

# Effect of water-to-binder ratio and fly ash content on the mechanical and deformation properties of bendable concrete

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**Abstract.** To investigate the effect of water-to-binder ratio and fly ash content on the properties of bendable concrete, we prepared four samples of different strength grades with water-to-binder ratios of 0.25 and 0.30 and fly ash contents of 60% and 80%. The effects of water-to-binder ratio and fly ash content on the compressive strength, flexural strength, elastic modulus, fracture toughness, and uniaxial tensile deformation of the samples were investigated. The results show that the strength of bendable concrete can be varied by varying the water-to-binder ratio and fly ash content. Water-to-binder ratio and fly ash content showed almost the same effect on fracture toughness, whereas fly ash content exhibited a greater effect on elastic modulus. With an increase in water-to-binder ratio and fly ash content of concrete, the initial crack stress and tensile strength decreased and the ultimate tensile strain increased, but the change of water-to-binder ratio showed a more significant effect on the ultimate tensile strain.

## 1 Introduction

High-ductility cementitious composites, also known as bendable concrete, are fiber-reinforced composites with strain-hardening and multiple cracking characteristics under tensile and shear loads<sup>[1]</sup>. Since the discovery by Li<sup>[2,3]</sup>, bendable concrete has recorded much progress in terms of the preparation methods, properties, and applications. In bridge engineering, link slabs in jointless bridge decks, expansion joint, seismic node, and other special structural parts produce large deformation under applied load<sup>[4-6]</sup>. The application of bendable concrete in these special parts can greatly improve the safety and durability of the structure. Studies on the preparation technology and performance of bendable concrete in bridges are still in the initial stage and the application technology is not developed. To promote the application of bendable concrete in bridges<sup>[7]</sup>, we studied the influence of water-to-binder ratio (W/B) and fly ash (FA) content on

the mechanical and deformation properties of bendable concrete to provide technical support for the application of new materials in bridge engineering.

## 2 Materials and methods

### 2.1 Materials

The materials used in this test were prepared using P-II 42.5 R Portland cement, grade I FA, calcium carbonate limestone powder with an average particle size of 20  $\mu\text{m}$ , river sand with a maximum size of 1.18 mm, ordinary tap water, and a polycarboxylate-type high-performance water-reducing admixture with a water reduction rate of more than 40%.

The physical and mechanical properties of the high tensile strength and high modulus polyvinyl alcohol (PVA) fibers used are listed in Table 1.

**Table1.** Physical and mechanical properties of PVA fibers

Ultimate tensile strength (MPa)	Elastic Modulus (GPa)	Ultimate elongation (%)	Equivalent diameter( $\mu\text{m}$ )	Length (mm)	Density ( $\text{g}/\text{cm}^3$ )
$\geq 1300$	$> 35$	8–10	$> 40$	12	1.3

### 2.2 Mix proportions

Table 2 shows the mix proportions of the bendable concrete.

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**Table2.** Mix proportions of bendable Concrete

Mix number	W/B	Cement	Fly ash	Stone powder	Sand	Water	Water reducer	PVA fiber
<b>0.25F60</b>	0.25	1.00	1.50	0.18	0.73	0.63	0.01	0.05
<b>0.25F80</b>	0.25	1.00	4.00	0.36	1.45	1.25	0.01	0.10
<b>0.3F60</b>	0.30	1.00	1.50	0.18	0.73	0.75	0.00	0.05
<b>0.3F80</b>	0.30	1.00	4.00	0.36	1.45	1.50	0.01	0.11

The mix number (in column 1) describes the W/B and mass percentage of FA in the bendable concrete; for example, 0.25F60 denotes a W/B of 0.25 and 60% of cement replaced with FA.

### 2.3 Test methods

**Flexural and compressive strength tests:** The mechanical properties were measured using 40 mm × 40 mm × 160 mm prism specimens, which were of 28 days old according to the “Method of testing cement-Determination of strength (ISO)” (GB/T 17671-1999).

**Uniaxial tensile tests:** According to the “Standard test method for the mechanical properties of ductile fiber reinforced cementitious composites (JC/T 2461-2018),” uniaxial tensile tests were conducted using dumbbell-shaped specimens with a thickness of 13 mm, parallel portion width and length of 30 and 100 mm, respectively, and an original reference-point distance of 100 mm. Details of the test system and process are available in Guo

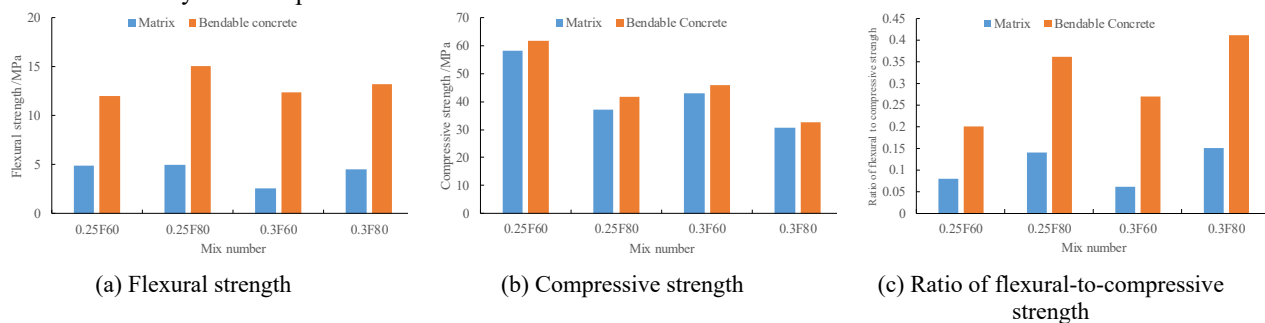
et al<sup>[8,9]</sup>.

**Fracture toughness test:** According to the “Norm of fracture test of hydraulic concrete (DL/T 5332-2005)” fracture toughness tests were conducted using 40 mm × 40 mm × 160 mm specimens. After curing the specimens to 28 days, cracks were prefabricated in the middle of the specimen span with a joint height ratio of 0.4, joint width of 2–3 mm, specimen span of 140 mm, and loading speed of 0.5 mm/min. The test was conducted using MTS 810.

## 3 Results and discussion

### 3.1 Flexural strength and compressive strength

The 28d flexural and compressive strengths of the four concrete samples were tested. The strength of the matrix and bendable concrete were measured, and the flexural-to-compressive strength ratio was calculated. The test results are shown in Fig 1.



**Fig.1** Flexural and compressive strengths of bendable concrete

Bendable concrete samples with different strength grades were obtained by varying the W/B and FA content. After adding PVA fiber into the matrix, the flexural strength increased by 2–3 times, the compressive strength increased slightly by 5%–13%, and the flexural-to-compressive strength ratio increased by 2.5–4.5 times. These results show that the addition of PVA fiber increases the ductility of bendable concrete.

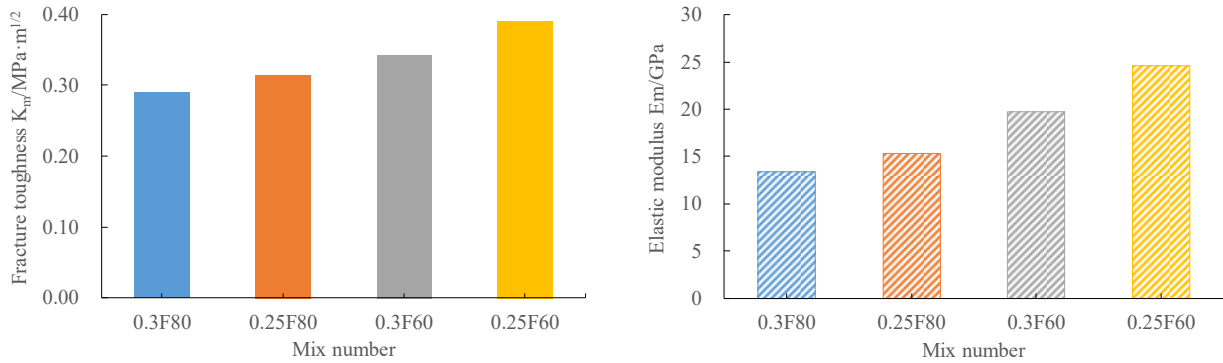
### 3.2 Fracture toughness and elastic modulus

Bendable concrete is designed based on multiscale theory. The macro properties of bendable concrete are determined by the microcosmic and mesoscopic properties, like fiber, fiber/matrix interface, and matrix properties. The fracture toughness and elastic modulus of a matrix are the mainly considered matrix properties. The two quantities can be used to calculate the fracture tip toughness  $J_{tip}$  of bendable concrete, which can be used as a criterion to judge the

ductility of the concrete. Therefore, it is necessary to investigate the fracture toughness and elastic modulus of the matrix.

According to DL/T 5332, the fracture toughness and elastic modulus of the four samples of bendable concrete were determined. The fracture toughness and elastic modulus of the matrix (Fig 2) were determined from the load vs crack-opening displacement curves.

Fig 2 shows that at a constant W/B, an increase in the FA content decreases the fracture toughness and elastic modulus of the matrix. At W/B of 0.25, as the FA content was increased from 60% to 80%, the fracture toughness and elastic modulus of the matrix decreased by 19.7% and 37.8%, respectively, and at W/B of 0.3, they decreased by 15.2% and 31.9%, respectively. Increasing W/B from 0.25 to 0.30, the fracture toughness and elastic modulus of the matrix decreased by 7.0% to 12.5% and 12.5% to 19.9%, respectively. We conclude that changes in W/B and FA content have almost the same effect on fracture toughness, whereas FA content has a greater effect on elastic modulus.

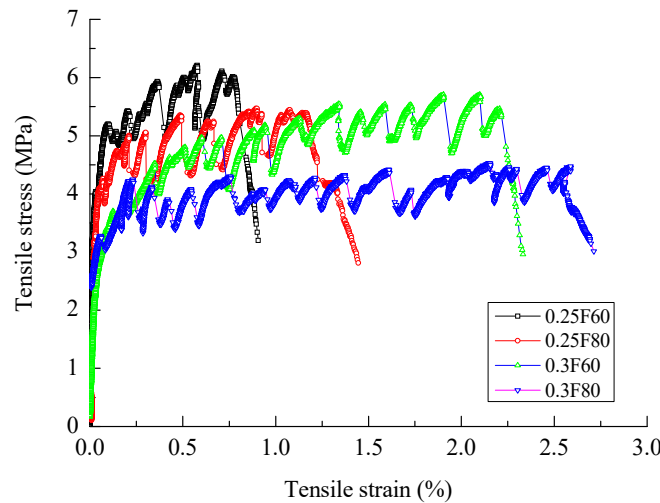


(a) Fracture toughness (b) Elastic modulus  
**Fig.2** Fracture toughness and elastic modulus of matrices

### 3.3 Uniaxial tensile test

Fig 3 shows the stress–strain curves of the four samples of bendable concrete under uniaxial tension. Under tensile loading, the material reaches the cracking strength under the action of load without failure due to strain softening, but the stress and strain continue to increase. This gives

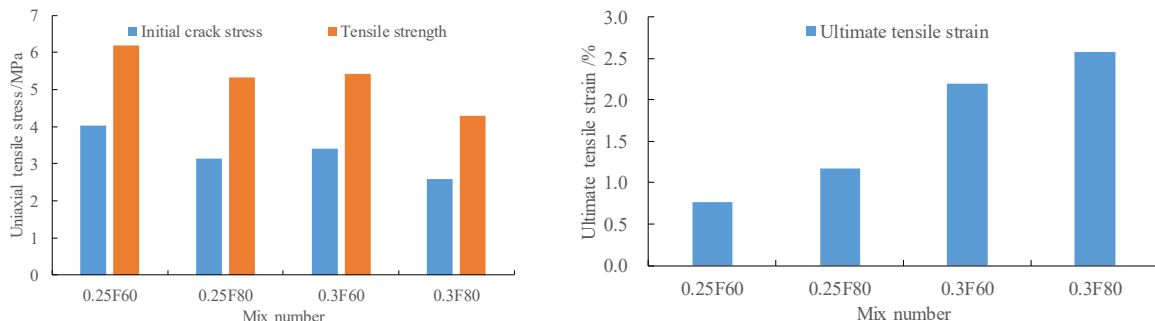
rise to the strain-hardening effect of the bendable concrete. Fig 3 shows that all four samples of bendable concrete exhibited the strain-hardening effect. After cracks occur, the stress suddenly decreases, and then increases under the fiber-bridging action. When the crack stress is reached, cracks would occur again, and the stress would be released. This process continues until the failure of the specimen occurs.



**Fig.3** Uniaxial tensile stress–strain curves of bendable concrete

The initial crack stress, tensile strength, and ultimate tensile strain of the samples were obtained from the tensile

stress–strain curves, and are depicted in Fig 4.



(a) Uniaxial tensile stress (b) Ultimate tensile strain  
**Fig.4** Uniaxial tensile stress and ultimate tensile strain of bendable concrete

The ultimate tensile strain of 0.3F80 was the highest (2.56%). The tensile strength decreased with the addition of FA, ranging from 14% to 26%. However, the ultimate tensile strain increased with an increase in the FA content, ranging from 18% to 54%. When W/B increased from 0.25

to 0.30, the initial crack stress and tensile strength decreased from 15.2% to 18.1% and from 12.4% to 19.5%, respectively. The ultimate tensile strain increased with an increase in W/B, ranging from 120.5% to 188.2%. In conclusion, an increase in FA content and W/B of

bendable concrete decreases the initial crack stress and tensile strength and increases the ultimate tensile strain. Additionally, the change in W/B has a more significant effect on the ultimate tensile strain.

## 4 Conclusions

Bendable concrete with different strength grades were prepared by varying W/B and FA content.

The change in W/B and FA content have almost the same effect on fracture toughness, whereas FA content has a greater effect on elastic modulus.

With an increase in FA content and W/B of a bendable concrete, the initial crack stress and tensile strength decrease, and the ultimate tensile strain increases. However, the change in W/B has a more significant effect on the ultimate tensile strain.

## Acknowledgments

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