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Compression and Flexural Behavior of ECC Containing PVA Fibers

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ABSTRACT

Research on Engineered Cementitious Composites (ECC) is overwhelming owing to its wide structural applications that can serve multi-functional purposes in civil and environmental infrastructures. Compared to other high-performance fiber reinforced concrete, ECC yields superior tensile ductility and multiple cracking behaviors when subjected to tensile loadings even with low to moderate volume of fibers. This paper presents the flexural properties of ECC made of cement, an industrial by-product, such as ground granulated blast-furnace slags (GGBS), local silica sand, polyvinyl alcohol (PVA) fiber, water, and superplasticizer (SP). Two series of ECC mixtures (ECC-G50 series and ECC-G60 series) and one control mixture were designed. The effect of two different fiber contents in volume fraction was investigated for the two series of ECC mixtures. The compression and flexural tests were conducted on ECC and control specimens after 28 days of curing. A compression test revealed that almost all ECC mixtures improved compressive strength between 20% to 30% compared to the control specimens. In addition, all ECC plate specimens demonstrated excellent strain-hardening states (i.e., displacement capacity at least ten times greater than the control specimens) and multiple fine-cracks failure modes after the three-point bending

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test. The increase in fiber content slightly reduced the compressive strength but enhanced the flexural behavior of the ECC-G50 series. However, this observation is not discovered in the ECC-G60 series. Outcomes of this research assist material scientists on the content of PVA fiber and GGBS used in making ECC.

Keywords: Compressive strength, cracking, ductility, engineered cementitious composites (ECC), flexural strength, ground granulated blast-furnace slag (GGBS), polyvinyl alcohol (PVA) fiber

INTRODUCTION

Engineered Cementitious Composites (ECC) appeared to solve the problem of normal concrete, which is commonly known as brittle material under tension loads. ECC is similar to high-performance fiber-reinforced cementitious composites. However, the main focus of this material relies on its ability to achieve tensile ductility and strain hardening rather than on compressive strength. According to Li et al. (2001), ECC can achieve strain capacity up to 5% under tensile stress depending on the design of ECC mixtures and selection of ingredients. Furthermore, unlike concrete, ECC exhibits multiple fine cracking of equal or lesser than 100 μm width (Li et al., 2001); this shows a remarkable damage tolerance feature that requires minor repair to none (Parra-Montesinos et al., 2005). A compatible deformation and improved bond-slip behavior were also observed in steel-reinforced ECC (Lee et al., 2016). With all these reliable features, ECC is suitable for earthquake resistance structures, as demonstrated by previous studies (Qudah & Maalej, 2014; Said & Razak, 2016; Lee et al., 2018a). In addition, ECC can be designed to cater to different functionalities, such as self-sensing and self-healing, as it is subjected to different types of loading and different exposure conditions or environments.

In terms of durability, ECC is recognized as superior compared to other high-performance fiber-reinforced cementitious composites because of its multiple tight crack widths that can provide better protection of steel reinforcement from corrosion. Therefore, it is important to ensure ECC infrastructures maintain their strength, stiffness, and serviceability throughout their design life span. Previous studies have confirmed that the use of ECC is feasible for more durable and sustainable development (Adesina & Das, 2021; Kewalramani et al., 2017; Li et al., 2004; Liu et al., 2017; Nemecek et al., 2006; Sahmaran & Li, 2007; Sahmaran & Li, 2008; Suthiwarapirak et al., 2002; Wang & Li, 2006).

Another interesting fact about ECC is the number of fibers incorporated in cementitious composites. Typically, a low to the moderate volume fraction of between 1.5% to 3% of fibers is sufficient to ensure ECC attains its desirable displacement capacity. Therefore, the additional cost of this material due to the use of fibers is still bearable if the purpose of using ECC is served. There are few types of fibers commonly employed in ECC mixtures, and it is found that ECCs that contain polyvinyl alcohol (PVA) fibers have consistently exhibited excellent durability, greater mechanical properties as well as enhanced structural performances (Meng et al., 2017; Pakravan et al., 2018; Yang & Li, 2014). Some researchers explored the use of polypropylene (PP) fibers instead of PVA in the making of ECC, together with some of the locally available materials (Zhang et al., 2014; Zhang et al., 2015; Lee et al., 2018b; Lee et al., 2019a, Lee et al., 2019b; Zhu et al., 2020). In one of these studies, PP fibers of volume fractions 1.5%, 2.0%, and 2.5% were employed in ECC with GGBS to study the flexural strength and ductility (Lee et al., 2018b). The results showed that ECC with PP fibers could not achieve the strain-hardening behavior under the three-point bending test. Another investigation by Lee et al. (2019a) reported that tensile softening behavior of ECC specimens was observed under direct tensile test. Therefore, this study aims to investigate the performance of ECC under compression and flexural loadings by substituting PP fibers with PVA fibers in the ECC design mix, as stated in Lee et al. (2018b). A compression test is accepted as the most basic test to determine the compressive strength for any cementitious material. Even though a direct tensile test is the best way to demonstrate the tensile ductility of ECC, this test setup is complicated and time-consuming. Therefore, as an alternative, the flexural bending test was conducted to provide equivalent flexural ductility of ECC. Flexural behaviors of ECC were evaluated through the first cracking strength, the ultimate flexural strength, and its corresponding displacement.

MATERIALS AND METHODS

Materials

The design method of ECC is based on micromechanics-strain hardening criteria, as mentioned in Yang et al. (2007). The composition mixture of ECC-GGBS in this study includes cement, GGBS, PVA fiber, silica sand, water, and SP, as shown in Table 1. There are two series of ECC, namely G50 and G60, that represent 50% and 60% of cement substitution with GGBS. In each series, two different contents of PVA fibers at 2.0% and 2.5% of volume fraction were investigated, represented by F2.0 and F2.5, respectively. The amount of water, superplasticizer, and silica sand were almost identical for all ECC design mixes, as shown in Table 1. Moreover, Table 1 also indicated the design mix proportions from the previous study compared to the design mixtures of ECC in this study (Lee et al., 2018b). With an exception for the river sand, which was substituted with silica sand and PVA fibers were replaced by PP fibers, all other ingredients were identical under the same series of ECC design.

The amount of water used was calculated based on the water to binder ratio (0.27). Binder refers to the total unit weight of cement and GGBS. It is worthy of mentioning that the fresh density of all ECC mixtures was designed in the range of 2133 to 2159 kg/m^3, which were comparable to standard ECC mixtures studied in the literature. Local silica sand with a grain size of an average of 285 µm was used in the ECC mixtures, and its physical properties are shown in Table 2. For PVA fibers, the diameter and the length were 40 µm and 8 mm, respectively. The tensile strength of this fiber was 1600 MPa,ea density of 910 kg/m^3 were employed, and local river sands below 600 µm were incorporated in the cementitious matrix (Lee et al., 2018b).

Table 1

Design mix proportion for control and ECC (kg/m^3)

Mixture	Cement	GGBS	Water	PVA fiber	Superplasticizer	Silica sand	Density
Control	1444	0	390	0	10	289	2133
G50F2.0	722	722	390	26	10	289	2159
G50F2.5	719	719	388	32	10	288	2156
G60F2.0	575	863	388	26	10	288	2150
G60F2.5	572	858	386	32	10	286	2144
G50S0.2F2.0*	723	723	390	18 (PP fiber)	10	289	2153
G50S0.2F2.5*	719	719	388	23 (PP fiber)	10	288	2147
G60S0.2F2.0*	575	863	388	18 (PP fiber)	10	288	2142
G60S0.2F2.5*	572	858	386	23 (pp fiber)	10	286	2135

*ECC mix proportions employed in the previous study (Lee et al., 2018b).

Table 2

Physical properties of silica sand

Physical percentage (%)	Properties
Loss of ignition	< 0.5
10 Mesh Residue	< 0.2
40 Mesh Residue	> 75

Table 3

Chemical composition of GGBS and silica sand

Chemical composition	GGBS (%)	Silica sand (%)
Silica (SiO_2)	33.2	> 98.0
Alumina (Al_2O_3)	12.1	< 0.3
Titanium Oxide (TiO_2)	0.54	-
Calcium Oxide (CaO)	44.2	-
Magnesia (MgO)	5.5	< 0.5
Sulphide Sulphur S^2	0.7	-

Table 3 *(Continue)*

Chemical composition	GGBS (%)	Silica sand (%)
Sulphate (SO_3)	2.0	-
Potassium Oxide (K_2O)	0.42	< 0.3
Sodium Oxide (Na_2O)	0.18	-
Alkalis	0.46	-
Ferric Oxide (Fe_2O_3)	-	< 0.3

ECC Mixing Procedure and Test Method

For the first step, the three dry ingredients–GGBS, cement, and silica sand, were placed and mixed for about three minutes in a standard concrete mixer of 40-liter capacity. Then, the liquid ingredients, i.e., SP and water, were added to the dry ingredients in the mixer while the mixing process was still running at a lower speed. After a few minutes, a mortar was formed, and when the mortar was uniformed and achieved certain fluidity, PVA fibers were carefully added. Special care was required in this step to avoid balling PVA fibers due to the fibers that were not evenly distributed yet. Fiber dispersion is very important to ensure the excellent workability of ECC. The overall mixing of ECC ended when all fibers were well-mixed in the mortar.

For each ECC mixture, three-cylinder specimens of size 50 mm diameter × 100 mm height were cast and cured for 28 days for the compression test. A Universal Testing Machine (UTM) of 1000 kN capacity was used to test the specimens under compression loads. Five plate specimens of 300 mm × 75 mm × 12 mm were cast according to the size employed in the previous study for a three-point bending test after 28 days of curing (Li & Yang, 2017). UTM of 50 kN capacity was used to test the flexural behavior of these ECC plates. The displacement control method at 0.5 mm/minute was employed in this test.

RESULTS AND DISCUSSIONS

Compressive Strength

Table 4 indicates the average compression strength and enhancement factor for each ECC mixture. It is worth mentioning that the average compressive strength of the ECC and control mixture was calculated based on three samples tested on the 28th day of curing. Generally, the compressive strengths of all ECC specimens are greater than the control specimen. The enhancement factors by incorporating the different variations of GGBS and PVA fibers into the mixtures are in the range of 1.2 to 1.3, as shown in Table 4. However, ECC G60F2.0 exhibits a relatively lower compressive strength of 35.92 MPa compared to the other mixtures. It could be due to some shortcomings during the mixing or casting of ECC, as this mixture was the first batch. The G50 series (replacement of cement by 50%

of GGBS) performs better than the G60 series under compression due to the higher cement content in the mixtures. On the other hand, the increase in fibers content from 2.0% to 2.5% of volume fraction slightly decreases the compressive strength for the G50 series, and this result agrees well with findings reported by Lee et al. (2018b).

Table 4
Result of compressive strength (28 days)

Mixture	Average Compressive Strength (MPa)	Enhancement Factor (compared with control)
Control	44.02	1.00
G50F2.0	57.02	1.30
G50F2.5	54.82	1.25
G60F2.0	35.92	0.82
G60F2.5	52.70	1.20

Comparison of Compressive Strength with Previous Study

Figure 1 shows the comparison of compressive strength on 28th days for the current study and the study carried out by Lee et al. (2018b). As described in the experimental program and shown in Table 1, the design mix compositions of both studies are similar except for the types of fibers and sand. Sahmaran et al. (2009) reported that aggregate characteristics, such as the surface texture and maximum aggregate size, did not influence the compressive strength in the case of ECC. Therefore, by neglecting the effect of sand, only the effect of types of fibers on the compressive strength of ECC is discussed. As shown in Figure 1, for the G50 series, the compressive strengths are identical when 2.0% of the volume fraction of either PVA or PP fibers were incorporated in ECC mixtures. However, when the number of fibers is increased to 2.5% of volume fraction, the compression strength of ECC with PVA fibers has improved by 24%. On the other hand, ECC with 60% of GGBS behaved differently under compression when PVA fibers increased from 2.0% to 2.5% of volume fraction. As mentioned earlier, the lower compressive strength obtained by ECC G60F2.0 in this study is possibly due to faults during the mixing or casting of this design mix. For the same mixture, ECC with PP fibers yields better compression capacity compared to ECC that contains PVA fibers. Nevertheless, for ECC mixtures with a 2.5% volume fraction of fibers and 60% GGBS, the incorporation of PVA fibers shows slightly enhanced compression capacity by 3.9% compared to PP fibers.

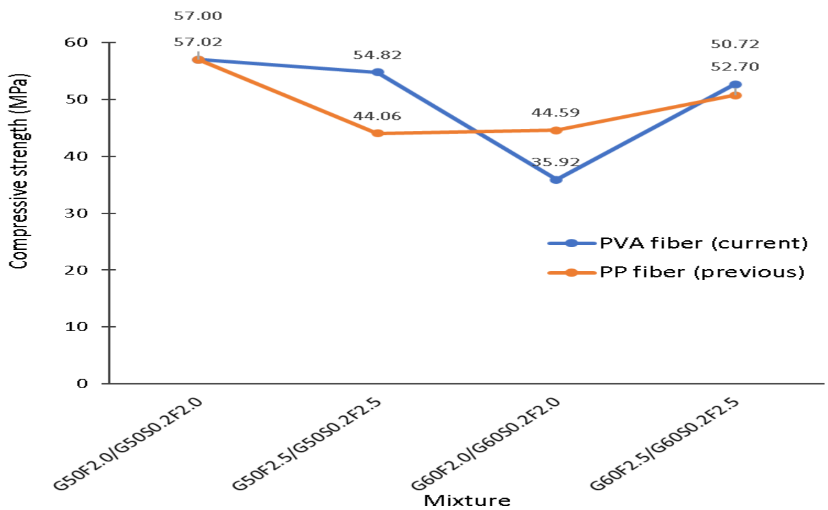

Figure 1. Comparison of compressive strength at 28 days

Flexural Behavior

The results of ECC plates under the three-point bending test are presented by the flexural stress-displacement curves as shown in Figure 2. It should be noted that each curve represents a typical flexural behavior of each ECC mixture. Apparently, the control specimen demonstrates brittle behavior in which the plate specimen failed directly upon reaching its first cracking strength. This behavior is similar to normal concrete, as demonstrated in a study by Lee et al. (2019b). For the control specimen, neither GGBS nor PVA fibers were incorporated in the cementitious matrix, and it consisted of only cement mortar. The high cement content can improve flexural strength compared to normal concrete, but no significant effect was discovered in terms of ductility.

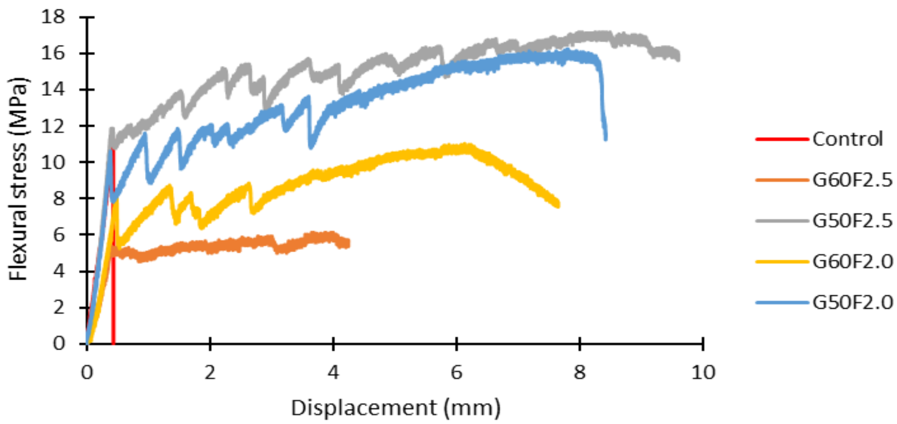

Figure 2. Flexural behavior of ECC-PVA

The G50 series yields greater flexural strength and a larger displacement capacity than the G60 series, as presented in Figure 2. ECC G50F2.5 shows the highest first cracking and ultimate strength of 11.34 MPa and 16.65 MPa, respectively. The displacement corresponds with the ultimate strength is 8.54 mm, which indicates that this mixture can undergo a good strain-hardening behavior of ECC. In this series, it is observed that increasing the PVA fibers content to 2.5% of volume fraction has improved the modulus of toughness (area under the curve). A similar observation was also noted in the study by Lee et al. (2018b).

For the G60 series, G60F2.0 demonstrates relatively greater flexural behavior compared to G60F2.5 despite the fact that its compressive strength is merely at 35.92 MPa. The enhancements in the ultimate strength and the displacement corresponding to the ultimate strength are 79% and 57%, respectively. However, these series give a contradicting result when compared to the G50 series. The increase of PVA fiber content in the G60 mixture had a detrimental effect on flexural strength and ductility. The poor performance of G60F2.5 could be attributed to the shortcomings during the preparation of specimens or test setup, and more tests are required to achieve a solid conclusion.

Table 5

Performance of ECC-PVA under three-point bending test

Mixture	First cracking strength (MPa)	Ultimate strength (MPa)	Displacement corresponding to ultimate strength (mm)
Control	11.24	11.24	0.43
G50F2.0	10.15	15.66	7.94
G50F2.5	11.34	16.65	8.54
G60F2.0	8.06	10.87	6.27
G60F2.5	5.36	6.09	4.00

Table 5 shows the first cracking strength, the ultimate flexural strength, and the displacement that correspond with the ultimate strength of ECC plates. The first cracking strength is defined as the first drop in stress in which the flexural stress-deflection response deviates from linearity. In contrast, the ultimate strength refers to the maximum flexural strength before the specimens fail. In the current study, ECC-PVA fibers have shown significant improvement, especially in the strain-hardening behavior of ECC as compared to ECC-PP fibers in another study by Lee et al. (2018b). In addition, all ECC mixtures successfully demonstrate good flexural ductility, by at least ten times better than the control mixture. For example, the displacement corresponding to ultimate strength for G60F2.5 is 4.00 mm, while only 0.43 mm can be obtained in the control mixture, as shown in Table 5.

Comparison of Flexural Behavior with Previous Study

The effect of types of fibers in flexural behavior can be examined through comparison with a previous study (Lee et al., 2018). Figures 3 and 4 demonstrate the comparisons of flexural behavior of the ECC G50 and ECC G60 series, respectively. Apparently, PVA fibers play a significant role in achieving the flexural ductility of ECC as compared to ECC-PP fibers of similar design mix proportion. As shown in Figure 3, the modulus of toughness measured by the area under the curve for ECC-PVA fibers of the G50 series (ECC G50F2.0 and ECC G50F2.5) are significantly higher than that of ECC-PP fibers (ECC G50S0.2F2.0 and ECC G50S0.2F2.5). For the ECC G60 series, the flexural strength obtained by ECC G60F2.5 in the current study was lower than ECC-PP fibers in Lee et al. (2018b) (G60S0.2F2.0 and G60S0.2F2.5), the modulus of the toughness of this mixture is greater than its counterpart. Therefore, the PVA fibers employed in the design mix compositions of this current study are more effective compared to PP fibers in terms of flexural performance. The findings in this study confirm that PVA fibers are better than PP fibers to be used in developing ECC that exhibit strain hardening and multiple fine cracking behaviors, and this is parallel with the evidence found in previous investigations (Huang & Zhang, 2014; Li et al., 2001; Li et al., 2004; Liu et al., 2018; Pakravan et al., 2018; Yang & Li, 2014; Yang et al., 2007).

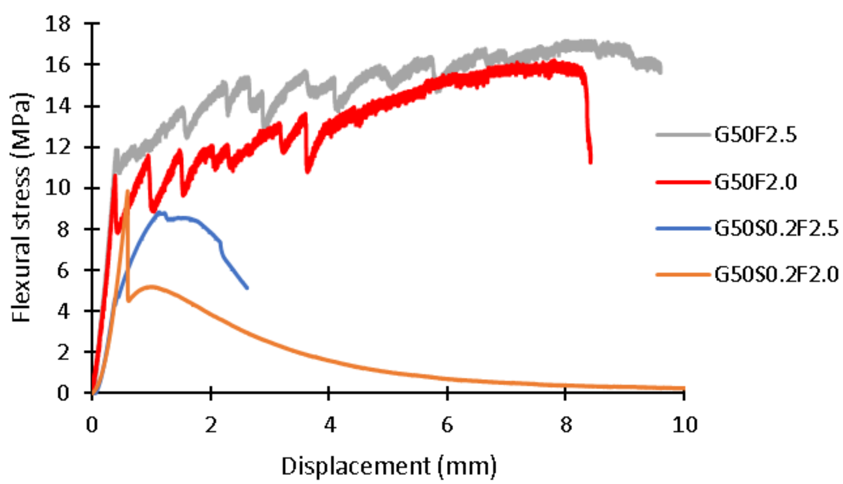

Figure 3. Comparison of flexural behavior for ECC G50 series

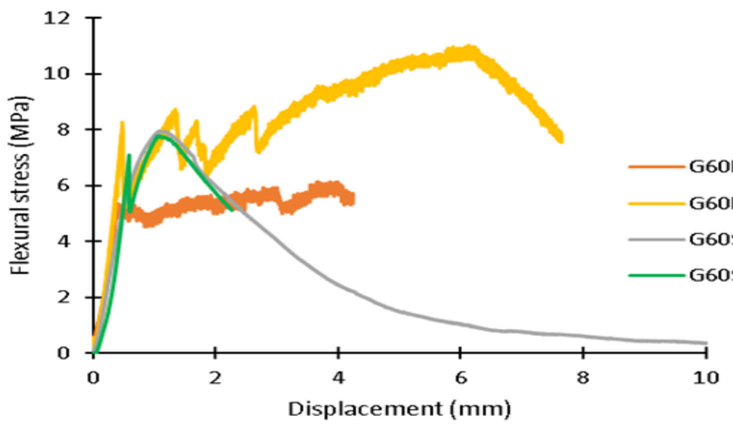

Figure 4. Comparison of flexural behavior for ECC G60 series

Failure Mode of Specimens

As shown in Figure 2, all ECC mixtures in the current study were able to go beyond their first cracking strength until they achieved the ultimate strength and finally failed under increasing applied point load. All ECC specimens failed in ductile modes, as shown in Figure 5b. Unlike the control specimens, ECC specimens exhibit multiple cracking with very fine crack widths, which required minor or no repair. As indicated in Figure 5a, the control specimens showed a single big crack at the mid-span of the plate. This mode is considered a brittle failure, even though the average compressive strength of 44.02 MPa is obtained from this mixture.

Figure 5. Failure modes under three-point bending test

CONCLUSION

The performances of ECC mixtures are found to be satisfactory for both compression and flexural tests in this study. From the compression test results, all ECC specimens except

G60F2.0 demonstrated greater compressive strength compared to control specimens. On the other hand, all ECC plate specimens demonstrated good strain-hardening and multiple cracking behaviors under the three-point bending test. The ECC G50 series performed better than the G60 series in both compression and flexural tests, as observed in this study. Among all, ECC G50F2.5 is considered the best mixture as it achieves the highest flexural strength of 16.65 MPa with the ultimate displacement of 8.54 mm, while its compressive strength is 54.82 MPa. Even though increasing the content of PVA fibers up to 2.5% of volume fraction is not beneficial in improving the compressive strength, it slightly enhances the flexural properties of the ECC G50 series. This observation is not discovered in the ECC G60 series. Hence, more experimental studies are required to confirm this trend. Compared to the previous study by Lee et al. (2018b), incorporating PVA fibers instead of PP fibers in ECC has improved flexural ductility and modulus of toughness under the same design mix proportion. However, the trend in the compressive behavior of ECC is inconsistent when the results of these two fibers are compared. Hence, the effect of the type of fibers (PVA or PP) on the compressive strength of ECC is less significant.

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