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Research on the Abrasion Resistance of Concrete with Nano-SiO$_2$, Super-Fine Slag and Rubber Powder

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ABSTRACT

The influence of nano-SiO$_2$ (NS), super-fine slag (SS) and rubber powder (RP) on the abrasion resistance of concrete was explored. Concrete incorporated with 5wt.% NS, 40wt.% SS were investigated respectively, as well as 40% super-fine slag combining 20% replacement of sand volume with RP. The mechanical properties of concrete mentioned above including compressive strength, modulus of elasticity and abrasion resistance were examined. The comparison experiment results showed that the reference concrete had the lowest compressive strength, modulus of elasticity and abrasion resistance； the concrete containing SS had the highest compressive strength and modulus of elasticity；the concrete containing SS combining RP had the highest abrasion resistance. Therefore, incorporation of NS or SS can both improve the abrasion resistance of concrete. Although incorporation of the rubber powder would decrease the compressive strength of concrete, it can be advantageous to the abrasion resistance. When SS combining RP are incorporated, the abrasion resistance of concrete will be significantly improved.

INTRODUCTION

With the implementation of China's strategy of west China development and power transmission from west to east, more and more high head hydropower stations have been constructed or planned, which are even more than 300 m in height such as Jinping dam, with a flow velocity more than 30 m/s or even 50 m/s [Lian et al. 2008]. At the same time, the sediment concentration of rivers is large in China so that higher abrasion resistance of concrete is required.
The prevailing opinion is that coarse aggregate has the most significant effect on the abrasion resistance of concrete and the hardest available coarse aggregate should be used to the maximum [Liao 1993; Graham et al. 1987]. In addition, dense paste and interface between aggregate and mortar are essential for improvement of abrasion resistance. Therefore high-range water-reducing admixtures and silica fume are often used to enhance performances of concrete. Good impact toughness is also essential and important for abrasion resistant concrete. The common used silica fume concrete, steel fiber reinforced concrete, steel fiber and silica powder concrete, polypropylene fiber concrete have conformed to this guiding ideology.

At present, the main problems involved in abrasion resistant concrete include: (1) silica fume concrete is easy to crack due to the early shrinkage, and it is expensive; (2) fibers and epoxy resins and other polymer systems are not only expensive but also unsuitable for large scale application because of the complex construction technology. Therefore, it is necessary to develop other kinds of high reactivity cement admixtures and toughening components. According to Wang et al. [2003], NS has good adaptability and can improve the performance of Portland cement, and the appropriate content is 5~6% of the total binder content by mass. The research by He [1999] indicates that SS is beneficial for abrasion resistant concrete, and the appropriate content is 40% of the total binder content by mass. But so far, there are a few researches about application of NS and SS in abrasion resistant reported in literatures. Li and Wang [2010] have reported that rubber powder concrete presents a higher abrasion resistant strength comparing with silica fume concrete and ordinary concrete. The research by Fan [2010] shows that when RP contents are 5%, 7.5%, 10% and 15% of the total sand content by volume, the increment rate of abrasion resistant of concrete are 35.5%, 46.9%, 93.8% and 115.8% respectively compared to the reference concrete, and would continue to increase with the increasing content of RP.

Aiming at these problems, this paper investigated the effect of NS or SS as reinforcing components and RP as toughening component on concrete mechanical properties including compressive strength, abrasion resistant strength and elastic modulus, as well as modification mechanism, by analysis of X-Ray diffraction (XRD) and Scanning Electron Microscopy (SEM).

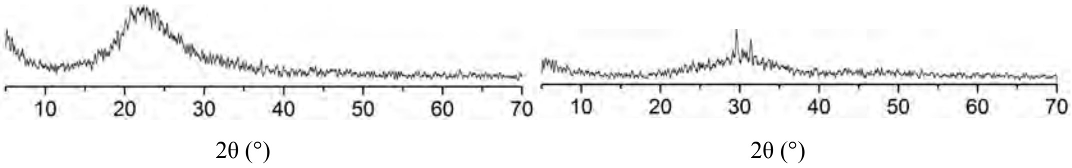
EXPERIMENTAL INVESTIGATION

Materials Used

Cement used in this study is the P.O.42.5 cement. The water requirement of normal consistency was 26%. Initial and final setting time of the cement were 112 min and 164 min respectively. The Blaine specific surface area was 348 m^2/kg and the chemical compositions are given in Table 1. The NS used in this study had a specific surface area of more than 600000 m^2/kg and the chemical compositions are given in Table 1. Fig.1 (a) shows the XRD pattern of NS which reveals that the morphology of nano-grains are pure amorphous. Fig.2 (a) shows the SEM image of the nano-grains' morphology which also verifies the amorphous nature of the nano-grains. The SS used in this study had a specific surface area of 1200 m^2/kg and the chemical compositions are given in Table 1.The XRD pattern of SS is shown in Fig.1 (b) and the morphology of SS is shown in Fig.2 (b). The RP used in this study had three kinds of particles which were characterized of size of 0.6 mm (RP1), 0.25 mm (RP2) and 0.18 mm (RP3). Natural river sand with a fineness modulus of 2.45 and crushed granite (size 5~20 mm) were used. The superplasticizer (SP) had a water reducing rate of 25% and the solid content was 40%.

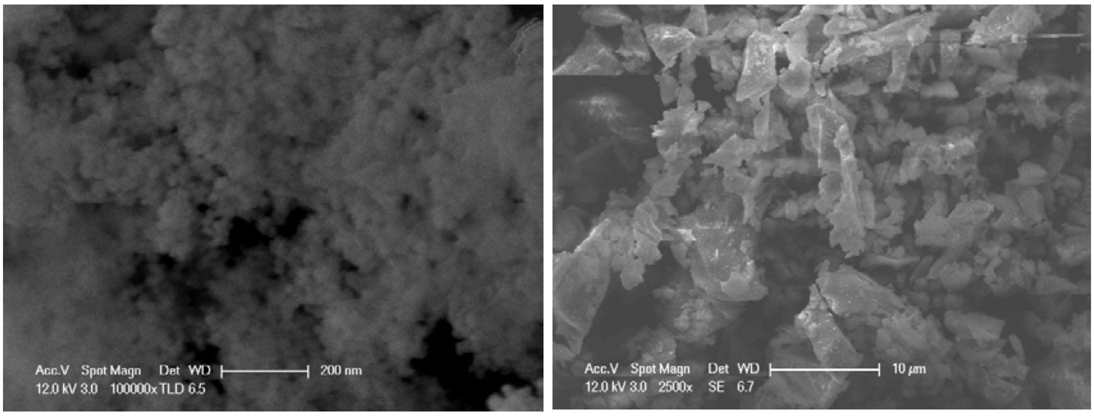
Table 1. Chemical Compositions of Cement, NS and SS（%）

Materials	SiO_2	CaO	Al_2O_3	MgO	SO_3	Fe_2O_3	K_2O	Na_2O
Cement	19.94	62.40	5.26	3.78	3.00	2.98	1.00	0.13
NS	98.05	0.06	0.26	0	0.73	0.04	0.01	0.76
SS	29.62	37.17	16.87	9.99	3.38	0.40	0.48	0.51



(a) NS (b) SS

Fig.1. XRD Patterns of NS and SS



(a) NS (b) SS

Fig.2. SEM Images of NS and SS

Mixture Proportion, Specimen Preparation and Curing

Replacement of NS and SS were respectively 5% and 40% by weight. RP was added into the concrete to replace the sand particles of the same size in order to obtain good gradation curve, and it was 20% replacement of sand volume. In order to study the influence of NS and SS on concrete's strength and abrasion resistance, C-1 and C-2 were made. In view of failure characteristics of high speed sediment-laden flow, in order to improve the abrasion resistance of concrete, the design of mixed proportion of abrasion-erosion resistant concrete was mainly aimed at improving strength and reducing elastic modulus. Based on the former study [Chen 2012], the effect of NS and SS on mortar's strength was just the same. And considering the high cost of NS concrete, we selected SS to be used together with RP, and C-3 were made.

Table 2. Mix Proportions of Abrasion Resistant Concrete

Mix	Materials（kg/m^3）						
	C	W	S	G	NS	SS	SP
C-0	488	146	610	1220	0	0	3.90
C-1	464	146	610	1220	24	0	9.76
C-2	291	146	606	1213	0	194	0

Table 3. Mix Proportions of Rubber Concrete

Mix	Materials（kg/m^3）							
	C	W	SS	S	G	RP		
						RP1	RP2	RP3
C-3	291	146	194	485	1213	8.9	24.8	24.2

Cubic samples with side of 100 mm were prepared for compressive strength test and abrasion test, and cylindrical samples with dimensions of ф150 mm × 300 mm were prepared for elastic modulus test. All samples were demoulded at 1 day, then cured in curing chamber with a moisture of 95% and temperature of (20±1) ℃. The compressive strength, the abrasion resistant strength and the elastic modulus were tested at 28 days and 90 days.

Test Methods

The compressive strength test and the elastic modulus test was performed according to SL352-2006 [2006]. Fig.3 shows the abrasion testing apparatus. The angle of attack was 90°. The abrasion medium was quartz sand (size 0.16~2.50 mm). The wind pressure was kept at 0.4Mpa, and the distance between the upper surface of the samples and the sandblasting pipe outlet was 30cm. Three samples of each batch were tested at each specified age. The test procedure and the calculation of abrasion resistant strength were according to DL/T 5150-2001[2001].

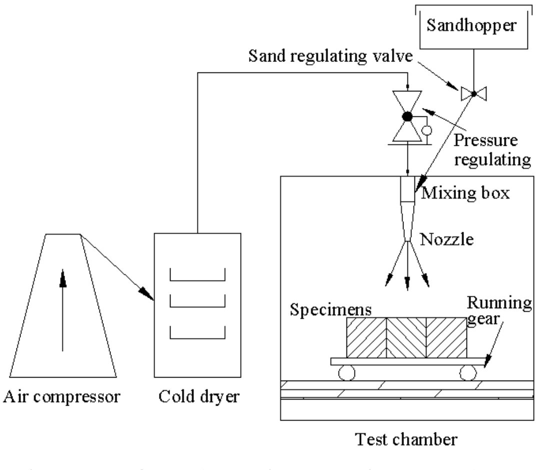


Fig.3. Diagram of the Abrasion Erosion Test Apparatus

Crystalline phases of the raw materials and the hydrated pastes were analyzed with a D8ADVANCE diffractometer with Cu Kα radiation. The samples were scanned from 5º to 70° at a scanning speed of 4º/min. SEM observation of the morphology of the paste was conducted based on JSM-5610LV.

RESULTS AND DISCUSSIONS

Influence of Different Components on Compressive Strength of Concrete

Since the size of concrete samples for compressive strength test was not the standard size, the compressive strength should be multiplied by 0.95. The converted date are presented in Table 4. It can be seen that compared to the reference concrete, either NS or SS considerably improved the compressive strength of concrete. The increment ratios of strength at 28 and 90 days were 1.86 and 1.82 for NS concrete respectively and 2.03 and 1.95 respectively for SS concrete. Obviously, the effect of SS on compressive strength was more significant than NS at each age. The compressive strength decreased with the incorporation of RP, yet increased with incorporation of RP and SS. For either NS concrete or SS concrete, the increment ratio of strength at 90 days were similar to that at 28 days, which indicated that either NS or SS can ensure early strength development of concrete as well as late strength development.

Table 4. Compressive Strength, Abrasion Resistant Strength and Elastic Modulus of Concretes

Mix	Compressive strength（MPa）		Abrasive strength（h/cm）		Elastic modulus（GPa）	
	28d	90d	28d	90d	28d	90d
C-0	42.5 (1.00)	46.7 (1.00)	0.24 (1.00)	0.55 (1.00)	32.9 (1.00)	34.2 (1.00)
C-1	79.2 (1.86)	85.2 (1.82)	0.36 (1.50)	0.72 (1.31)	40.6 (1.23)	43.5 (1.27)
C-2	86.1 (2.03)	91.1 (1.95)	0.32 (1.33)	0.71 (1.29)	51.3 (1.56)	55.2 (1.61)
C-3	69.3 (1.63)	75.5 (1.62)	0.41 (1.71)	0.74 (1.35)	33.1 (1.01)	37.7 (1.10)

The date in bracket: strength ratio of each concrete and the reference concrete at each age.

The occurrence of compressive failure for concrete without RP was abrupt and explosive which observed in concrete with RP was just the reverse. Fig.4 presents the compressive failure mode of concrete samples. It can be observed that the failure path of the reference concrete was along the paste and paste-aggregate interface. However, the collapse of coarse aggregate was observed in concrete with NS or SS, which illustrated that strength of the paste and bond strength of mortar-aggregate interface were obviously improved. RP-SS concrete did not disintegrate and the failure duration was more gradual, which indicated that RP-SS concrete was less brittle than the other concrete samples.

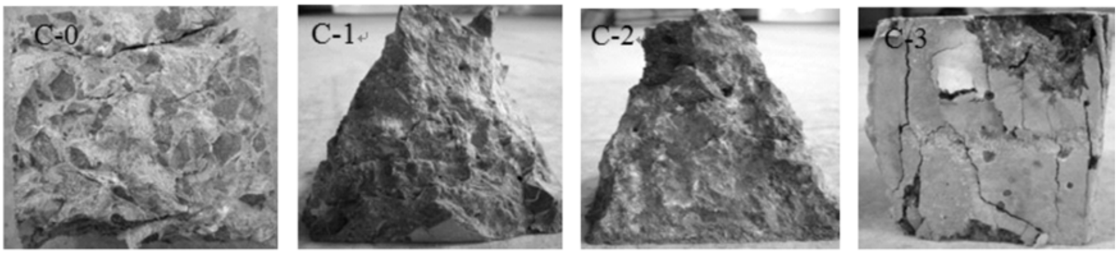


Fig. 4. Destroyed Specimens after Compression Failure

Influence of Different Components on Abrasive Strength of Concrete

The results of the abrasion tests are presented in Table 4. It can be seen that NS, SS and RP were all beneficial for the abrasive strength development of concrete. The increment ratios of abrasive strength at 28 and 90 days were 1.50 and 1.31 respectively for NS concrete, 1.33 and 1.29 for SS concrete, 1.71 and 1.35 for SS-RP concrete. The truth that NS is more efficient than SS to improve abrasive strength was evidenced. Incorporation of the enhancement component (SS) and the toughening component (RP) had the maximum increment ratio at each age., which was not accordance with the influence on compressive strength.

Fig.5 presents the abrasion failure mode of concrete samples. It can be observed that the concrete was destroyed in the form of whole spalling of sand particles and layered spalling of paste and coarse aggregate. For the reference concrete, concaves appeared in the region of paste and paste-aggregate interface, and sand particles and coarse aggregate were bulged. The concrete with admixtures (NS, SS) maintained a relatively plain surface and had less bulged aggregate. This phenomenon indicated that replacement of NS and SS significantly improved the abrasive strength of the paste which almost equal to the coarse aggregate. Rubber powders inlaying the paste were scattered on the surface of RP-SS concrete and firmly bonded with the paste.

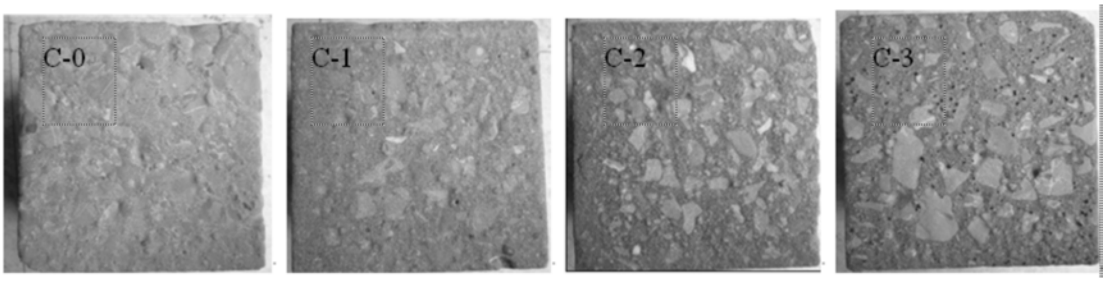


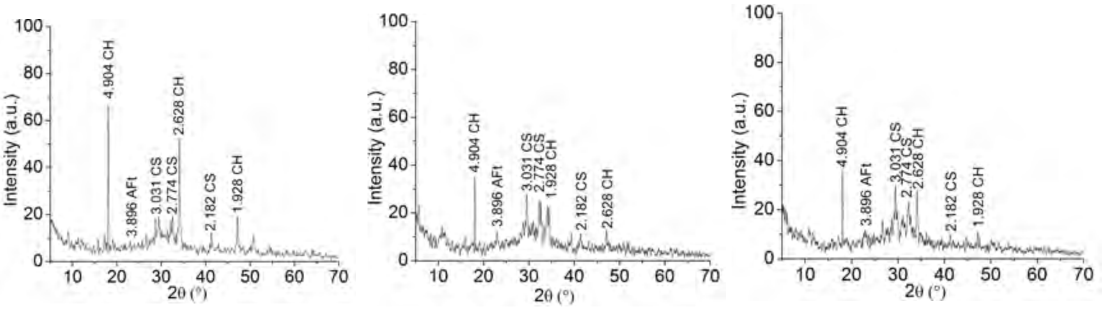
Fig. 5. Picture of Specimens after Abrasion

Influence of Different Components on Elastic Modulus of Concrete

The results of elastic modulus are presented in Table 4. It can be seen that the elastic modulus of concrete was improved with incorporation of NS or SS, or both, which proved the improvement of concrete brittleness. The elastic modulus of NS concrete was lower than SS concrete, indicating that the deformation performance of NS concrete was better than SS concrete, and this may account for the phenomenon that the abrasive strength of NS concrete was higher than that of SS concrete. The elastic modulus of RP-SS concrete was much lower than SS concrete, indicating that RP can offset the brittleness increment of concrete with SS.

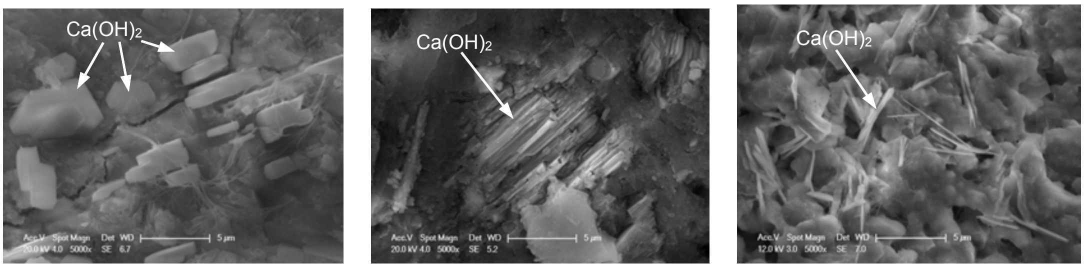
Mechanism of Different Components to Improve the Performance of Concrete

According to Sobolev et al. [2009], the role of nanoparticles can be summarized in four aspects: nanoparticles act as fillers in the empty place; well distributed nanoparticles act as crystallization centers of hydrated products increasing hydration rate; nanoparticles assist towards the formation of small in size $Ca(OH)_2$ crystals and homogeneous clusters of C-S-H composition; nanoparticles improve the structure of the transition zone between aggregate and paste. Fig.6 shows the XRD patterns of pastes of the three hydrated cementitious systems. It can be seen that the $Ca(OH)_2$ diffraction peak intensity was significantly reduced with the addition of NS and SS. It might suggest that due to the generation of calcium silicate hydration by reaction of amorphous silica with calcium hydroxide, the $Ca(OH)_2$ was significantly consumed. Fig.7 presents typical crystalline $Ca(OH)_2$ SEM images of pastes of the three hydrated cementitious systems. The $Ca(OH)_2$ crystal shown in Fig.7(a) was well crystallized with a hexagonal platelike structure and an obvious orientation. The $Ca(OH)_2$ crystal shown in Fig.7(b) was incompletely crystallized with a tightly stacked layered structure. The $Ca(OH)_2$ crystal shown in Fig.7(c) was small sized and randomly arrayed with a layered structure. It might suggest that NS and SS can decrease the size of $Ca(OH)_2$ crystal and its orientation as well, and thus decrease the disadvantage influence of $Ca(OH)_2$ crystal to concrete strength.



(a) C (b) C+5%NS (c) C+40%SS

Fig.6. XRD Patterns of Cement Paste Cured for 28



（a）C （b）C+5%NS （c）C+5%SS

Fig. 7. CH Morphology of Cement Paste Cured for 28d

At present, the mechanism of improvement of abrasion resistance of RP concrete is still not thorough enough. Some scholars think that replacement of sand with RP can reduce the porosity in the paste and thus increase the density. With the bonding function of the paste, RP together with the periphery of the pore formed a structure distortion center which have certain strength and can not only constrain the formation and development of microcracks but also absorb strain energy, resulting in decrement of paste rigidity. As a result, the energy absorption capacity of the paste during impact increases and the impact resistance of the paste increase [Li and Wang 2010]. Some scholars have different opinion that due to characterization of high toughness and strong impact energy absorption capacity, RP is exposed after abrasion, so that the exhibition of high abrasion resistance is observed [Fun 2010].

CONCLUSION

NS, SS and RP all improved the abrasion resistance of concrete while they have different effect on compressive strength. The addition of NS and SS improved the compressive strength but the addition of RP decreased it. These findings illustrated that the abrasion resistance of concrete was not only related to the compressive strength but also the toughness.

NS and SS improved the strength of the paste and the paste-aggregate interface so as to make the failure modes of the concrete different with the reference concrete under compression and abrasion. The composition and microstructure of the paste explained the mechanism why NS and SS could improve the performance of concrete.

SS combining RP could not only improve the strength of the concrete, but also the toughness. The findings of this study provided a reference for the design of concrete with high-strength and low-elastic modulus and a support for the design of mixed proportion of concrete which operates under the abrasion and impact conditions.

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