Mechanical Properties of Engineered Cementitious Composites Using Local Ingredients

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ABSTRACT

This research focuses on the mechanical properties of Engineered Cementitious Composites (ECC). Few ECC mixtures were designed and tested under direct tensile test and compression test. The novelty of this research is the utilization of available local materials in Malaysia, which is significantly different from the ingredients employed by previous researchers in the US, Japan and other countries. The ingredients used for ECC mixtures in this research were Ordinary Portland Cement (OPC), ground granulated blast-furnace slag (GGBS), sand, water, superplasticizer (SP) and polypropylene (PP) fibers. Local ingredients such as river sand and GGBS were used to replace micro silica sand and fly ash in the standard mix of ECC. Test results demonstrated that tensile ductility and compressive strength in ECC improved as compared to normal concrete. The effect of cement replacement ratio and fibres content are discussed based on the performance in both tensile and compressive properties. Comparison with previous studies was carried out to identify the weaknesses of the current ECC mixture, so that improvement can be done in future studies. The best ECC mixture is proposed according to the performance in mechanical properties.

Keywords: *ECC, Ductility, Tensile Strain Capacity, Compressive Strength, Fibres.*

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Introduction

Concrete is commonly classified as brittle material as it has the lowest tensile strain capacity, therefore it must be reinforced by steel reinforcement to resist tensile forces in most of the structural elements. The emerging of Engineered Cementitious Composites (ECC) which featuring ultra-high ductility becomes popular since few decades ago to solve the brittleness of concrete. ECC strains-hardens in tension, accompanied by the sequential development of multiple cracking after first cracking. Its ultimate tensile strain capacity can be up to 5%, while its crack width is limited to below 100μm [1-2]. This superior behaviour makes it attractive to be used in earthquake-resistant structures. Under compression, ECC has a lower elastic modulus compared with normal concrete due to the lack of coarse aggregates, but it reaches its compressive strength at a larger strain [3]. Its greater compressive strain also contributes to enhancing the seismic performance of structures. The post-peak response reveals that ECC is well confined, and therefore, it relaxes requirements for confinement reinforcement in critical regions of earthquake-resistant structures such as the beam-column joints. Therefore, both tensile and compressive behaviour make ECC an ideal material in seismic-resistant structures.

Previous experimental investigations have revealed the advantageous behaviour of ECC in structures subjected to cyclic loading [4-9]. Compatible deformations between steel reinforcement and ECC were observed at multiple cracking stages [10-11]. Moreover, steel reinforcement embedded in ECC could developed significantly higher bond strength rather than in concrete [12]. Previous research [7, 9, 13-14] demonstrated that the elimination of transverse reinforcement is possible when ECC is used in the beam-column joints. In addition, damage tolerance of ECC structural elements can reduce structural repair and maintenance cost. Therefore, it is worth to explore a new version of ECC which can meet the required mechanical properties based on structural applications.

Basically ECC is made of cement, cement replacement materials (fly ash or ground granulated blast-furnace slag (GGBS)), sand, water, chemical addictive and fibres. By far, the common types of fibres used are polyethylene (PE), polyvinyl alcohol (PVA) and polypropylene (PP) fibres. Among all, PVA fibres gained popularity due to its excellent performance in tensile ductility [1, 7, 15-16] at a lower cost if compared to PE fibres. It can be eight times cheaper than PE fibres [1]. On the other hand, the use of PP fibres in ECC is rather limited [9, 17-18] despites of its lower cost and environmental friendly. In previous study [9], when 3.0% of PP fibres combined with fly ash, cement, sand and water, strain hardening behavior can be observed from the uniaxial test. Therefore in this study, PP fibres were chosen to be explored as they are widely available and low cost in Malaysia. The percentage of fibres incorporated in production of ECC was generally around 1.5% to 3.0% in volume fraction.

Due to the removing of coarse aggregate from ECC, a larger portion of cement is needed in ECC matrix. To minimize of the amount of cement used, cement-replacement materials such as fly ash and ground granulated blast-furnace slag is widely employed since few decades ago. Fly ash-ECC appeared to be the most desirable material compared to GGBS-ECC in exhibiting strain hardening behavior [16, 19]. However, its compressive strength was generally lower than that in the GGBS - ECC. Previous studies on the use of 50-80% replacement of GGBS in ECC [20] revealed that the tensile strain capacity of 1.5-2.7% and compressive strength of 50-70 MPa can be achieved. Thus, GGBS was employed in this study due to the cheaper cost of this ingredient compared to fly ash.

Materials and Methods

A total of seven mixtures of ECC was designed and tested under compression and tension after 28 days of curing. The aim of this study is to investigate the feasibility of using local available materials to produce ECC mix which can perform well in compression and tension. Other than ground granulated blast-furnace slag (GGBS), cement, polypropylene (PP) fibres, river sand was used (instead of silica sand) in this study. The dimensions of the PP fibres are 6 mm in length and 19.5μm in diameter with density of 910 kg/m3. Figure 1 shows the raw ingredients employed and Table 1 shows the design mix proportion of ECC, respectively.

Figure 1: Raw ingredients.

Table 1: Mix proportion of ECC

Mixture	**Unit Weight (Kg/m^3)**				
	Cement	**GGBS**	**Sand**	**Water**	**PP fibers**
G50C50F2.0	722	722	289	390	18
G60C40F1.5	578	867	289	390	14
G60C40F2.0	575	863	288	388	18
G60C40F2.5	572	858	286	386	23
G70C30F1.5	435	1008	289	390	14
G70C30F2.0	430	1001	286	386	18
G70C30F2.5	428	1000	286	386	23

In the notations, designation of G50C50F2.0 refers to 50% of GGBS, 50% of cement and 2.0% of fibres (in volume fraction). The effect of cement replacement ratio was studied through the use of 50%, 60% and 70% of GGBS at 1.5%, 2.0% and 2.5% of fibres in volume fraction. The water to binder ratio and sand to binder ratio were fixed at 0.27 and 0.2, respectively. The binder is the combination of cement and GGBS. The amount of SP was controlled at 3.0-3.5 Kg/m^3 to provide workability of the ECC mortar.

For every mixture, three samples of 50 mm diameter by 100 mm long cylinders were prepared and tested under compression (Figure 2). On the other hand, six samples of dog-bones were prepared and tested under the uniaxial tensile machine (Figure 3). The size geometries of dog-bones samples are shown in Figure 3. During the preparation of specimens, solid ingredients (cement, GGBS and sand) were first mixed for 1-2 minutes. Water and superplasticizer were then added slowly until fluidity and uniformity of mortar were achieved, this process took longer time (about 3-5 minutes). Fibres can be added in when the mortar matrix was in the consistent and uniform state. Fibres need to be inserted slowly to avoid fibres balling that could cause inaccuracy of the test results. Mixing process was terminated when all fibres were evenly distributed. The fresh mortar was then cast into moulds according to the planned tests. After 24 hours, specimens were demolded and curing took place in the air condition at room temperature for 28 days. During the test, specimens were loaded at a constant loading rate of 0.15 mm/minute.

Figure 2: Compression test.

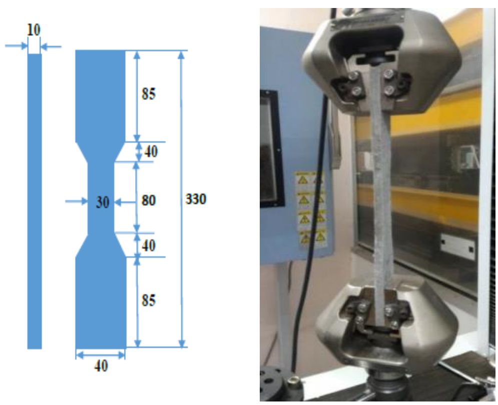

Figure 3: Tensile test.

Results and Discussion

Compressive Properties

The compressive strength of ECC cylinders was obtained through uniaxial compression test on 28 days of curing. Table 2 shows the ultimate compressive strength for every sample of testing and the average value for each mixture. Mixtures with 50% and 60% of GGBS replacement yield better compressive strength compared with mixtures with 70% of GGBS replacement. This compressive strength range (approximately 33-35 MPa) is comparable with normal concrete grade C30/37 as stated in Eurocode 2 [21]. This trend of result indicates that compressive strength is reduced when the amount of cement used is reduced. However, mixture G60C40F2.0 performed badly in terms of compression, it is merely at 21.40 MPa. It could be possibly due to the poor workmanship such as lack of compaction or excessive water has been added into the mix to achieve uniformity and workability. In terms of the desirable cement-replacement ratio, it is suggested that the use of GGBS has to be limited at 60%, i.e. ratio of 1.5 (GGBS/cement) only if normal concrete grade C30/37 is used as a benchmark. Besides, adding of fibres has no significant effect in compression strength under the same series of GGBS and cement as shown in Figure 4. Therefore, fibers content can be kept in minimum level i.e. 1.5% for economic design of ECC mix. Figure 5 shows the specimens after compression test. All specimens failed by crushing under compression load.

Table 2: Compressive Strength

Mixture	Compressive strength (MPa)			
	Sample 1	Sample 2	Sample 3	Average
G50C50F2.0	33.40	34.90	33.40	33.90
G60C40F1.5	33.12	35.98	34.06	34.39
G60C40F2.0	22.70	20.59	20.90	21.40
G60C40F2.5	36.11	34.11	35.67	35.30
G70C30F1.5	22.09	22.79	20.07	21.65
G70C30F2.0	17.54	18.28	23.74	19.85
G70C30F2.5	23.71	17.15	20.53	20.46

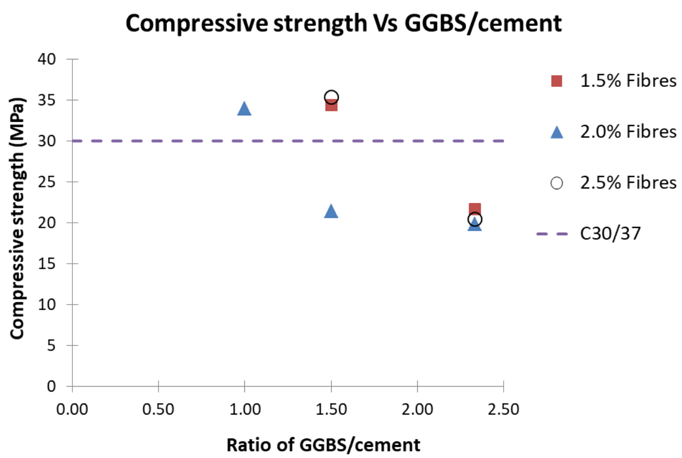

Figure 4: Effect of GGBS/cement ratio in compressive strength.

Figure 5: ECC cylinders after compression test.

Tensile Properties

The results of uniaxial tensile tests are plotted in Figure 6. Only one typical stress-strain curve is performed for each mixture. The maximum tensile strength and tensile strain capacity are listed in Table 3. No trends on the effect of the GGBS replacement ratio and fibers content can be observed, but all specimens showed tensile strain capacity of 0.5-1.6% which is 50-160 times better than normal concrete. Generally, tensile strengths of the tested specimens are in the range of 1.6-3.4 MPa. The modulus of elasticities (stiffness of the curves) is poorly performed for all specimens, possibly due to the gap existed during test set-up and also inappropriate instrumentation. It can be seen that mixture G60C40F2.0 gives the best tensile properties among all, with the tensile strength of 3.43 MPa and 1.56% of strain capacity. Multiple transverse cracks were not observed in any of the specimens, most of the specimens failed by local crack along the gauge length. This test result indicates that poor test set-up and it need to be improved for future studies.

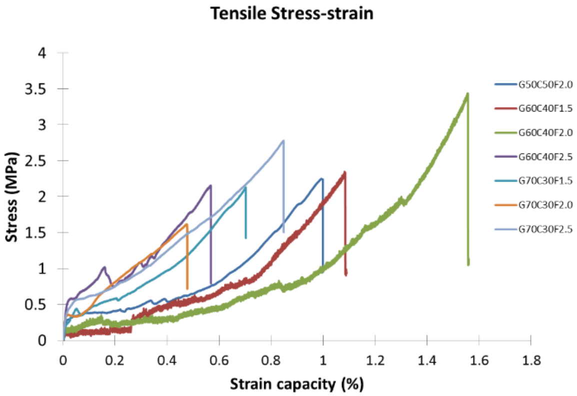

Figure 6: Tensile stress-strain curves.

Table 3: Tensile Properties

Mixture	Tensile strength (MPa)	Tensile strain Capacity (%)
G50C50F2.0	2.22	1.00
G60C40F1.5	2.30	1.09
G60C40F2.0	3.43	1.56
G60C40F2.5	2.15	0.57
G70C30F1.5	2.14	0.70
G70C30F2.0	1.61	0.48
G70C30F2.5	2.77	0.85

Comparison with Previous Studies

Mechanical properties

The result of the compressive and tensile properties for one of the mixture, i.e. G60C40F2.0 is compared with previous studies [12, 20] as shown in Table 4. Despite some of the raw ingredients and mix proportion were varied, but the variations are in minimum level. All the three mix design consisted of 60% of GGBS and 40% of cement, 2.0% of fibers and comparable water to binder ratio. The effects of the type of fibers and sand as well as sand to binder ratio were investigated through this comparison. It was found that the compressive strength of the G60C40F2.0 is far below than the other studies. In addition to the possible reason that explained in the previous section, the use of local river sand may be the main cause that led to the poor performance in compression. As a matter of fact, silica sand is well known in terms of improving matrix uniformity [20]. However, according to a study by Meng [15], the average compressive strength 59.86 MPa can be achieved when 55% of fly ash combined with 2.2% of PVA fibers when river sand was employed. In terms of tension, the value of tensile strength and tensile strain capacity are closer to the other two studies. Overall, the use of greater sand to binder ratio, i.e. 0.36 [15, 20] yield enhancement in mechanical properties. This suggests that the sand to binder ratio can be increased in future studies.

Table 4: Comparison of Mechanical Properties with previous research

Mixture	**Current study**	**Study by Lee, 2016 [12]**	**Study by Chen, 2013 [20]**
GGBS/cement	1.5	1.5	1.5
Sand/binder	0.2	0.2	0.36
Water/binder	0.27	0.27	0.25
Fiber in volume fraction (%)	2.0	2.0	2.0
Type of Fiber	PP	PVA	PVA
Type of sand	Local river sand	Silica sand	Silica sand
Mechanical Properties (28 days)			
Compressive strength (MPa)	21.4	50.3	66.0
Tensile strength (MPa)	3.43	3.20	4.68
Tensile strain capacity (%)	1.56	1.20	1.63

Cost Analysis

Table 5 shows the cost analysis between normal concrete, ECC G60C40F2.0 (current study), ECC mix by Lee (2016) and ECC mix by Chen (2013). It is worthy to mention that only the main ingredients such as cement, GGBS, aggregates, sands and fibres were considered in the cost analysis. Water and superplasticizer are excluded due to the insignificant cost in the ECC mix. It can be seen from Table 5, ECC cost is about 4-8 times than that of normal concrete C30/37 due to the elimination of aggregates and the use of fibres in matrix composition. In the current study, the use of river sand and PP fibres instead of silica sand and PVA fibres can save up to 41% and 43% of total cost per cubic meter respectively if compared to ECC mixtures by Lee (2016) and Chen (2013). Notable the mix proportions of these ECC mixtures were identical as shown in Table 4, except the amount of silica sand employed in Chen's study was about 1.8 times than that in current and Lee's study.

Table 5: Comparison of cost analysis

Main Ingredients	**Unit weight kg/m^3**	**Unit price (Rm/kg)**	**Cost per m^3 (Rm/m^3)**
Normal concrete C30/37			
Cement	460	0.36	165.60
Aggregates	1077	0.04	44.16
River sand	718	0.04	26.57
		Total:	**236.32**
ECC G60C40F2.0			
Cement	578	0.36	208.08
GGBS	867	0.30	260.10
River sand	289	0.04	10.69
pp fibre	18	30.80	554.40
		Total:	**1033.27**
Study by Lee, 2016 [12]			
Cement	574	0.36	206.64
GGBS	860	0.30	258.00
Silica sand	287	0.75	215.25
PVA fiber	26	41.60	1081.60
		Total:	**1761.49**
Study by Chen, 2013 [20]			
Cement	491	0.36	176.76
GGBS	736	0.30	220.80
Silica sand	446	0.75	334.50
PVA fibre	26	41.60	1081.60
		Total:	**1813.66**

Conclusion

Results of compressive test and tensile test indicate that the ECC mix employed in this study has shown some enhancement in the mechanical properties over normal concrete. Also, the effect of cement replacement ratio and fibres content are investigated. Compression strength is reduced when cement replacement ratio is increased up to 70%, thus 60% of GGBS is suggested to keep its compressive strength of at least 30 MPa. On the other hand, the increasing of fibres content has no significant effect in enhancing mechanical properties of ECC. Therefore, 1.5-2.0% of fibers in volume fraction is sufficient in this series of ECC mix.

The main focus of this study is to find out the best mixture of ECC that can perform well in tension (ductility) with no compensation on its compressive strength. ECC G60C40F2.0 is identified to be the most desirable mix in tension, but gave undesired compressive strength. Further investigation on this mix is needed to confirm its material properties, all the procedure and steps of preparation, mixing, casting, compacting and curing have to be carried out carefully. Besides, ECC G50C50 and G60C40 yield medium ductility without compensation on their compressive strength. Therefore, these mixtures can be suggested for further investigation.

Even though ECC mix employed in this study performed fairly good if compared with previous ECC version, but the cost analysis demonstrates material cost can be reduced due to the use of local sand and PP fibers. Hence, the acceptance of ECC material to replace normal concrete in the local industry will be more positive if the implication of the cost is in minimum level.

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