WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.146093

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 3 2023

pp. 491 –506

Research paper

Flexural performance of hybrid fiber reinforced cement-based materials incorporating ceramic wastes

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Abstract: Ceramic waste generated by demolition and manufacturing processes is a kind of widely discharged solid waste; its sustainable use can reduce resource extraction, energy consumption, and carbon emissions, thereby reducing the environmental impact. In this study, ceramic powder and ceramic sand were prepared using waste ceramic wall tiles. By using three water-to-binder ratios of 0.30, 0.32, and 0.34, five ceramic powder replacement rates of 10% to 50%, and completely using ceramic sand as the fine aggregate, specimens with large differences in mechanical properties were prepared. Firstly, the compressive strength was investigated. On this basis, hybrid fibers were employed to strengthen the new matrix material, and its bending resistance was experimentally studied. It was found that the incorporation of ceramic powder reduced the compressive strength of the matrix. The water-binder ratio significantly affects compressive strength at an early age. The effect of PVA fiber on improving the ductility of the new composite is distinct. Increasing the amount of steel fiber can effectively enhance the bending bearing capacity. With a ceramic powder dosage of 50%, the new composite has shown ductile failure characteristics, even with low total fiber content. The bending properties of this new composite material, which makes extensive use of ceramic waste, are well adjustable. The bearing capacity and ductility balance can be achieved with the steel fiber content of 1% and the PVA fiber content of 1.2% to 1.50%.

Keywords: cement-based materials, ceramic wastes, mechanical performance, PVA fiber, steel fiber

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1. Introduction

Cement-based material is a kind of quasi-brittle material. The approach of incorporating fibers into the matrix to improve crack resistance and toughness was proposed at the beginning of the 20th century [1–3]. Fiber-reinforced materials have been widely used in structural strengthening and new construction [4–6]. The use of fiber can effectively reduce the crack width under load. Considering that the permeability coefficient of cement-based material is proportional to the third power of the crack width, the reasonable use of fiber can effectively enhance durability [7, 8]. The safety and durability of engineered cementitious composites (ECC) can be further improved due to their unique multiple microcracking and strain-hardening characteristics [9, 10]. Common fiber-reinforced cementitious materials mostly use one type of fiber. By incorporating fine and short steel fiber, the tensile strength and compressive strength of reactive powder concrete (RPC) can be effectively improved [11]. The use of PVA fibers enables ECC to achieve excellent ductility [12]. Since a single variety of fiber can only play a bridging role in a limited crack width, researchers have begun to try to mix fibers with different mechanical properties and sizes in order to optimize the performance of composite materials. According to the strengthening mechanisms, the current hybrid methods can be mainly divided into three categories [13, 14]: (1) hybridization based on fiber size: the fiber of a smaller size bridges microcracks at the beginning of loading, controls crack development, delays crack penetration, and improves material strength; the other fiber of a larger size bridge macroscopic cracks, thereby improving the toughness of the material; (2) hybridization based on fiber constitutive relationship: fiber with a higher strength and stiffness controls cracking strength and ultimate strength; the other fiber with relatively better flexibility and ductility improve the deformation ability and toughness of the composites; (3) hybridization based on fiber function: one fiber is used to improve the properties of the fresh mixture (such as fluidity, plastic shrinkage, etc.), while the other fiber mainly enhances the mechanical properties of the hardened mixture.

Incorporating an appropriate amount and certain fineness of industrial wastes, such as fly ash, silica fume, slag, etc., can improve the internal compactness, crack resistance, and resistance to chloride intrusion of concrete-like materials [15]. In the meantime, the amount of cement needed is reduced, which can save resources and energy and reduce carbon emissions. Ceramic waste is a relatively new type of solid waste that cannot degrade naturally. More than 10 billion tons of ceramic waste is discharged annually [16], and its reuse is of common interest in academia and engineering. Ceramic wastes can be collected in the production of bricks, roof tiles, wall and floor tiles, sanitary wares, et al. Currently, the utilization of ceramic wastes in many countries is still a big challenge. Relevant sectors are encouraging the use of solid waste, including ceramic waste. However, the existing knowledge and technology are insufficient to realize this vision. Ceramic wastes can be used as a partial replacement for Portland cement or as aggregates in cement-based materials production [17–19]. Regarding the mechanical properties of concrete, the compressive strength of ceramic aggregate concrete is better than that of conventional concrete, even if ceramic wastes have the disadvantages of low density and high water absorption [20]. The compressive strength of mortar incorporating ceramic sand was improved with increasing ceramic aggregate content [21]. Despite using ceramics to replace 50%, 75%, and 100% of the aggregate by weight, the mechanical characteristics were still satisfactory. In recent years, it has been realized that grinding ceramics into a certain fineness to replace Portland cement partially is another effective way to utilize ceramic wastes [22–25]. Mechanical strength generally decreases with the replacement rate of cement by ceramic powder [26, 27].

This research tried to use as many ceramic wastes as possible to prepare the matrix to obtain a new kind of environmentally friendly fiber-reinforced cementitious material. First, a new type of mortar mix was designed through various cement replacing rates with ceramic powder and completely using ceramic sand instead of ordinary river sand. Next, the effects of age, ceramic powder dosage, and water-binder ratio on the compressive performance of this cement-based material were investigated. Then a hybrid fiber system was introduced using polyvinyl alcohol fiber (PVA) and steel fiber and added to the cement-based material matrix containing ceramic wastes. Finally, the four-point bending test was carried out to investigate the bending characteristics of this new composite.

2. Raw materials and mix proportion

2.1. Raw materials

The cement used was Portland cement with a strength grade of 42.5, complying with the Chinese National Standard GB 175-2007 (equivalent to European CEM I 42.5). The early strength was tested at three days, and the standard strength was tested at 28 days. These strengths were determined in accordance with Chinese National Standard GB/T 17671-2020 (equivalent to EN 196-1) and were provided by the manufacturer (Fushun Cement Co., Ltd). A ceramic powder made from demolished ceramic wall tiles was used as the supplementary cementitious material. Photos and SEM images of cementitious materials used are shown in Fig. 1.

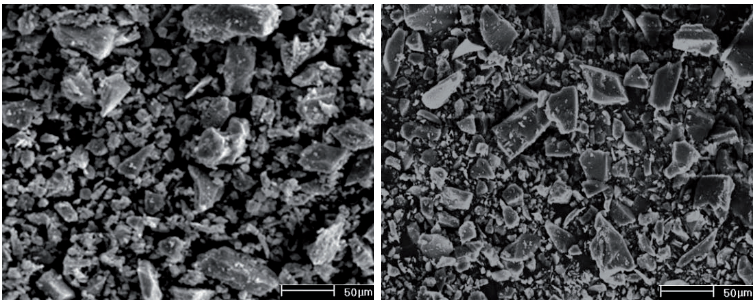
The particle size of cementitious materials was tested by a laser diffraction analyzer, and the testing results were shown in Fig. 2. The overall fineness of cementitious materials is close, and the particle size of ceramic powder is somewhat smaller, and the fine powder content is slightly higher. The distribution of ceramic powder particles is more concentrated than that of cement particles, mainly concentrated in the vicinity of 10 µm, while cement particles are primarily concentrated around 45 µm.

The chemical composition of binders was investigated by a BRUKER S4 Explorer utilizing X-Ray Fluorescence Spectroscopy, see Fig. 3.

The measured chemical compositions of ceramic powder and Portland cement are shown in Table 1.

The physical properties of cement are provided by the manufacturer and are shown in Table 2. The test method meets the Chinese national standard GB175 (comply with ASTM C150/C150M).

(a) Left: cement; right: ceramicpowder



(b) Left: cement; right: ceramicpowder

Fig. 1. Photo (a) and SEM images (b) of cementitious materials used

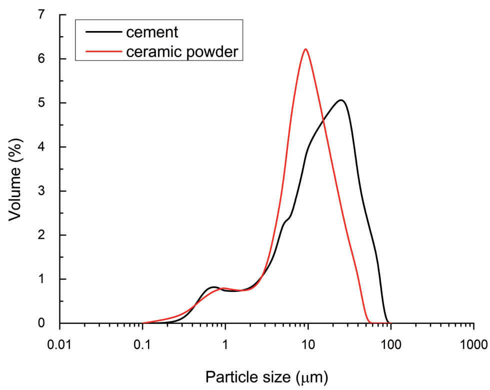


Fig. 2. Particle size distribution of cementitious materials

Fig. 3. X-Ray Fluorescence Spectroscopy tester(BRUKER S4 Explorer)

Table 1. Chemical composition of cementitious materials (%)

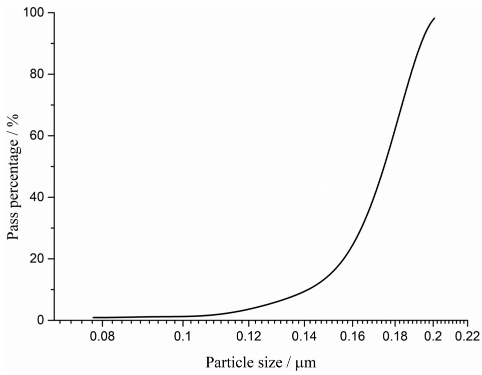
Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl^-
Ceramic powder	68.26	17.10	0.76	1.55	1.41	–	2.20	2.01	0.06
Portland cement	20.58	4.97	3.76	63.57	2.29	2.00	0.53	0.75	0.026

Table 2. Physical properties of Portland cement used

Specific surface (m^2/kg)	Density (g/cm^3)	Time of setting by Vicat needle (min)		3 d compressive strength of cement mortar (MPa)
		Initial	Final	
355	3.12	99	158	27.0

Crushed ceramic sized 0.075 mm ~0.2 mm was used as fine aggregate. The photo and particle size distribution of ceramic sand are shown in Fig. 4.

(a) photo

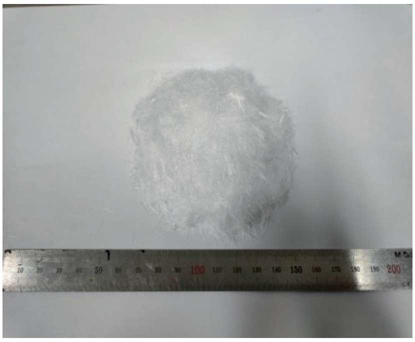


(b) particle size distribution

Fig. 4. Photo and particle size distribution of crushed ceramic sand used

PVA fiber morphology is shown in Fig. 5a, and the mechanical properties of PVA fiber are shown in Table 3. Copper-coated microwire steel fibers were used in this study, and the morphology is shown in Fig. 5b.

Both the PVA fibers and steel fibers are produced by Shandong Tongying New Materials Co., Ltd., and their physical and mechanical properties are also provided by the company. The properties of fibers are listed in Table 3 for comparison.



(a) short cut polyvinyl alcohol fibers

(b) fibers copper-coated microwire steel

Fig. 5. Fiber morphology

Table 3. Physical properties of PVA and steel fibers

Project	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation at break (%)	Length (mm)
PVA fibers	1.20	1200	50	15-17	6
Steel fibers	7.81	2750	206	6.0-8.0	13

2.2. Mix proportions and specimen preparation

2.2.1. Mix proportions

To investigate the effect of replacing rate of cement with ceramic powder on the compressive strength of the mortar specimen, five groups of ceramic powder replacement (by mass), 10%, 20%, 30%, 40%, and 50%, were selected, and a control mix without ceramic powder was also employed. Three water-binder ratios of 0.30, 0.32, and 0.34 were adopted. The sand-to-binder ratio of strain-hardened cementitious composites is generally between 0.3–0.9. Considering that the water absorption of crushed ceramics is higher than that of river sand or quartz sand, from the perspective of workability, the sand-to-binder ratio was taken as 0.25. The mix design of mortars for compressive strength testing is listed in Table 4.

Table 4. Mix proportions of mortar

Mixture	Proportions by weight (cement: ceramic powder: ceramic sand: water)	Water/binder ratio	Cement replacement ratio
I-F0	1.0:0:0.25:0.30	0.30	0%
I-F1	0.90:0.10:0.25:0.30	0.30	10%

Continued on next page

Table 4 – *Continued from previous page*

Mixture	Proportions by weight (cement: ceramic powder: ceramic sand: water)	Water/binder ratio	Cement replacement ratio
I-F2	0.80:0.20:0.25:0.30	0.30	20%
I-F3	0.70:0.30:0.25:0.30	0.30	30%
I-F4	0.60:0.40:0.25:0.30	0.30	40%
I-F5	0.50:0.50:0.25:0.30	0.30	50%
II-F0	1.0:0:0.25:0.32	0.32	0%
II-F1	0.90:0.10:0.25:0.32	0.32	10%
II-F2	0.80:0.20:0.25:0.32	0.32	20%
II-F3	0.70:0.30:0.25:0.32	0.32	30%
II-F4	0.60:0.40:0.25:0.32	0.32	40%
II-F5	0.50:0.50:0.25:0.32	0.32	50%
III-F0	1.0:0:0.25:0.34	0.34	0%
III-F1	0.90:0.10:0.25:0.34	0.34	10%
III-F2	0.80:0.20:0.25:0.34	0.34	20%
III-F3	0.70:0.30:0.25:0.34	0.34	30%
III-F4	0.60:0.40:0.25:0.34	0.34	40%
III-F5	0.50:0.50:0.25:0.34	0.34	50%

To study the flexural strengthening effect of hybrid fibers, the volume fraction of steel fiber was set as 0.5% and 1.0%, while the volume fraction of PVA fiber was set as 0.6%, 0.9%, 1.2%, 1.5%, and 1.8%. The mix proportions of hybrid fiber-reinforced cement-based materials are shown in Table 5.

Table 5. Mix proportions of hybrid fiber-reinforced cement-based materials

Mixture	Proportions by weight (cement: ceramic powder: ceramic sand: water)	Cement replacement ratio	PVA fiber (vol.%)	Steel fiber (vol.%)
I-PVA0.6%-ST0.5%	1.0:0:0.25:0.32	0%	0.6	0.5
I-PVA0.6%-ST1.0%	1.0:0:0.25:0.32	0%	0.6	1.0
I-PVA0.9%-ST0.5%	1.0:0:0.25:0.32	0%	0.9	0.5
I-PVA0.9%-ST1.0%	1.0:0:0.25:0.32	0%	0.9	1.0
I-PVA1.2%-ST0.5%	1.0:0:0.25:0.32	0%	1.2	0.5
I-PVA1.2%-ST1.0%	1.0:0:0.25:0.32	0%	1.2	1.0
I-PVA1.5%-ST0.5%	1.0:0:0.25:0.32	0%	1.5	0.5

Continued on next page

Table 5 – *Continued from previous page*

Mixture	Proportions by weight (cement: ceramic powder: ceramic sand: water)	Cement replacement ratio	PVA fiber (vol.%)	Steel fiber (vol.%)
I-PVA1.5%-ST1.0%	1.0:0:0.25:0.32	0%	1.5	1.0
I-PVA1.8%-ST0.5%	1.0:0:0.25:0.32	0%	1.8	0.5
I-PVA1.8%-ST1.0%	1.0:0:0.25:0.32	0%	1.8	1.0
II-PVA0.6%-ST0.5%	0.70:0.30:0.25:0.32	30%	0.6	0.5
II-PVA0.6%-ST1.0%	0.70:0.30:0.25:0.32	30%	0.6	1.0
II-PVA0.9%-ST0.5%	0.70:0.30:0.25:0.32	30%	0.9	0.5
II-PVA0.9%-ST1.0%	0.70:0.30:0.25:0.32	30%	0.9	1.0
II-PVA1.2%-ST0.5%	0.70:0.30:0.25:0.32	30%	1.2	0.5
II-PVA1.2%-ST1.0%	0.70:0.30:0.25:0.32	30%	1.2	1.0
II-PVA1.5%-ST0.5%	0.70:0.30:0.25:0.32	30%	1.5	0.5
II-PVA1.5%-ST1.0%	0.70:0.30:0.25:0.32	30%	1.5	1.0
II-PVA1.8%-ST0.5%	0.70:0.30:0.25:0.32	30%	1.8	0.5
II-PVA1.8%-ST1.0%	0.70:0.30:0.25:0.32	30%	1.8	1.0
III-PVA0.6%-ST0.5%	0.50:0.50:0.25:0.32	50%	0.6	0.5
III-PVA0.6%-ST1.0%	0.50:0.50:0.25:0.32	50%	0.6	1.0
III-PVA0.9%-ST0.5%	0.50:0.50:0.25:0.32	50%	0.9	0.5
III-PVA0.9%-ST1.0%	0.50:0.50:0.25:0.32	50%	0.9	1.0
III-PVA1.2%-ST0.5%	0.50:0.50:0.25:0.32	50%	1.2	0.5
III-PVA1.2%-ST1.0%	0.50:0.50:0.25:0.32	50%	1.2	1.0
III-PVA1.5%-ST0.5%	0.50:0.50:0.25:0.32	50%	1.5	0.5
III-PVA1.5%-ST1.0%	0.50:0.50:0.25:0.32	50%	1.5	1.0
III-PVA1.8%-ST0.5%	0.50:0.50:0.25:0.32	50%	1.8	0.5
III-PVA1.8%-ST1.0%	0.50:0.50:0.25:0.32	50%	1.8	1.0

2.2.2. Specimen preparation

Specimens sized $70.7 \times 70.7 \times 70.7$ mm were used for compressive strength testing of the matrix. Cement, ceramic powder, and ceramic sand were weighed and added to a compulsory concrete mixer when preparing the specimen. After stirring for two minutes, water and an appropriate amount of superplasticizer were added and stirred for another two minutes. Finally, the upper surface of the specimen was wrapped with a plastic film to prevent water evaporation. The specimens were cured at room temperature for 24 h after preparation. After demolding, specimens were moved to a standard curing chamber for curing.

The size of the bending test specimen is 100×100×400 mm. After the matrix slurry was stirred well, the rotation speed of the mixer was reduced appropriately, and the fibers were slowly spread into the flowing slurry and stirred well to ensure that the fibers were evenly dispersed. After stirring for two minutes, the mixture was poured into 100 × 100 × 400 mm cast iron molds in two layers and vibrated to ensure compactness. After demolding, the specimens were moved to a standard curing chamber for 28 d curing.

3. Test and analysis

3.1. Compressive strength of the matrix

3.1.1. Test process

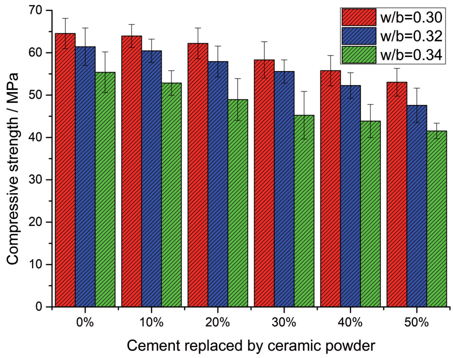
The testing age was set as 28 d, 84 d, and 180 d. The compression test was carried out on a YEW-2000 electro-hydraulic servo pressure testing machine manufactured by Jinan Shijin Testing Machine Co., Ltd. The compressive strength was measured using cube specimens following ASTM C109 standards. The displacement control mode was adopted, and the loading speed was 1 mm per minute. Three specimens were used for each mix ratio, and the average strength was collected.

3.1.2. Test results and analysis

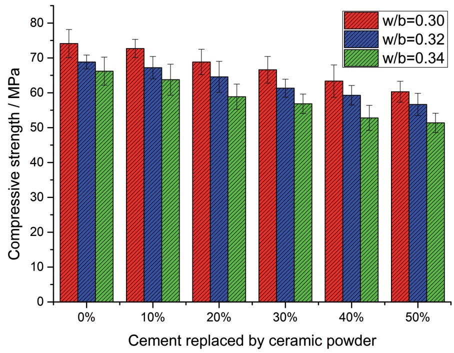
The compressive strength of mortars with different water-binder ratios and ages is plotted in Fig. 6.

It can be seen from Fig. 6 that the compressive strength of the specimens decreases with the increase of the water-binder ratio, and the 28 d compressive strength is most affected by the water-binder ratio. At the age of 28 days, the hydration degree of ceramic powder is deficient [26, 27]. Therefore, the water consumption is minimal, so the actual water-binder ratio of cement is larger than the nominal water-binder ratio. In the case of a high water-binder ratio, the compressive strength is more affected by the water-binder ratio. With the increase of age, the hydration degree of ceramic powder increases, and the actual water-binder ratio of cement gradually approaches the nominal water-binder ratio. At 180 days, the water-binder ratio had the least effect on the compressive strength. With the hydration of the cementitious material, the compressive strength gradually increases. In the scope of this study, the compressive strength improvement rate accelerates with the increase of the water-binder ratio.

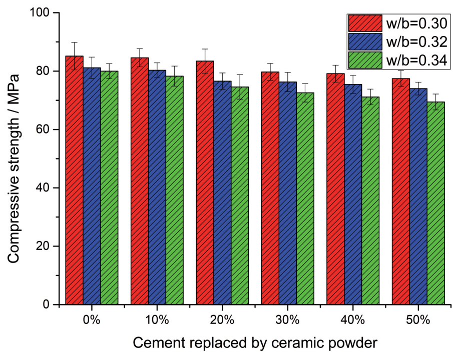
Fig. 6 also shows that the compressive strength of the specimen gradually decreases with the increase of the substitution rate of ceramic powder. Adding ceramic powder changes the internal structure of the cement mortar [27]. Taking specimens with a water-binder ratio of 0.32 as an example, the compressive strength of mortar with a ceramic powder substitution rate of 50% is 23.4% lower than that of Portland cement mortar at 28 d and 9% lower at 180 d. This is because the hydration rate of ceramic powder is slower than that of Portland cement, resulting in a lower strength at an early age [27]. In the later hydration stage, with the increase of age, the compressive strength has been improved to a certain extent due



(a) 28 d compressive strength



(b) 84 d compressive strength



(c) 180 d compressive strength

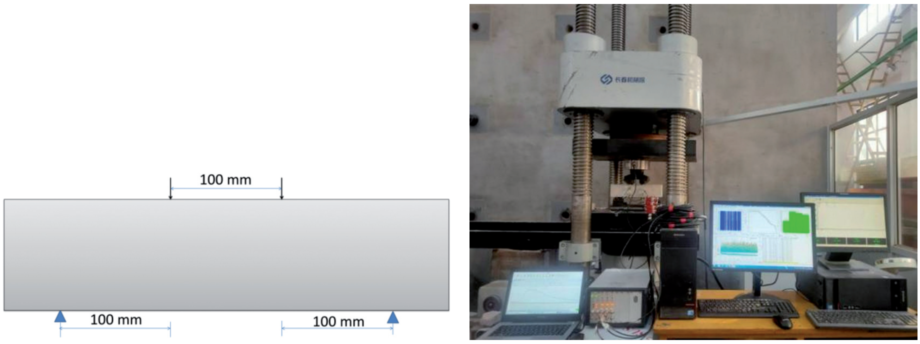
Fig. 6. The compressive strength of mortar contains ceramic wastes

to the combined effect of continuous hydration of cement and the pozzolanic reaction of ceramic powder. With the increase of the water-binder ratio, the influence of the ceramic powder content on the compressive properties of cement-based materials increases firstly and then decreases. The addition of ceramic powder has the slightest effect on cement-based materials with a water-binder ratio of 0.32.

3.2. Flexural performance test of hybrid fiber-reinforced beams

3.2.1. Experimental process

Four-point bending test was carried out on a YNS-Y3000 electro-hydraulic servo universal testing machine manufactured by Changchun Mechanical Research Institute Co., Ltd. Deflection Behavior test is based on ASTM C1609/C1609M-12. The displacement control mode with a loading rate of 1 mm per minute was adopted. The load diagram for the beam is shown in Fig. 7.

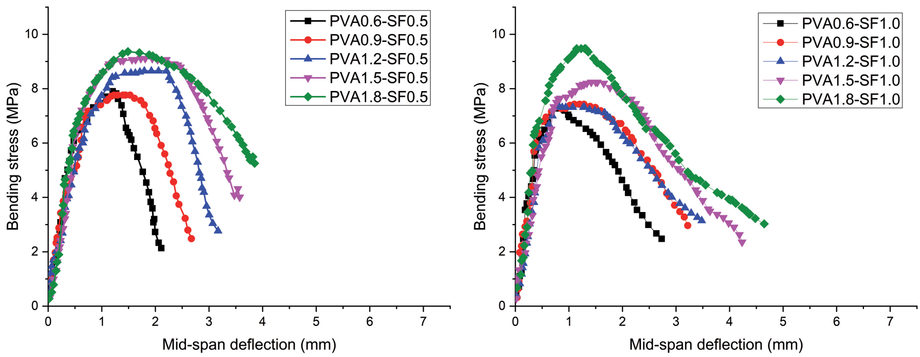


(a) Schematic (b) Photo

Fig. 7. Loading of a beam

3.2.2. Test results and analysis

Load-midspan deflection curves of hybrid fiber reinforced beams under four-point bending are shown in Figs. 8–10 (In each figure, (a) shows the steel fiber content of 0.5%, and (b) shows the steel fiber content of 1.0%).

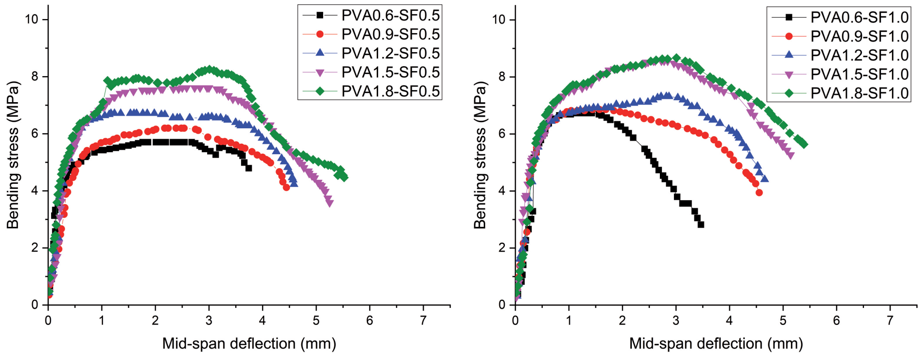


(a) ST-0.5% (b) ST-1.0%

Fig. 8. Flexural stresses versus midspan deflection curves of beams with 0% ceramic powder

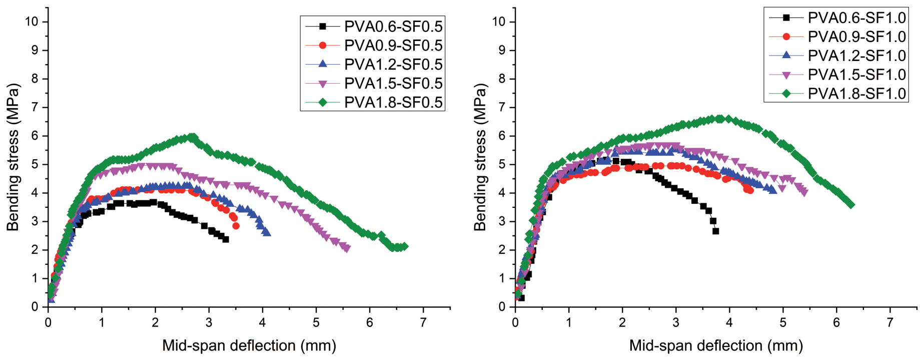
The specific values of flexural strength and midspan deflection of specimens are shown in Table 6.

It can be seen from Fig. 8 to Fig. 10 that with the increase of ceramic powder substitution, the bending capacity of the beams is significantly reduced; however, the midspan deflection increases considerably, reflecting the improvement of the deformation ability of beams. When the fiber content is low, such as PVA fiber of 0.6% and steel fiber of 0.5%, for the case of ceramic powder content of 50%, the flexural strength decreases from 7.95 MPa to 3.67 MPa (a 53.8% reduction). Increasing the ceramic powder content to 50% increases the ultimate deflection by more than 30% for all fiber contents in this study. By observing the



(a) ST-0.5% (b) ST-1.0%

Fig. 9. Flexural stresses versus midspan deflection curves of beams with 30% ceramic powder



(a) ST-0.5% (b) ST-1.0%

Fig. 10. Flexural stresses versus midspan deflection curves of beams with 50% ceramic powder

cross-sectional morphology after the failure of the beams, it is found that with the increase of ceramic powder content, the fibers lose their bearing function by pulling out rather than breaking. The amount of energy absorbed during fiber pulling is generally more substantial than the energy absorption in the case of fracture, and the effect on the ductility is also more apparent. Under the medium substitution rate of ceramics, when the fiber content is not too low (excluding steel fiber content of 0.5% and PVA fiber content of 0.6%), the flexural strength reduction value is less than 20%. In contrast, the deformation ability increase value is greater than 20%, and the beam's bending strength and deformation ability can achieve a better balance.

When the dosage of ceramic powder is high (50%), if the steel fiber content is low (such as 0.5%), the ultimate deflection of beams tends to increase with the increase of PVA fiber content. It can be seen from Table 6 that when the PVA fiber content is 0.6%, the maximum deflection of the beam is 3.34 mm; when the PVA fiber content rises to 1.80%, the ultimate

Table 6. Flexural strength and midspan deflection of specimens

Performance Metrics	0% Ceramic powder		30% Ceramic powder		50% Ceramic powder	
	Flexural strength / MPa	Maximum deflection / mm	Flexural strength / MPa	Maximum deflection / mm	Flexural strength / MPa	Maximum deflection / mm
PVA0.6-SF0.5	7.95	2.11	5.77	3.77	3.67	3.34
PVA0.9-SF0.5	7.84	2.70	6.24	4.47	4.10	3.51
PVA1.2-SF0.5	8.75	3.18	6.80	4.61	4.26	4.12
PVA1.5-SF0.5	9.09	3.59	7.68	5.26	4.94	5.55
PVA1.8-SF0.5	9.40	3.86	8.30	5.53	5.97	6.68
PVA0.6-SF1.0	8.02	2.75	6.75	3.48	5.20	3.75
PVA0.9-SF1.0	8.24	3.25	6.83	4.58	5.00	4.39
PVA1.2-SF1.0	8.25	3.50	7.37	4.68	5.55	4.81
PVA1.5-SF1.0	9.08	4.25	8.58	5.14	5.74	5.40
PVA1.8-SF1.0	10.51	4.66	8.71	5.59	6.67	6.27

deflection of the beam reaches 6.68 mm (twice as much as the former). When the steel fiber content is 1%, for the case of PVA fiber of 0.6% and 1.8%, the ultimate deflection of the beam is 3.75 mm and 6.27 mm, respectively, and the increase is 67%. The reason for this is that when the steel fiber content is low, the bridging effect on cracks is small. Increasing the PVA fiber content has a more apparent constraining effect on crack propagation. When the steel fiber content is 1.0%, its bridging effect is strong; if a larger PVA fiber content is used, it may cause the fiber to be unevenly distributed in the matrix, which will cause stress concentration in the beam, which harms the performance of the beam.

When Portland cement is wholly used as the binder material, and crushed ceramic sand is used as the fine aggregate, the effect of increasing steel fiber content on flexural strength is not as evident as increasing the PVA fiber content. When the steel fiber content is increased from 0.5% to 1.0%, the flexural strength increase is less than 12%. For comparison, when the steel fiber content is 0.5% if the PVC fiber content is increased from 0.6% to 1.8%, the flexural strength is increased by 18%, and when the steel fiber content is 1.0%, it is increased by 31%. Due to the hydrophilic nature of PVA fibers, there is a solid chemical adhesion at the interface between PVA fiber and Portland cement hydration products. Its bonding strength is more significant than that of steel fiber and matrix, which makes PVC fiber lose its bearing effect in fracture mode. Although the strength of steel fiber is more than twice the strength of PVA fiber, the failure mode of steel fiber is pulling out, and its tensile strength is not fully utilized.

When the ceramic powder content is large (50%), and the PVA fiber content is low, the increase in steel fiber content obviously improves flexural strength. When the PVA fiber content is 0.60%, if the steel fiber content is increased from 0.5% to 1.0%, the flexural strength increases from 3.67 MPa to 5.29 MPa (an increase of 41%). In contrast, when the PVA fiber content is 1.50%, by increasing the steel fiber content, the flexural strength of the beam increases from 4.94 MPa to 5.74 MPa (an increase of only 16%). Most of the PVA and steel fibers fail by debonding for large ceramic powder substitutions, and the fibers lose their bearing capacity in pull-out mode. When the PVA fiber content is low, its bridging effect is weak, and the increase of steel fiber content will make the inhibition ability to crack propagation more prominent. For high PVA fiber content, the flexural strength has been dramatically improved by PVA fiber, and the enhancement effect of increasing the steel fiber content is not as apparent as in the case of low PVA fiber content.

It can be seen from Figure 8 that if Portland cement is used as the only binder material, when the fiber contents are low, the bearing capacity is reduced obviously after the beam reaches peak stress. This brittle failure characteristic is improved only under high fiber content. With the increase of ceramic powder's content, the beam's ductile failure property has already appeared, even with low fiber content. If the fiber content is increased, the ductility can be further enhanced. By increasing the ceramic powder and hybrid fiber content, the ultimate deflection of the new composite beam can be grown from 2.11 mm to 6.68 mm, which shows that the flexural resistance of beams made from this new cementitious material is well adjustable.

For all the mix ratios in this study, compared with increasing the steel fiber content, increasing the PVA fiber content has a more noticeable effect on the ultimate deformation ability. Increasing the steel fiber content from 0.5% to 1.0% increases the maximum deflection by 30% (occurring in the case of PVA fiber content of 0.6% and ceramic powder content of 0%), and the others are all below 25%. Adjusting the PVA fiber content from 0.6% to 1.2% increases the ultimate deflection by up to 50% (in the case of ceramic powder content of 0% and steel fiber content of 0.5%), with an average increase of 31%. Increasing the PVA fiber content from 0.9% to 1.8% increases the ultimate deflection by up to 90% (in the case of ceramic powder content of 50% and steel fiber content of 0.5%), with an average increase of 44%. Because the elastic modulus of PVA fiber is relatively low, only 1/4 of that of steel fiber, PVA fiber mainly controls the deformation ability of the material, which is similar to the role of hybrid fibers in other cementitious materials.

4. Conclusions

This study presents the bending performance of an environmentally friendly cement-based material incorporating ceramic wastes and hybrid fibers. The main conclusions are drawn as follows:

1. At the age of 28d, increasing the amount of ceramic powder significantly reduced the compressive strength of composite cementitious mortar. With the increase of age, even if the amount of ceramic powder instead of cement reaches 50%, the difference between its compressive strength and the strength of Portland cement specimen is still narrowing.

2. A new cement-based material with good deformability can be produced using demolished ceramic wall tiles and hybrid fibers. By increasing the amount of ceramic powder, the failure mode of PVA fiber can be transferred from fracture to pull-out, effectively improving ductility. When the steel fiber content is low, increasing the PVA fiber content is more obvious to improve the ductility of the new material beam. Under high ceramic powder content, if the PVA fiber content is low, increasing the steel fiber content improves the bearing capacity considerably.
3. In order to improve the flexural ductility of beams containing ceramic wastes, the effect of increasing the amount of PVA fiber is more evident than that of increasing the amount of steel fiber. If Portland cement is replaced by half with ceramic powder, good bending performance can still be obtained using hybrid fibers with matched contents.

Acknowledgements

This work was financially supported by the Natural Science Foundation of Hebei Province (E2021210088) and the Beijing-Tianjin-Hebei Basic Research Cooperation Special Project (E2021210136).

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Received: 2023-04-19, Revised: 2023-05-25