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THE INFLUENCE OF PVA CONTENT ON THE FLEXURAL BEHAVIOR OF ENGINEERED CEMENTITIOUS COMPOSITE USING LOCAL MATERIALS

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Abstract

Engineered cementitious composite (ECC) creates many potential civil engineering applications due to its outstanding ultimate tensile strain capacity (normally exceeding 2%) compared to conventional concrete and fiber reinforced concrete. The high tensile ductility of ECC is mainly influenced by fiber characteristics. In this study, the effect of polyvinyl alcohol (PVA) content, i.e. from 2 to 6% by vol. of concrete, on the flexural behavior of ECC with a desired compressive strength of over 60 MPa, in which fly ash and silica fume were selected as supplementary cementitious materials. The experimental results show that the addition of PVA fiber gives little influence on compressive strength but can significantly affect the flexural behavior of ECC. Besides the optimum fiber content, the ratio between the ultimate and first crack strength of ECC was also evaluated.

Keywords: engineered cementitious composite; PVA fiber; flexural behavior; fly ash; silica fume.

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1. Introduction

Engineered cementitious composite (ECC) is a high strength, ductile fiber reinforced cementitious composite with an outstanding tensile strain beyond 2% [1, 2]. ECC consists of fine aggregate, cement, water, fiber, and admixtures. The ultimate tensile strain capacity of ECC can be obtained up to 5% depending on the ECC mixture. This is the most distinguishing feature of this material compared with ordinary concrete and fiber reinforced concrete (FRC) [2, 3]. FRC usually has high fiber content and thus high tension and flexural strength. However, the damage of this type of concrete usually occurs locally. In contrast, ECC possesses a property similar to many ductile metals after the first crack with a formation of many closely spaced microcracks that can carry an increasing load. This

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unique tensile strain-hardening behavior can result in over 300 times more strain capacity than ordinary concrete [4–6]. This has given ECC many potential applications such as high energy absorption structures/devices, structures subjected to impact loads, large deformation structures, etc.

Fresh and hardened properties of ECC are influenced by ingredients and their proportions, i.e. fine aggregates, admixtures, fibers; physical and chemical properties of ingredients; mixing ratios, i.e. water to binder (W/B) ratios, sand to binder ratios; curing conditions and other factors [2, 7]. It is recommended that fly ash (FA) and ground granulated blast furnace slag (GGBS) are the proper choices to obtain the strength of ECC in the range from 45 MPa to 60 MPa [7]. Additionally, silica fume (SF) combined with FA, GGBS, metakaolin, or other mineral admixture are the appropriate option to achieve higher strength of ECC over 60 MPa and make a positive impact on our environment, especially in the Vietnamese context [8, 9]. SF with a high pozzolanic reactivity has positive effects on both early and long-term properties of concrete compared with any other mineral admixtures, which is the main reason for the recommendation of SF used to produce ECC [7]. Besides, the selection of fine aggregates also influences the properties of ECC. For example, silica sand with a size range from 150 μm to 300 µm is an appropriate choice for producing ECC with compressive strength from 45 MPa to 60 MPa. However, the cost of silica sand is very high compared to other sands; thus, promising alternatives to produce ECC need to be considered such as river sand, sea sand, or the combination of sands with a particle size of less than 300 µm to obtain a desired compressive strength of about 45 MPa [7].

The load-deformation behavior of reinforced concrete members is influenced by the characteristics and properties of fibers, i.e. different types and shapes of fibers, their contents and strength parameters; cementitious matrix, and their interaction. For example, PVA fiber is recommended to be more suitable for attaining better mechanical properties of ECC [7]. The combinations of PVA fibers with other ones such as polypropylene, steel, or PET fibers are good alternatives for producing hybrid ECC. Additionally, it is necessary to select the proper W/B ratio and superplasticizer to achieve the desired workability and mechanical properties of ECC. Moreover, ECC is a unique type of high-performance fiber reinforced cementitious composite that possesses high tensile strain capacity with the typical addition of 2% fiber by volume [10]. In some exceptional cases with a high tensile strain, the fiber content is even beyond 4% to maintain very tight crack widths of about 60–80 µm [11]. These aforementioned analyses show that flexural behavior of ECC, e.g. the formation of cracks and improvement of tensile strain capacity, etc. depends on the type and content of fiber, and properties of concrete without fiber, especially using available local materials in Vietnam where the research and development of ECC is still limited. Therefore, in this study, the influence of PVA fiber content from 0 to 6% by vol. on the flexural behavior of ECC using local materials in Vietnam with a desired compressive strength over 60 MPa was investigated, in which FA and SF were selected as SCMs. Besides the optimum fiber content, the ratio between the ultimate and first crack strength was also evaluated.

2. Materials and methods

2.1. Materials

The local materials were used in this study. In particular, cementitious materials including Portland cement PC40 Nghi Son in accordance with Vietnamese standard TCVN 2682 [12], condensed silica fume (SF), and type F- fly ash (FA) as specified in ASTM C618 [13] were selected. The chemical composition and properties of these materials are given in Table 1 and Table 2. Note that the LOI is the loss on ignition. Besides, silica sand with a mean particle size of approximately 300 µm and a density of 2.65 g/cm^3 was used for all mixtures. A polycarboxylate-based superplasticizer (SP) with 30% solid content by mass was used to achieve desired flow value from 200 mm to 250 mm which is a common value to make ECC mixtures [7].

Table 1. Chemical composition of cementitious materials

Material	Chemical composition (% by weight)									
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	LOI
Cement	20.3	5.05	3.51	62.81	3.02			2.00		1.83
SF	92.3	1.91	0.86	0.32	0.85	0.38	1.22	0.30		1.68
FA	46.82	12.3	25.29	1.20	1.16	1.09	2.50	0.60	0.08	4.04

Table 2. Properties of cementitious materials

Properties		Unit	Cement	SF	FA
Fineness (Blaine)		cm^2/g	4130		
Mean particle size		µm	10.76	0.15	5.43
Density		g/cm^3	3.15	2.20	2.44
Pozzolanic reactivity index		%		111	103
Compressive strength	After 3 days	MPa	31.6		
	After 28 days	MPa	49.5		

The mechanical and physical properties of PVA fibers were obtained according to the supplier's declaration and are given in Table 3.

Table 3. Characteristics of PVA fiber

Diameter (µm)	Length (mm)	Nominal strength (MPa)	Young's modulus (GPa)	Elongation (%)	Density (kg/m^3)
39	12	1620	42.8	7.0	1300

2.2. *Mix proportions*

In this study, the water to binder and sand to binder ratios of all mixtures were fixed at 0.3 and 1.2 by weight, respectively. The cement was replaced by 10% SF and 20% FA by weight. These

Table 4. Mix proportions of ECC mixtures

Mix	The proportion of materials						The material content, kg/m^3						
	W/B (by weight)	S/B (by weight)	FA (wt.% of binder)	SF (wt.% of binder)	SP (wt.% of binder)	PVA fiber (% by vol. of concrete)	C	FA	SF	S	Water	SP	PVA
REF	0.30	1.2	20	10	1.0	0	633	181	90	1085	263	30.2	0
M2	0.30	1.2	20	10	1.0	2	621	177	89	1064	257	29.5	26
M4	0.30	1.2	20	10	1.0	4	608	174	87	1042	252	28.9	53
M6	0.30	1.2	20	10	1.0	6	595	170	85	1020	247	28.3	79

proportions were selected following from reference [7], especially in the Vietnamese context [14, 15], and based on the adjusted experimental results by using Vietnamese materials. The superplasticizer dosage was chosen at 1% by weight of binder for all mixtures. The addition of 2%, 4%, and 6% PVA by vol. of concrete with the corresponding notations of M2, M4, M6 was utilised. The mix proportions of the mixtures are given in Table 4.

2.3. Methods

a. Sample preparation

All ECC mixtures were prepared using a Hobart planetary mixer with a 60-liter bowl capacity. A mixing procedure is represented (see Fig. 1) to produce ECC mixtures with the desired workability as follows: (1) the dry mixture of sand, cement, FA, and SF was first mixed for 3 min; then (2) added 70% mixing water and mixed for 3 min; and (3) the remaining 30% of the mixing water including superplasticizer was added and mixed for another 4 min; (4) fibers were added to the mixtures and mixed for 5 min.

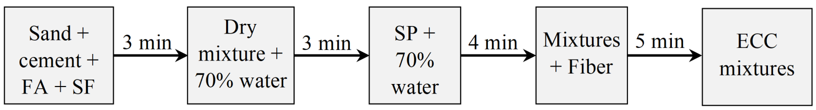


Figure 1. Mixing procedure of ECC mixtures

After mixing, the flowability of the concrete mixture was measured by a mini cone according to ASTM C1856:2017. The fresh ECC mixtures were cast into 100 × 100 × 100 mm cubes for testing compressive strength and 400 × 100 × 20 mm specimens for the four-point bending test with a detailed diagram and tested specimens shown in Figs. 2 and 3. The size of the flexural test specimen was followed the suggestion of the Korean Standards Association [16]. The compression test was performed according to ASTM C109/C109M with a specimen size of 100 × 100 × 100 mm. All specimens were cured at a standard curing condition (27±2°C, RH ≥ 95%) for 24 h. After that, the specimens were demolded and continuously cured under the standard curing condition (27±2°C, RH ≥ 95%) until testing.

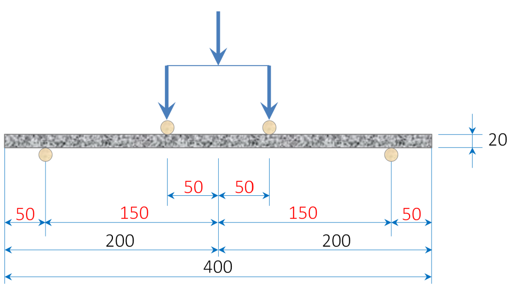


Figure 2. The diagram of the four-point bending test [16]

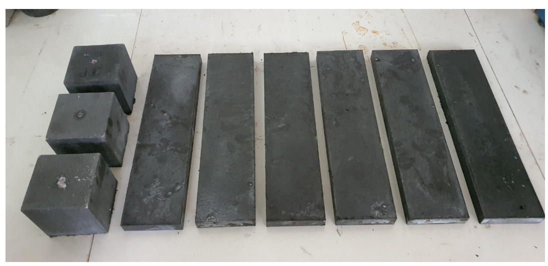


Figure 3. Testing specimens 400 × 100 × 20 mm

b. Experimental setup

The four-point bending test was conducted using the Instron 5985 testing machine to investigate the flexural behavior of ECC specimens. The 400 × 100 × 20 mm specimens with different PVA contents were employed for testing to study the influence of the content of PVA on the mechanical performance of the ECC material. The displacement control with a constant loading speed of 0.5 mm/s was applied during the test until the failure completely occurred.

The strain measurement operates using a video extensometer, which is designed to accurately measure specimen strain during a material test without contacting the specimen. In fact, in applying the non-contacting measurement, there is no mechanical influence on the testing sample. The non-contacting method employs a high-solution digital camera to capture the video and accurately detect the gauge length markers. The experimental setup is shown in Fig. 4.

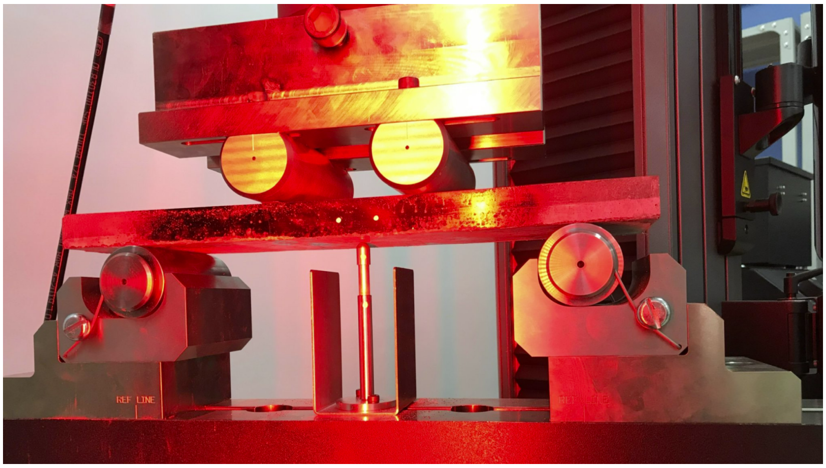


Figure 4. Experimental setup for four-point bending test of ECC specimens

3. Results and discussions

3.1. Effect of PVA content on compressive strength of ECC

The properties of ECC are shown in Table 5. It can be seen that the flowability of the reference specimen mixture without fibers increased up to 255 mm and the addition of PVA fiber decreases the flowability of ECC mixtures. However, the compressive strength of ECC was not significantly influenced by different PVA contents.

Table 5. Compressive strength of ECC using different PVA contents

Specimen	PVA fiber (% by vol. of concrete)	Flow value (mm)	Compressive strength (MPa)
REF	0	255	63.0
M2	2	245	63.8
M4	4	205	63.0
M6	6	120	62.6

3.2. Effect of PVA content on flexural behavior of ECC specimens

The load-midspan deflection curves taken from the tests for three specimens with different PVA fiber ratios are shown in Fig. 5. It is noted that the M6 has the highest fiber ratio while the M2 has the lowest ratio. The more detailed mix proportions of ECC mixtures for each specimen can be seen in Table 4.

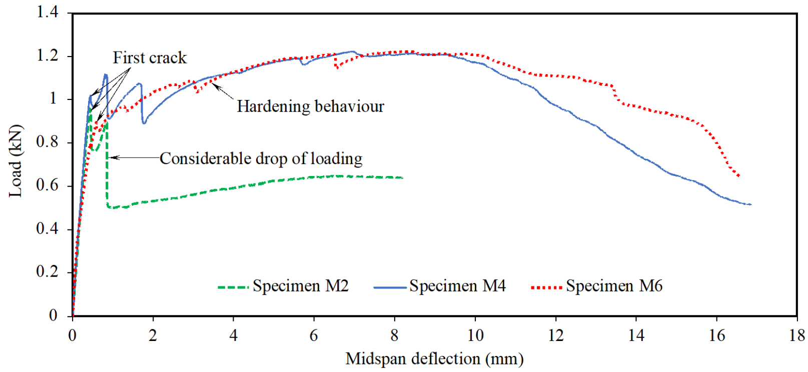


Figure 5. Load vs midspan deflection of ECC specimens

A significant difference in the flexural behavior of low PVA samples and high PVA samples can be observed in Fig. 5. Overall, the increase in the PVA content can enhance both the loading capacity and ductility of the ECC specimens. In particular, the lowest PVA specimen (M2) fails at the loading of 0.95 kN, while the highest PVA specimen (M6) reaches the loading capacity of 1.21 kN. Moreover, after the first crack, the specimen M2 experiences a considerable drop in the load versus midspan deflection curve, in contrast, the hardening behavior is observed in the higher PVA specimens (M4 and M6). This is because the fiber can help to carry the tensile strength after concrete cracking, resulting in higher ductility and better loading capacity.

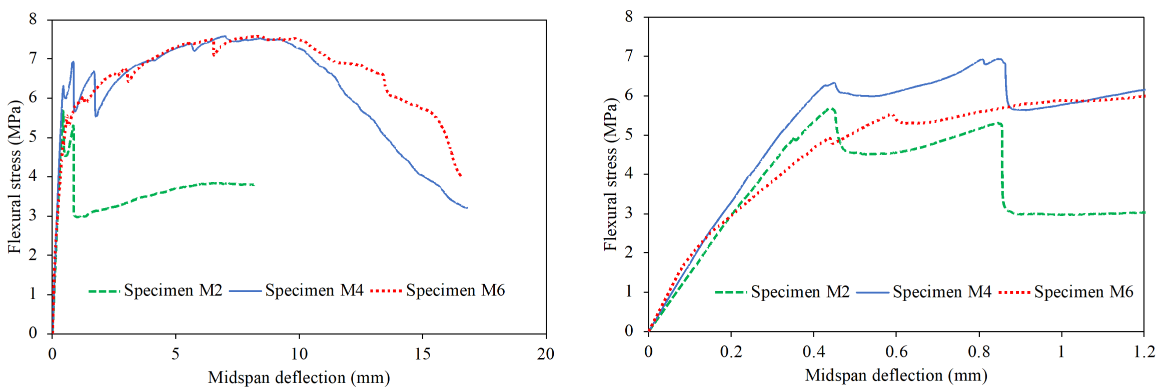


Figure 6. Flexural stress vs midspan deflection of ECC specimens (a) overall behavior and (b) zoom into the initial stages

Fig. 6 shows the flexural stress-midspan deflection relation of the three samples. The overall behavior is demonstrated in Fig. 6(a), and the initial stages are illustrated in Fig. 6(b). It is shown that the specimens with more PVA content (M4 and M6) experienced the three main stages: the linear stage, strain hardening stage, and linear softening stage, respectively. In the linear stage, flexural stress increases linearly with the midspan deflection until the first crack occurs. Consequently, there is a small drop of flexural stress in specimen M4, while the strain hardening behavior is immediately exhibited in specimen M6. The first crack strengths of the specimens M4 and M6 are 6.26 MPa and

4.86 MPa, respectively. In the second stage, the flexural stresses of both specimens increase following an increase of inelastic strain until the specimens reach their ultimate strength. As a result, more cracks developed in both specimens. After reaching the ultimate strength, the softening behavior takes place, in which the flexural stress decreases slightly with the midspan deflection. The stage continues until the specimens are completely failed.

Differently, specimen M2 shows the typical behavior of the brittle material. The stress–midspan deflection curve initially experiences linear behavior until the first crack appears. Consequently, the specimen shows a considerable drop in flexural stress after the first cracks. And then, the flexural stress increases slightly until the appearance of the second crack. It can be seen that for this lower PVA content specimen (M2) the softening stage occurs immediately after each macro-crack. For the above observation, it is clear that higher PVA helps to enhance both the ductility character and fracture energy in the ECC material.

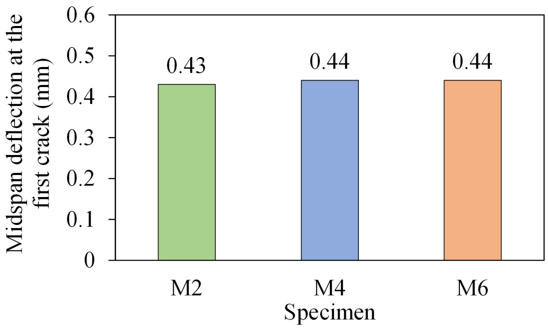


Figure 7. Midspan deflection at the first crack

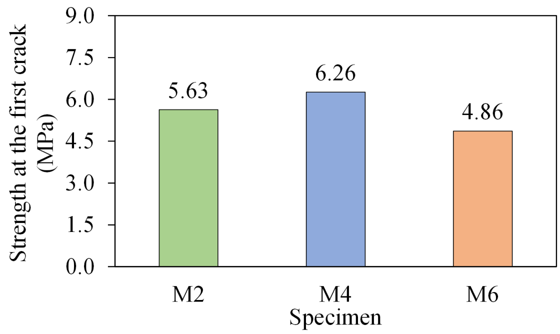


Figure 8. Strength at the first crack

Fig. 7 compares the midspan deflection, while Fig. 8 shows the strength at the first crack of the three ECC specimens. It is observed that the deflection at the first crack is almost identical for the three specimens. In other words, the PVA content has very little effect on this material property. Nevertheless, the influence of PVA on the flexural strength at the first crack is significant. For example, the first crack strengths of specimens M2 (2% PVA by vol. of concrete), M4 (4% PVA by vol. of concrete), and M6 (6% PVA by vol. of concrete) are 5.629 MPa, 6.259 MPa, and 4.862 MPa respectively. The average PVA specimen shows to have the highest first crack strength. It can be explained that PVA plays an important role in strengthening the crack resistance capability as it can bridge the concrete part of the specimen. However, superfluous PVA content can lead to weaken the connection between the PVA and concrete matrix, thus reducing the first crack strength of the ECC material.

The elastic modulus and ultimate strength of the three ECC specimens are illustrated in Figs. 9 and 10, respectively. It is shown that the PVA content can significantly affect both elastic modulus and ultimate strength of ECC specimens. In particular, a mean content of PVA (e.g. 4% PVA by vol. of concrete) added to concrete can improve the value of elastic modulus. For instance, specimen M4 has the highest modulus of elastic (9.98 GPa), while specimen M6 containing 6% PVA by vol. of concrete has the lowest elastic modulus with only 7.68 GPa. It is worth noting that the elastic moduli of M2, M4 and M6 were automatically obtained by the Instron testing machine based on determining the slope of the initial linear stage of stressstrain curve. The slope calculation was based on the least-square fit of the test data applying on a number of specified regions of the lower and upper bounds concerning the ultimate strength, as shown in Fig. 10, an increase in the PVA ratio in concrete can enhance the ultimate strength of the ECC specimen. However, at a high ratio of PVA content, the influence of the

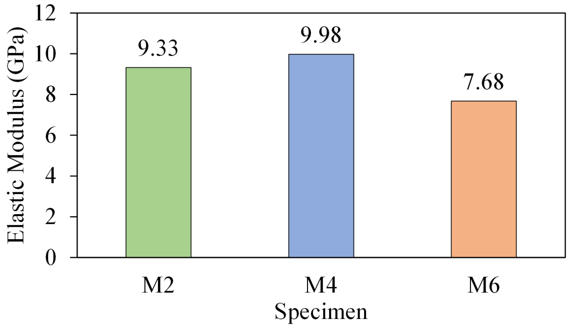


Figure 9. Elastic modulus

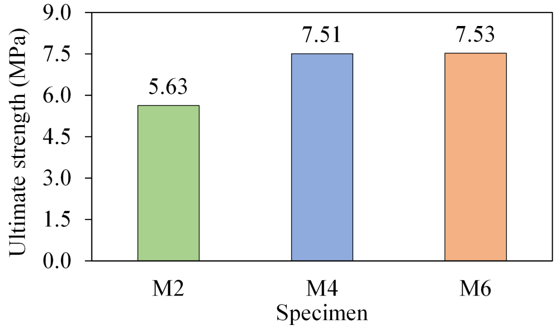


Figure 10. Ultimate strength

PVA on this mechanical property of the ECC specimen is shown to be less significant. Nevertheless, the ratio of ultimate strength and first crack strength improves considerably following an increase in PVA content, as shown in Fig. 11. In particular, the ratio surges forward 54.8% as the PVA content increase from 2% (in specimen M2) to 6% (in specimen M6). It can be explained that the PVA fiber can help to bridge the gap between the concrete parts whenever a new crack develops. Thus, it plays an important role in enhancing the ductile behavior of the ECC material.

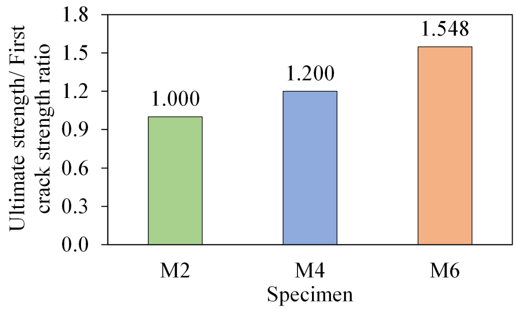
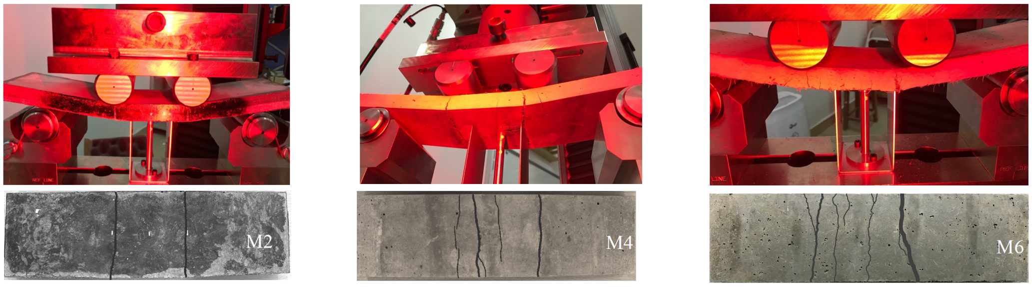


Figure 11. The ratio between the ultimate strength and first crack strength

3.3. Effect of PVA content on crack pattern

Figs. 12 and 13 indicate crack patterns and the development of those macro-crack corresponding with stress-deflection curves for the three ECC specimens. As shown in Fig. 12, specimen M2 with low PVA content has a local failure, in which the specimen is completely failed after the second macro-crack developed. In contrast, multi-cracks are exhibited in specimens M4 and M6. Thus, global failure is achieved for those specimens. Particularly, four macro-cracks are observed in specimen M4, and six macro-crack are developed in specimen M6. From the above observation, it can be concluded that an increase of PVA content can help to improve the mechanical performance of the ECC specimen, from a local crack to a global failure with multiple macro-cracks.

A comparison of cracking development concerning flexural stress versus midspan deflection of the three ECC specimens is shown in Fig. 13. It is clear that the development of multiple cracks can help enhance the strain hardening stage and thus the ductility of the ECC material. While specimen M2 shows the typical response of brittle concrete, specimens M4 and M6 indicate the common behavior of ductile material. It is worth noting that each drop of flexural stress in the stress-deflection curve corresponds to the development of a macro-crack within the specimen. Both flexural behaviour and crack pattern of ECC specimens M4 and M6 show a good agreement with existing studies found in the literature [3–6].



(a) Specimen M2 (b) Specimen M4 (c) Specimen M6

Figure 12. Crack pattern in three ECC specimens

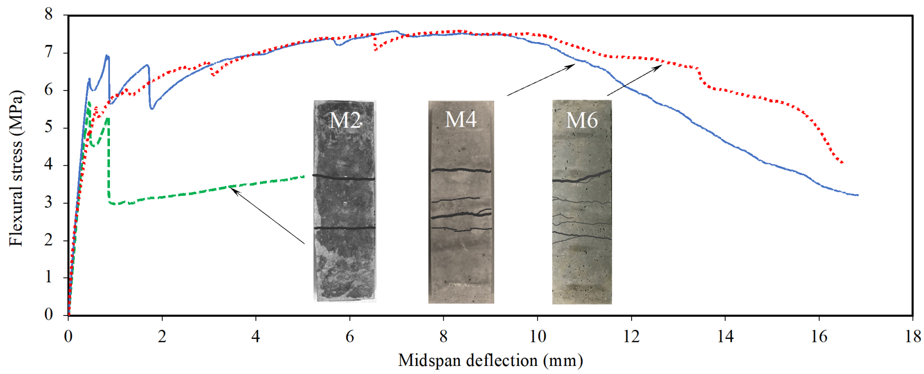


Figure 13. Cracking development and corresponding stress-deflection curve of the three ECC specimens

4. Conclusions

In this study, the influence of PVA content on the mechanical behavior and crack development of the ECC specimen under a four-point bending test was investigated. The study was conducted by testing three ECC specimens M2, M4, and M6 with 2%, 4%, and 6% PVA by vol. of concrete, respectively. From the observation and discussion, the following findings and conclusions can be made:

- The addition of PVA fiber enhances the mechanical performance of the ECC specimen by improving the ductility capacity and ultimate strength of the material.

- The different PVA contents have little effect on the strain at the first crack, but the appropriate PVA content can help to increase both elastic modulus and flexural strength at the first crack of the ECC specimen.

- The typical brittle behavior is shown in the specimen with a low PVA content (e.g. 2% PVA by vol. of concrete), while strain-hardening behavior is dominant in the specimen with higher PVA content. The ductility is enhanced with increased PVA content in the mixture.

- The ratio between the ultimate and first crack strength is higher in the ECC sample with more PVA fiber added. However, the optimal PVA content should be carefully added to achieve the best ultimate strength.

- Local cracks on the ECC specimen can be evaluated with a low PVA content, whereas multi-cracks are dominant in high PVA content specimens.

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The experimental data were performed in Laboratory of Strength of Materials, Hanoi University of Civil Engineering.

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