Research Article

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Bending resistance of PVA fiber reinforced cementitious composites containing nano-SiO₂

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Abstract: In this study, the effects of polyvinyl alcohol (PVA) fiber content and nano-SiO₂ (NS) on bending resistance of cementitious composites were investigated including bending strength and toughness. PVA fiber contents from 0.6% to 1.5% were added in the composites. The NS contents was 0% and 2% by mass. The water to binder ratio (w/b) was 0.38 for all composites. The specimens were cured for 28 days under 20°C and relative humidity of 95% before bending test. The results show that the bending strength was improved with PVA fiber content increasing and the maximum bending strength was obtained at PVA fiber content of 1.5%. Although PVA fiber increased bending resistance regardless of NS addition, the optimal content was 1.2%. When the fiber content was less than 1.2%, the bending resistance of cementitious composites increased with fiber content. However, the toughness began to decrease as PVA fiber content increased from 1.2 % to 1.5%. 2% NS addition decreased both bending strength and toughness due to the fact that NS was prone to self-desiccation and flock together, resulting in micro crack and strength loss.

Keywords: PVA fiber reinforced composite, nano-SiO₂, bending test, toughness

1 Introduction

The biggest challenges of traditional cementitious composites are low ductility and high fracture risk which have brought many limitations in their structural applica-

tions [1, 2]. A variety of researches have been carried out to investigate the performance and advantages of fiber reinforced composites in the last few decades. The commonly used fibers in cementitious composites include steel, glass, polyethylene, polypropylene, polyvinyl alcohol, polyester, aramid and natural plant [3–10], among which polyvinyl alcohol (PVA) fiber is one of the most popular and widely studied fibers in research to improve ductility and reduce the propagation rate of cracks [11]. The mechanism of PVA fiber is mainly to reduce stress concentrations on internal defects of cementitious composites leading to an increase in toughness and ductility [12]. Yu *et al.* studied the tensile behavior of PVA reinforced concrete. Their concretes had enhanced tensile stress and strain capacities because PVA fiber increased toughness [13]. Cadoni *et al.* found that PVA fiber addition noticeably reduced fracture energy and improved tensile strength and tensile strain capacity [14] using a dynamic tensile test. Haskett *et al.* concluded that after adding PVA fibers, the crack amount in compression zone of concrete was effectively reduced [15]. Even after cracking, PVA fiber reinforced composites exhibited strain hardening behavior due to the bridging effect of fibers [16]. Ling *et al.* conducted an investigation on flexural bending behavior of PVA fiber reinforced cementitious composites. Their observation showed that bending strength and toughness were significantly increased by adding PVA fiber up to 1.5% volume content [17]. Many researchers have confirmed that fiber content greatly affects bending resistance of cementitious composite. Atahan *et al.* addressed that fiber volume content between 0.5% and 2.0% considerably improved flexural behavior of cementitious composites [18]. High amount of PVA fiber increased bending resistance and durability of composites [19, 20].

However, a large number of studies have pointed that PVA fibers can be easily pulled out under bending due to low bond strength between matrix and fibers which weakens its bridging effect. Especially for the cementitious composites containing fly ash, low reaction rate of fly ash hurt the interfacial bond strength between cementitious matrix and PVA fibers [21]. The failure mode of fibers under bending load consists of pullout with slight abrasion, surface abrasion and a partially peeled end [22]. Similar

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Table 1: Composition of cement and fly ash

Composition (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃
Cement	21.05	5.28	2.57	63.14	3.58	0.17	0.58	2.39
Fly ash	52.12	17.86	6.57	9.12	3.26	2.38	2.05	0.23

Table 2: Physical properties of PVA fiber

Specific gravity	Dry fracture elongation (%)	Fiber length (mm)	Fiber diameter (μm)	Tensile strength (MPa)	Water absorption (%)	Melting point (°C)
1.32	15	9	20	1400	<1	220

occurrence of pullout PVA fibers was also found in fly ash geopolymer composites [23]. Such reduction in bond strength is also related to the increased porosity of composites induced by PVA fibers [23, 24]. Therefore, it is critical to find a solution for reducing porosity and improving bond strength between cementitious matrix and PVA fibers in order to enhance the bridging effect of PVA fibers in cementitious composite.

The use of nanoparticles in the concrete has been increasing in decades. Previous study results indicated that nano-SiO₂ (NS) could significantly enhance strength and durability of concrete as an additive as a cementitious material due to their effects on hydration acceleration and microstructure evolution [25–27]. This improvement in concrete performance is not only attributed to its filler effect and its pozzolanic reaction, but also related to its larger surface area, which speeds up the rate of cement hydration and pozzolanic reactions [28]. Gonzalez *et al.* added NS to increase the compressive strength and durability of concrete [29]. A study from Zhang *et al.* found that 2% nanoparticles in cementitious composite noticeably promoted compressive and bending strength [30] which was associated with the filling effect in voids and between unreacted particles to decrease total porosity of the system [31, 32]. Sikora *et al.* used nano-Fe₃O₄ in cementitious composites to greatly improve the microstructure of cementitious composites and decrease the porosity, thus increasing density of the composites [33]. Li *et al.* put forward that the addition of nanoparticles significantly promoted bending resistance, microstructure and ductility of cementitious composites [34]. In addition, NS has been found that it can substantially enhance the bond strength in cementitious composites due to the nanometer effects [35–38]. Therefore, understanding the effects of nanoparticles on bending resistance of PVA fiber reinforced composite is important to evaluate bond strength between cementitious matrix and PVA fibers. Relative studies on the bend-

ing resistance of such composites containing NS are very limited.

Although many researches have been conducted on the bending resistance of PVA fiber reinforced cementitious composites or NS reinforced cementitious composites, the studies on the bending resistance of cementitious composites simultaneously added with PVA fiber and NS were still in lack. In present study, NS were adopted to manufacture the PVA reinforced cementitious composites. A bending test was performed on the composites containing NS with various PVA fiber contents. The effects of varied PVA fiber contents and NS addition on bending properties of cementitious composites were investigated. The recommended dosages of PVA fiber and NS particles in cementitious composite were also provided based on the experimental results.

2 Experiments

2.1 Materials

A Portland cement with 3.13 specific gravity and 3266 cm²/g specific surface was specified as P.O42.5 [39]. The low calcium fly ash complied as first grade in GB/T 1596-2017 [40] with 2.13 specific gravity and 2464 cm²/g specific surface. Table 1 presents the chemical composition of cementitious materials (cement and fly ash). Table 2 lists the physical properties of PVA fiber. Nano-SiO₂ (NS) from Hangzhou Wanjiang New Material Co. LTD were employed as nanoparticles in this study, and their properties are shown in Table 3. The workability of fresh mixtures was adjusted using a high range water reducing admixture with its properties provided in Table 4. The sand had grain size within 212–380 μm.

Table 3: Basic properties of nanoparticles

Nano particles	Average size (nm)	Content (%)	Specific surface (m ² /g)	Bulk density (g/cm ³)	PH
SiO ₂	30	99.5	200	0.055	6

Table 4: High range water reducing admixture properties

Specific gravity	Alkali Content (%)	PH	Chloride ion content (%)	Effective rate (%)
1.06	1.2	4.62	0.078	22.0

Table 5: Mixture proportions of composites

Mixture	Cement (kg/m ³)	Fly ash (kg/m ³)	NS (kg/m ³)	PVA fiber (%)	Sand (kg/m ³)	Water (kg/m ³)	High range water reducing admixture (kg/m ³)
P0.6	650	350	0	0.6	500	380	3
P0.9	650	350	0	0.9	500	380	3
P1.2	650	350	0	1.2	500	380	3
P1.5	650	350	0	1.5	500	380	3
P0.6-N	630	350	20	0.6	500	380	3
P0.9-N	630	350	20	0.9	500	380	3
P1.2-N	630	350	20	1.2	500	380	3
P1.5-N	630	350	20	1.5	500	380	3

Note: All mixtures are named as P or P-N, where P is PVA fiber content and N is NS.

2.2 Mixture proportions

Based on the study from Yew *et al.*, the recommended dosage of PVA fiber in concrete materials is from 0.1% to 3.0% [30]. Therefore, in this study, Six volume contents of PVA fiber (0.6%, 0.9%, 1.2% and 1.5% of composite) were respectively added to the cementitious composites with 0% and 2% NS by mass of binder (cement, fly ash and NS). In total, 8 cementitious composite mixtures were prepared with 0.38 w/b and 2 binder to sand ratio (b/s). Mixture proportions are presented in Table 5.

2.3 Experimental methods

2.3.1 Mixing

A laboratory Hobart mixer was used to mix the fresh cementitious composites in accordance with ASTM C305 [41]. A dry mixing with silica sand, cement, fly ash and nanoparticles was first proceeded for 2 min. Secondly, one in three water with half high range water reducing admixture was introduced and agitated for 60 seconds. Next, another third of water along with the rest high range water reducing admixture was added and mixed for 60 seconds. Then

last third of water was added and stirred for 60 seconds. At last, PVA fibers were evenly quadripartite and respectively mixed with the mixture for 2.5min. Before engineering property tests, all cast specimens were demolded in 24 hours and have 28-day curing of 20°C and 95% relative humidity.

2.3.2 Bending test

A four-point bending test was carried out on a beam specimen to evaluate bending behavior of the cementitious composite as illustrated in Figures 1 and 2. For each mix, three beams with a dimension of 400mm×100mm×100mm were cast and the reported result was the average of three specimens. To perform the test, the tested beam was simply supported with a support span of 300 mm as illustrated in Figure 1. Two bending loads were applied symmetrically at 100 mm from the supports using a loading machine. The loading span was one-third of the support span. One LVDT was installed on the side of beam to monitor the mid-span deflections of the beam as seen in Figure 1. In accordance with JG/T 472-2015 [42], the loads were applied at a rate of 30 N/s until specimen failed. The bending stress in the

Figure 1: Data collection of bending test

Figure 2: Testing apparatus of bending test

tested slab was calculated according to Eq. (1):

$$f = \frac{FL}{bd^2} \quad (1)$$

Where f is bending stress; F is the load; L is the length of the support span; b is the width of slab and d is thickness of slab.

Figure 3: A typical curve of load vs. mid-span deflection

2.3.3 Evaluation of bending resistance

A typical load vs. mid-span deflection plot was presented in Figure 3. The entire fracture process can be separated to three phases: OA, AB and BC. In OA, matrix and PVA fiber are bearing load together. The specimen behaves elastically. Deflection is changing linearly with load. As load increases, the deformation of tensile zone of the cement matrix composites will reach the material's initial crack strain, and cracks begin to appear. At point A, traditional cement composites fracture immediately, while PVA fiber reinforced composites exhibit deflection hardening behavior, i.e. load keeps going up with deflection increasing until peak load (point B), which is due to bridging effect of PVA fibers. In AB, cracks in specimen propagate stably. The relationship between load and deflection is non-linear, and the specimen is elastic-plastically deforming. Point B is the critical point of crack instable propagation, which reaches the ultimate load of the specimen. In BC, with PVA fibers fractured or pulling out, the specimen eventually fractures at point C.

In JG/T 472-2015 [42], bending resistance parameters are presented in a typical load-deflection (F - δ) curve (Figure 4). δ_p is the deflection at peak load and δ_k is the given deflection.

Initial flexural toughness ratio ($R_{e,p}$) and flexural toughness ratio ($R_{e,k}$) were used to characterize the bending resistance before peak load and the bending resistance after peak load respectively. $R_{e,p}$ can be determined by Eq. (2) and Eq. (3)

$$R_{e,p} = f_{e,p}/f_{ftm} \quad (2)$$

$$f_{e,p} = \frac{\Omega_p L}{bh^2 \delta_p} \quad (3)$$

Figure 4: Bending resistance parameter calculation

Where $f_{e,p}$ (MPa) is equivalent bending strength at peak load; b (mm) is width of beam; h (mm) is thickness of beam; L (mm) is support span; δ_p (mm) is deflection of peak load; Ω_p (N·mm) is area under load-deflection curve before peak load; f_{ftm} (MPa) is bending strength of specimen.

While $R_{e,k}$ is expressed as Eq. (4)-Eq. (6)

$$R_{e,k} = f_{e,k} / f_{ftm} \quad (4)$$

$$f_{e,k} = \frac{\Omega_{p,k} L}{b h^2 \delta_{p,k}} \quad (5)$$

$$\delta_{p,k} = \delta_k - \delta_p \quad (6)$$

Where δ_k (mm) is the given deflection L/k , $k=500, 300$ mm; $f_{e,k}$ (MPa) is equivalent bending strength at deflection of δ_k ; $\delta_{p,k}$ (mm) is the increment from δ_p to δ_k ; $\Omega_{p,k}$ (N·mm) is the area under load-deflection curve from δ_p to δ_k . The average of three duplicates was reported in this paper.

3 Results and discussion

3.1 Bending behavior

Figure 5 presents the relationships of load and mid-span deflection for composites with different PVA contents. It implies that irrespective of NS addition, a significant increment in ductility and toughness (area under curve) was achieved by increasing PVA content. This tendency is associated with that PVA displayed bridging effect by taking partial load on composite matrix which restrained crack development and sudden failure of specimen [43]. PVA content did not impact bending strength very much.

Figure 6 depicts the load vs. mid-span deflection for the NS composites with different PVA contents. Similar as those composites without NS, the ductility and toughness

Figure 5: Load vs. mid-span deflection for composites with different PVA contents

Figure 6: Load vs. mid-span deflection for NS composites with different PVA contents

of the composites containing NS also greatly increased with PVA content increasing from 0%-1.5%. Comparing Figure 5 and Figure 6, NS addition conversely reduced flexural leak load of composites. This is because too much NS was prone to self-desiccation, leading to micro crack in composite [44].

In summary, PVA fibers play a significant role in bridging microcracks when applied to cementitious composites, and the bond strength between the cementitious matrix and PVA fibers has a certain anti-cracking effect. Besides, the disordered PVA fibers distributing in three dimensions could form a structural support inside the composites which improved bending strength. Under the loads, microcracks appeared with high stress concentration on crack tip. When the crack tip reached PVA fibers, PVA fibers inhibited the propagation of the cracks, since PVA fiber had much larger strength and size than the matrix and the crack tip respectively [45]. Consequently, with an appropriate content, the addition of PVA fibers remarkably improve the flexural properties of the composites containing NS.

Figure 7: Initial flexural toughness ratio ($R_{e,p}$) of composites with different PVA fiber contents

Figure 8: Flexural toughness ratio ($R_{e,500}$) of composites with different PVA fiber contents

Figure 9: Flexural toughness ratio ($R_{e,300}$) of composites with different PVA fiber contents

However, if its content was too high, PVA fibers themselves increased the amount of microcracks and cause dun expected defects inside the composites. Therefore, PVA fiber content more than 2% decreased bending strength and resistance of the cementitious composites containing NS.

Figure 10: Initial flexural toughness ratio ($R_{e,p}$) of NS composites with different PVA fiber contents

Figure 11: Flexural toughness ratio ($R_{e,500}$) of NS composites with different PVA fiber contents

Figure 12: Flexural toughness ratio ($R_{e,300}$) of NS composites with different PVA fiber contents

3.2 Bending resistance

The flexural toughness ratios along with PVA fiber contents are shown from Figures 7-12 for both composites with-

Table 6: Summary of bending parameters

Mix	$f_{e,p}$ (MPa)	$R_{e,p}$	$f_{e,500}$ (MPa)	$R_{e,500}$	$f_{e,300}$ (MPa)	$R_{e,300}$
P0.6	4.16	0.76	3.41	0.62	1.56	0.28
P0.9	4.29	0.77	3.93	0.71	1.97	0.36
P1.2	4.96	0.85	4.54	0.78	2.21	0.38
P1.5	5.28	0.83	4.74	0.74	2.02	0.32
P0.6-N	3.18	0.70	3.14	0.70	1.27	0.28
P0.9-N	3.46	0.74	3.35	0.72	1.76	0.38
P1.2-N	3.99	0.81	3.79	0.77	2.16	0.44
P1.5-N	4.48	0.74	4.48	0.74	2.33	0.39

out and with NS. As shown in Figures 7-9, without NS addition, all flexural toughness ratios ($R_{e,p}$, $R_{e,500}$, and $R_{e,300}$) were significantly increased when PVA content altered from 0% to 1.2%, while they declined at 1.5% PVA. This trend indicates that PVA fiber could considerably improve bending resistance and its improvement on bending resistance after peak load was much higher than that before peak load. Coincident findings were obtained on the cementitious composites with NS. This is associated with the fact that the bond between PVA and composites was taking partial load until PVA was fractured or pulled out from the matrix. Moreover, the bridging effect of PVA fibers inhibited the crack propagation which reduced the stress concentration on tip of crack [43]. Comparing with 0.6%, 1.2% PVA addition increased $R_{e,p}$, $R_{e,500}$, and $R_{e,300}$ by 11.8%, 25.8% and 35.7% respectively for the composites without NS, and 15.7%, 10.0% and 57.1% respectively for the composites with NS. However, for the excessive PVA fiber addition (1.5%), the flexural toughness ratios were decreased due to non-uniform distribution of PVA fibers caused in matrix [23, 46]. Such phenomenon is related to the agglomeration of PVA fibers leading to an increase in porosity which weakened the bond strength between PVA fibers and cementitious matrix [46]. It should be noted that the addition of NS did not noticeably increase the flexural toughness ratios. Its reason needs further investigation.

The bending resistance parameters are summarized in Table 6. It can be concluded that the bending strengths ($f_{e,p}$, $f_{e,500}$ and $f_{e,300}$) were improved by adding PVA fibers up to 1.5%, regardless of NS. This improvement in bending strength was due to the linkage created by PVA which enhanced the strength in tensile zone [47]. Overall, in comparison of 0.6%, 1.5% PVA addition increased $f_{e,p}$, $f_{e,500}$, and $f_{e,300}$ by 26.9%, 39.0% and 29.5% respectively for the composites without NS, and 40.9%, 42.7% and 83.5% respectively for the composites with NS. The optimum PVA fiber volume content for toughness was 1.2%. However, 2% NS addition slightly reduced bending strengths. Ide-

ally, the particle size of NS is smaller than cement, which can effectively improve the interfacial structure properties. NS can also react with Ca(OH)_2 to form CaSiO_3 , which has filling action and improve the microstructure inside the composites. Consequently, the bonding force between PVA fibers and the matrix should be strengthened [45]. In fact, the excessive NS tends to flock together and reduces strength because of large molecular force [48] implying that 2% was beyond the optimum content for NS addition in cementitious composites.

4 Conclusions

In this paper, the bending resistance of PVA fiber reinforced cementitious composites with NS addition was systematically investigated. The effects of PVA fiber content and NS addition on bending resistance of the cementitious composites were initially evaluated. The following conclusions were drawn according to experimental results:

1. The bending strength was considerably enhanced with PVA fiber content increasing (0.6-1.5% by volume) and the maximum bending strength was obtained at PVA fiber content of 1.5%.
2. Although PVA fiber significantly improved bending resistance regardless of NS addition, there was an optimum PVA content of 1.2% by volume to achieve the maximum toughness and ductility. When the fiber content was less than 1.2%, the bending resistance of cementitious composites increased with fiber content. However, the toughness began to decrease as PVA fiber content increased from 1.2 % to 1.5%.
3. 2% NS addition was too excessive to increase both bending strength and toughness because NS was prone to self-desiccation and flock together, leading to micro crack and strength loss in composite. An

NS dosage lower than 2% was recommended to improve bending strength and toughness, as well as the bond strength between cementitious matrix and PVA fibers.

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