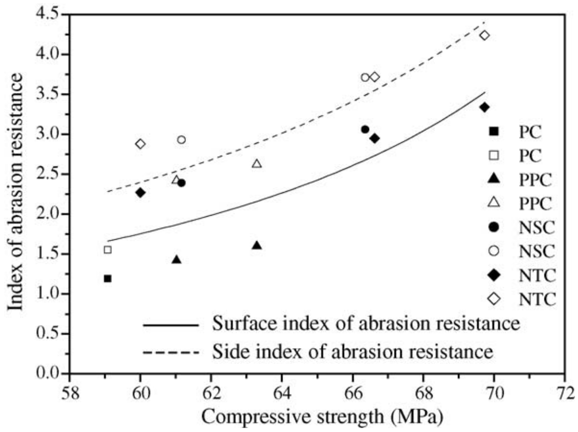

Fig. 2. The relationship between the index of abrasion resistance and compressive strength for all mixtures.

Table 6
Regression coefficient in the Eq. (2)

Index of abrasion resistance	θ_1	θ_2	Correlation coefficient r^2
Surface index of abrasion resistance	−1.47819	122.867	0.67625
Side index of abrasion resistance	−0.94309	81.5936	0.78734

The relationship between the index of abrasion resistance and compressive strength can be expressed by

$$I_a = \frac{f_{cu}}{\theta_1 f_{cu} + \theta_2} \quad (2)$$

where, I_a is the index of abrasion resistance of concrete; f_{cu} is the compressive strength (MPa); θ_1 and θ_2 are constants that can be obtained by curve fitting techniques and reported in the Table 6.

4. Conclusions

The data collected in this study lead to the following primary conclusions:

(1) The abrasion resistance of concrete can be considerably improved with the addition of nano-particles or PP fibers. However, the indices of abrasion resistance of concrete containing nano-particles are much larger than that of concrete containing PP fibers. So the nano-particles are more favorable to the abrasion resistance of concrete than PP fibers.
(2) The enhanced extent of the abrasion resistance of concrete containing nano-particles decreases with increasing content of nano-particles. The abrasion resistance of concrete containing nano-TiO_2 is better than that containing the same amount of nano-SiO_2.
(3) The abrasion resistance of concrete containing nano-particles increases with increasing compressive strength. The relationship appears to be linear. For all concretes referred in this study, the relationship between abrasion resistance and compressive strength approaches hyperbola basically. So the abrasion resistance of concrete is strongly dependent on their compressive strength.

Acknowledgements

This study was financially supported by NSFC grant no. 50238040, and Ministry of Science and Technology grant no. 2002AA335010 together.

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