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Numerical and Parametric Studies on Flexural Behaviour of ECC Beams by Considering the Effect of Slag and Micro-PVA Fibre

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Abstract-*Engineered cementitious composite (ECC) refers to the group of cementitious mixtures possessing the strain-hardening and crack control abilities. In this research, the mechanical performance of ECC beams will be investigated with respect to the effect of aggregate size and amount, by employing nonlinear finite element method. The proposed models would be justified by means of the experimental results of the ECC beams functioning under monotonic loads. Followed by this, nonlinear parametric study was made as per the arithmetical analysis method which investigates the impact of ECC aggregate content (AC) and ECC compressive strength (f_{ECC}) parameters upon the flexural stress and flexural deflection of ECC beams. The comparative analysis showed that an increase in the total size and quantity, there was observed no particular change in flexural strength, while the ductility of ECC had a negative influence. Besides, the ECC beams were observed to cause significant improvements in flexural stress, strain, and midspan deflection when measured against the reference beam (microsilica MSC), i.e. the average improvement percentages were 77.51%, 800% and 863.5%, respectively. These results are quite similar to that of the experimental results, which provides that the finite element model is in accordance with the desirable flexural behaviour of the ECC beams. The provided models may also be employed to obtain a precise estimate of the flexural behaviour of ECC beams.* ***Copyright © 2016 Penerbit Akademia Baru - All rights reserved.***

Keywords: Engineered cementitious composite (ECC), Flexural behaviour, Ductility, Finite element modelling, Parametric study

1.0 INTRODUCTION

Concrete is a quasi-brittle material in which upon reaching the particular tensile strength limit, a crack is formulated which keeps increasing in width with the passage of time. In most of the structures the crack width control abilities are below satisfaction, even when having steel reinforcements. Cracking tends to decrease the durability of structures as harmful chemical substances can easily attack the concrete surfaces. For this reason, various preventive measures are employed to reduce the quasi-brittle properties of concrete [1-7]. Recently, engineered cementitious composites (ECCs) have been proposed as a new class of concrete materials which have considerably greater level of ductility. ECC is a unique kind of cementitious composite having high ductility and damage tolerance properties under intense mechanical loadings, including tensile and shear loadings [8-14]. The material is optimized as per the principles of micromechanics [8, 15-19] which increases the tensile strain capacity of material up to 3-5% where operating uniaxial tensile loading making it achievable through only 2% polyvinyl alcohol (PVA) or polyethylene fibre (PE) quantity by volume [8, 20-22]. The strain-hardening property of ECC tends to enable significant development of multiple micro-cracks, i.e. the crack width limit remains within the range of 50 to 80 µm, even under extreme loads.

A micromechanics-based material design theory is employed to enhance the strength and energy ratios of the mixture proportions of ECC to acquire high composite ductility [8, 9, 23]. The crack control properties of ECCs with respect to controlling the width of occurring cracks depend upon the type, size, and amount of fibre, matrix ingredients and interface properties of the material. The manufacture of ECCs is done by employing particular quantities of high-quality mixtures, which when accompanied by the bristly material in the paste, helps to enhance the matrix (ECC without fibre) toughness. As a result, the material attains the crack control characteristics i.e. delayed crack initiation and prevention of steady-state flat-crack propagation which might cause to reduce the tensile ductility of ECC [22, 24, 25]. Furthermore, if the mixtures include large sized particles as compared to the standard size of fibre spacing, it may lead to cause balling of fibres which may result in disturbing the uniformity of fibre dispersion [26, 27]. This proposes that ECC with fine aggregate must have a standard aggregate/binder ratio (A/B) of 0.36 and a maximum grain size of 250 µm [22, 28].

Owing to various ecological and economical reasons, industrial by-products are now used as supplementary materials in the manufacture of different classes of concrete mixtures. Slag (S) is the most widely used and extensively available mineral admixture. However, in the past few years, (S) has been used as a substitution of cement with regard to its application in ECC [29-31]. Higher concentration of cement is obtained when coarse aggregate is absent in ECC. Furthermore, partial replacement helps to reduce ecological loadings. As mentioned previously, employing larger quantities of mineral admixtures, helps decreasing the strength of matrix while enhancing that of ECC with respect to tensile ductility [31-33]. Moreover, anhydrite mineral admixtures having small particle size and even spherical shape are employed as filler particles, providing higher density of the fibre/matrix interface transition zone resulting to produce high frictional bonding [31, 34-36]. This enhances long-term stability of the structure by significantly decreasing the steady-state crack width.

Employing high-volume mineral admixture in the manufacture of ECC can lead to cause an increase in the amount and size of aggregates leading to increase the matrix strength of the material. In a research conducted by Sahmaran et al.[37, 38], the mechanical properties of high-volume FA-ECC are studied with respect to the effect of aggregate size. The obtained results showed that the aggregate size of up to 2.38 mm, did not affect the ductility of ECC as it had no effect on the uniform fibre dispersion. In addition to aggregate size, there is a desire to increase the amount of aggregates and explore the use of an alternative mineral admixture type beyond FA. Nevertheless, the flexural behaviour of the ECC beams has not been brought to considerable research with regard to its numerical aspects. Besides, the influence of using slag as a deliberate approach has also not studied in terms of limit the matrix toughness and restore tensile ductility when higher amounts of aggregates are used. It is aimed to bring this area of knowledge under research.

This research intends to study the effect of an increase in the amount and size of aggregate material, on the flexural properties of ECC beams by employing 3D nonlinear finite element simulation model through ANSYS software. The comparative analysis of these results with those obtained through experimental study of elements having similar geometric and mechanical characteristics, employing them as reference models. To study the effect of various factors upon the flexural stress and flexural deflection, a nonlinear parametric study was made. As per the results obtained through this study, a model has been put forward which accounts the ECC aggregate content (*AC*) and ECC compressive strength (f_{ECC}) factors having a significant influence upon the flexural stress and flexural deflection of ECC beams.

2.0 NUMERICAL MODELLING OF ECC BEAMS

2.1 ANSYS finite element models

ANSYS program was employed to determine the malfunctioning of nonlinear finite element model. The program is able to deal with the particular numerical models designed to account for the nonlinear course of actions of concrete and ECC beams operating under invariable loadings. The ECC beams and Microsilica concrete (MSC) were modelled by using SOLID 65 elements. Each of these elements entails eight nodes with three levels of freedom at each node and transformations in the nodal x-, y- and z-directions. SOLID 65 elements hold the properties of plastic deformation, three dimensional cracking and crushing. ANSYS employs linear isotropic and multi-linear isotropic material attributes for modelling concrete, along with supplementary concrete material properties, for replicating actual concrete behaviour [39].

The state of cracked surface is indicated through the shear transfer coefficient β_t, whose value ranges from 0.0 to 1.0, where 0.0 symbolizes a smooth crack while 1.0 represents a coarse crack [40, 41]. In this study, the value of shear transfer coefficient of an open crack, β_t is 0.2 [42] while the value of shear transfer coefficient of a closed crack, β_c is 0.8 [43]. For ECC beams, β_t=0.05 and β_c=0.45, were adopted [44].

The equation $E_c = 4700\sqrt{f_c^{'}}$, can be used to calculate the modulus of elasticity of the MSC while the tensile strength can be computed from the equation $f_r = 0.62\sqrt{f_c^{'}}$. The Poisson's ratio gave the value of 0.2. Furthermore, the following equations for the multi-linear isotropic stress–strain curve were used to obtain the compressive uniaxial stress–strain values for the MSC model [42, 43]:

$$E_c = f_{el}/\varepsilon_{el}\,, \quad \varepsilon_o = \frac{2f_c^{'}}{E_c} \quad \text{and} \quad f = \frac{E_c\varepsilon}{1+\left(\varepsilon/\varepsilon_o\right)^2} \tag{1}$$

In this equation,

- f_{el} represents the stress at the elastic strain (ε_{el}) in the elastic range ($f_{el} = 0.30f_c^{'}$),
- ε_o represents the strain at the ultimate compressive strength,
- $\sqrt{f_c^{'}}$ represents the compressive strength of the concrete obtained from testing cylinders,
- f is the stress at any strain ε

For ECC beams, the typical stress-strain curves acquired from uniaxial tension and compression experiments are represented through dotted lines as shown in Fig. 1 [33, 45-47]. The following equations were used to obtain the tensile stress-strain relationship of ECC [48]:

$$\sigma_t = \frac{\sigma_{tc}}{\varepsilon_{tc}}\varepsilon \qquad 0 \le \varepsilon < \varepsilon_{tc} \tag{2}$$

$$\sigma_t = \sigma_{tc} + \left(\sigma_{tu} - \sigma_{tc}\right)\left(\frac{\varepsilon - \varepsilon_{tc}}{\varepsilon_{tu} - \varepsilon_{tc}}\right) \qquad \varepsilon_{tc} \le \varepsilon < \varepsilon_{tu} \tag{3}$$

Where:

- σ_{tc} represents the first cracking strength in tension,
- ε_{tc} represents the strain at first cracking,
- σ_{tu} represents the ultimate tensile strength,
- ε_{tu} represents the tensile strain at σ_{tu}

The compressive stress-strain relationship of ECC can be expressed as [48]:

$$\sigma_c = 2\frac{\sigma_{c0}}{\varepsilon_{c0}}\varepsilon \qquad 0 \le \varepsilon < \frac{1}{3}\varepsilon_{c0} \tag{4}$$

$$\sigma_c = \frac{2}{3}\sigma_{c0} + \frac{\sigma_{c0}}{2\varepsilon_{c0}}\left(\varepsilon - \frac{\varepsilon_{c0}}{3}\right) \qquad \frac{1}{3}\varepsilon_{c0} \le \varepsilon < \varepsilon_{c0} \tag{5}$$

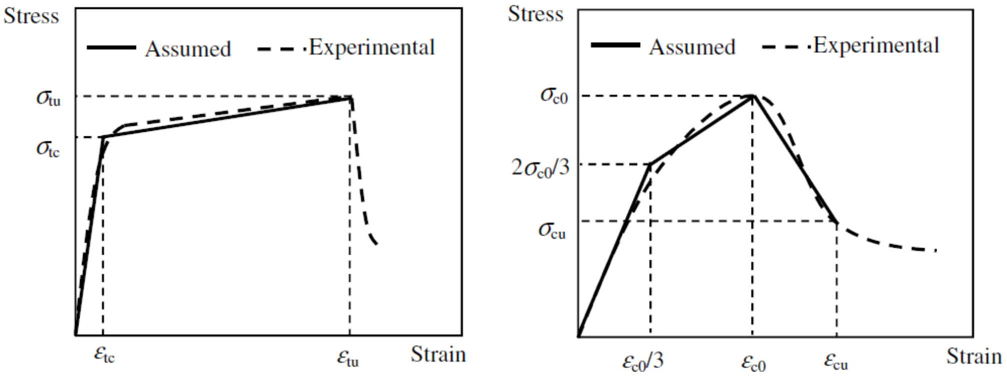
$$\sigma_c = \sigma_{c0} + (\sigma_{cu} - \sigma_{c0})\left(\frac{\varepsilon - \varepsilon_{c0}}{\varepsilon_{cu} - \varepsilon_{c0}}\right) \qquad \varepsilon_{c0} \le \varepsilon < \varepsilon_{cu} \tag{6}$$

Where:

- σ_{c0} represents the compressive strength,
- ε_{c0} represents the strain at peak stress,
- σ_{cu} represents the ultimate compressive stress (in the postpeak branch),
- ε_{cu} represents the ultimate compressive strain

In this study, $\sigma_{cu} = 0.5\sigma_{c0}$ and $\varepsilon_{cu} = 1.5\varepsilon_{c0}$ were adopted. The dimensions of concrete elements were used as 1mm in length, 1mm in height and 1mm in width.

The PVA fibres were modelled by using Link 8 elements. This is a 3D spar element having two nodes and three levels openings at each node. It holds the property of plastic deformation [39]. In this study, bond between the concrete and the PVA fibres is considered as effective as that between nodes of corresponding concrete solid elements. This helps to bring the same nodes to share same material. As per the finite element model, the fibres were considered as bilinear, isotropic, elastic and perfectly plastic material. A value of 0.42 was used for the poisson's ratio. Solid 185 element [39] were used to model the loading and support plates. The solid element has eight nodes with three degrees of freedom at each node, translations in the nodal x, y, and z directions. The steel plates incorporated into the finite element models were assumed to be linearly elastic materials with an elastic modulus of 200 GPa and a poisson's ratio of 0.3.

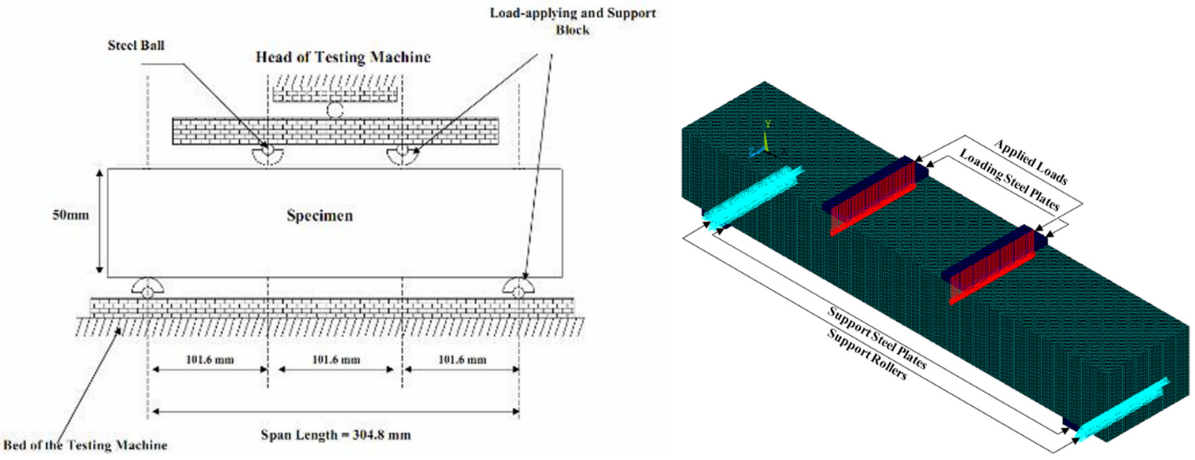


(a) (b)

Figure 1: Stress-strain relationship of ECC. (a) Under uniaxial tension; (b) under uniaxial compression.

2.2 Structural models

In order to study the flexural behaviour of ECC beams, six ECC beams with dimensions of (360×75×50) mm, have been modelled and compared with MSC beam model, as shown in Fig. 2. The beams were designed to be simply supported over a clear span of 304 mm and subjected to four-point loading. The basic mixture ingredients in ECC were: two different fine aggregate sizes (400 and 1000) µm, three aggregate contents (0.36, 0.45, and 0.55 A/B), Slag (S) mineral admixture type, (1.2 S/C ratio) mineral admixture replacement rate and a constant water-binder ratio (*w*/*b*) of 0.27 are considered. Details of this factorial design and designation of mixtures are presented in Table 1. PVA fiber 8 mm in length and 39µm in diameter extensively used in this study. To account for material inhomogeneity, a PVA fiber content of 2% by volume has been typically used in the mixture design. Table 2 illustrate the mechanic and geometric properties of PVA fibers. All the used data in this study based on confirmed experimental results, which have been achieved by [49].



(a) (b)

Figure 2: Experimental and numerical specimens. (a) four-point bending test; (b) 3 dimensional model.

Table 1: ECC mixture proportions containing slag by weight

Specimen ID.	Cement	*w/b*	Aggregate/Binder 0-400 μm	 0-1000 μm	S/C	HRWR (kg/m^3)
S-1.2-0.36-400	1	0.27	0.36	-	1.2	5.8
S-1.2-0.45-400	1	0.27	0.45	-	1.2	5.9
S-1.2-0.55-400	1	0.27	0.55	-	1.2	6.0
S-1.2-0.36-1000	1	0.27	-	0.36	1.2	4.9
S-1.2-0.45-1000	1	0.27	-	0.45	1.2	5.0
S-1.2-0.55-1000	1	0.27	-	0.55	1.2	5.0

Table 2: Mechanical and geometric properties of PVA fibres

Fiber Type	Nominal Strength (MPa)	Apparent Strength (MPa)	Diameter (μm)	Length (mm)	Young Modulus (GPa)	Strain (%)	Specific Weight (kg/m^3)
PVA	1620	1092	39	8	42.8	6.0	1300

3.0 VERIFICATION OF NUMERICAL MODELLING WITH EXPERIMENTAL RESULTS

3.1 Load-Deflection curves

Fig. 3 illustrates the flexural load-midspan beam deflection curves for all the ECC beams. In the flexural load-deflection curves,

- the load at the first descend corresponded with the first cracking is termed as the first cracking load
- the maximum load is termed as the flexural load
- the corresponding deflection is termed as the flexural deflection (midspan beam deflection) capability

Fig. 3 further shows that while operating under deflecting load, an ECC beam having maximum size of 1000 μm bends similar to that of a ductile metal plate due to its property of plastic deformation. In all ECC beams, the flexural cracks prevailing at the tension surface are the first cracks to appear. Following this, the load increases along with producing multiple cracking, enhancing the inelastic deformation with an increase in stress. Microcracks produced from the first cracking point continued to extend in the midspan of the flexural beam. However, upon reaching the certain limit of fibre strength of the microcracks, bending failure in ECC took place, leading to cause a particular extent of deflection in that part when it reached its limit of flexural strength.

The average load limit for first-crack in ECC beam ranges from 1250 to 1493 N with respect to the aggregate size. The aggregate size is negatively related with the crack-load i.e. an increase in the maximum aggregate size i.e. from 400 to 1000 μm, causes a 19% decrease in the first-crack load. Besides, the extent of first-crack load of the ECC beams is not affected by variation of aggregate quantity of material. In the same way, the rigidity of the beams is also not influenced by changes in aggregate size and quantity. These results are similar to those obtained through studies conducted previously [50-52].

3.2 Flexural strength

In Fig. 4 the contrast between experimental results and the numerical flexural strength data is provided. With respect to the deflection before yield strength, the anticipated stress value of 6.8 MPa for 1000 μm maximum aggregate size beams and 8.45 MPa for 400 μm maximum aggregate size beams. Till the ultimate moment capacity is attained the curve is kept horizontal after the abrupt change. Moreover, the comparative analysis was in accordance with the calculated results.

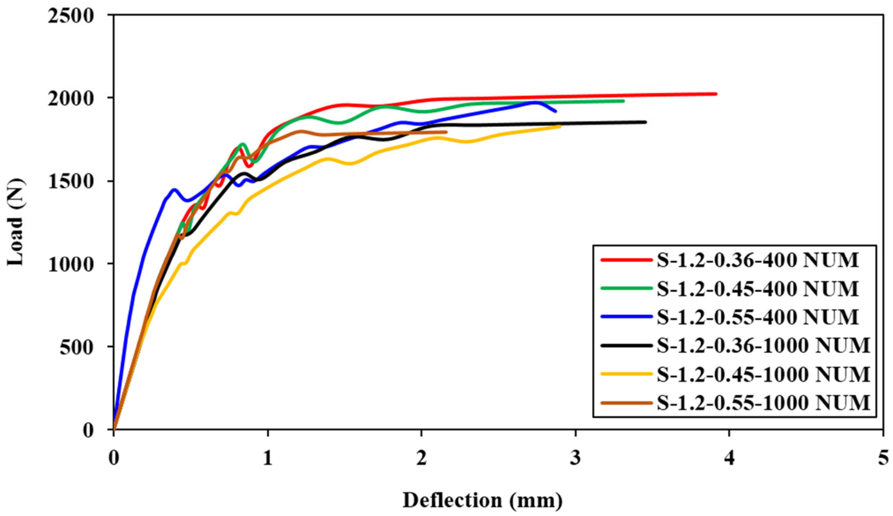


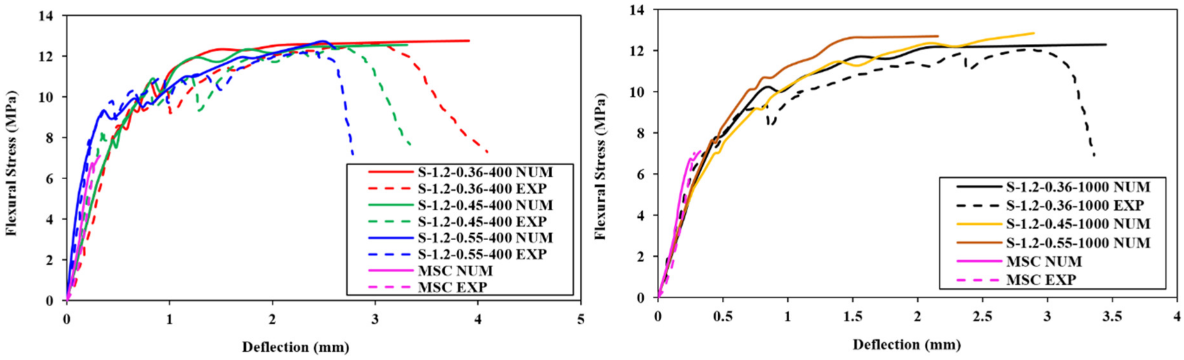
Figure 3: Numerical flexural load-deflection curves of ECC beams

For numerical results the average ultimate flexural strengths from 12.39 to 12.85 MPa fluctuate as seen in Fig. 5. Around 4% of ultimate flexural stress is decreased by the increase in the maximum aggregate size from 400 to 1000 μm. At any rate within the parametric range analysed in numerical and experimental research, the flexural strength is slightly influenced by the aggregate content and maximum aggregate size as per the compressive strength results.

Fig. 6 demonstrates the comparison between the practical results and the simulation. The experimental results are 1.5% less than the average ultimate strength from the numerical simulation for 400 and 100 μm maximum aggregate size beams. This implies that the comparative analysis is in accordance with the experimental value. Moreover, the results demonstrate that the ultimate flexural stress decreases with the increase in the aggregate content as per the maximum aggregate size which is in the accordance to the experimental value.

It is evident that the stresses of beam is decreased by the increase in aggregate content and maximum aggregate size as per the contour plots of the simulation results of flexural stress shown in Fig. 7. The cracks continued to spread over the top layer of the beam after cracking, without noticeable crack width. The constant moment region was also surrounded by various minute cracks with parallel to the major one. At the same time, amid the loading process the division of various minute cracks is also starting from the centre to both supports of the beams. After initial cracking, several cracking along the specimens and minor strain hardening behaviour is quite evident. Following that, the external moment causes to distort the adhering of fibres and cementitious matrix reducing their ability to withstand the tensile stresses. In this stage the load was continues to decrease gradually once the maximum load is applied. In the end, the ECC beams failed to sustain the stress, leading to cause multiple fibre fracture, giving rise to major cracks in the midspan [35].

Flexural stress increases when ECC beams are compared with the MSC beams as shown in Fig. 8. The experimental and numerical values for the mean percentage strength enhancement of 400 µm maximum aggregate size ECC beams in contrast with the MSC beams were 76.90% and 77.15%, respectively. Whereas, the experimental and the numerical values for 1000 µm maximum aggregate size ECC beams the mean improvement percentage in-flexural stress were 77.24% and 77.86%, respectively.



(a) (b)

Figure 4: Comparison between numerical and experimental flexural stress-deflection curves of ECC and MSC beams for: (a) 400 µm D_{max}; and (b) 1000 µm D_{max}.

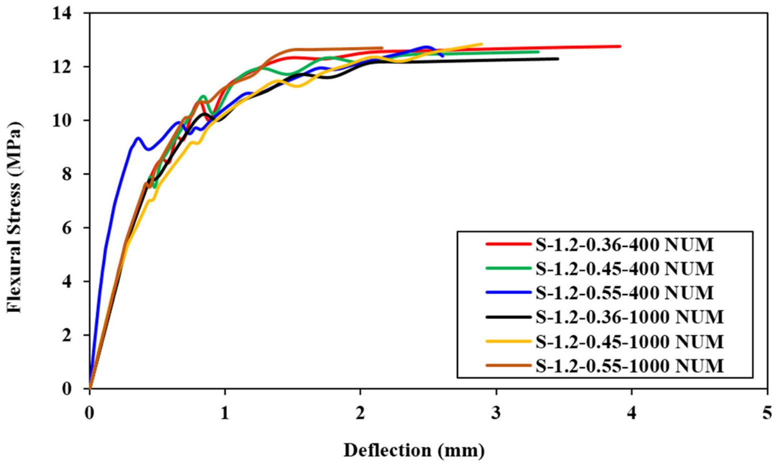


Figure 5: Numerical flexural stress-deflection curves of ECC beams

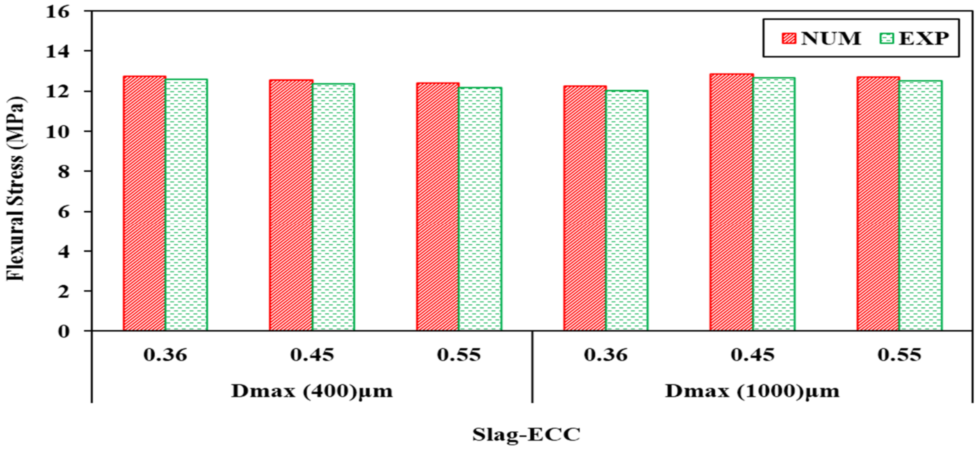
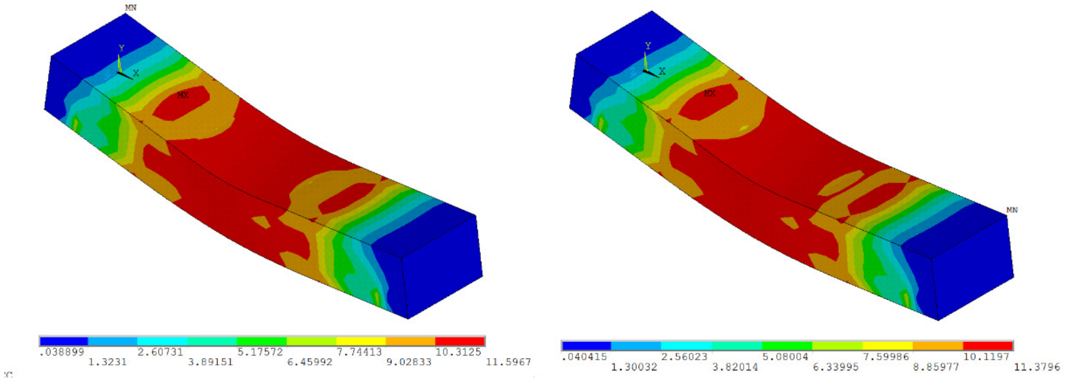
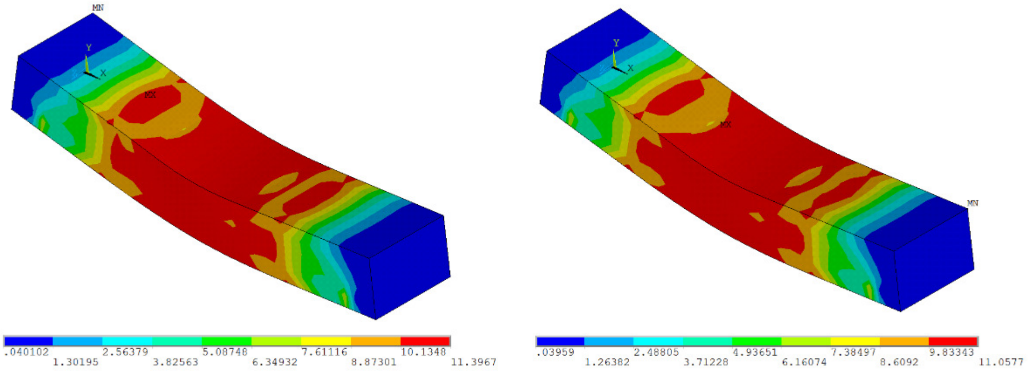


Figure 6: Comparison between numerical and experimental influence of aggregate size and amount on flexural stress



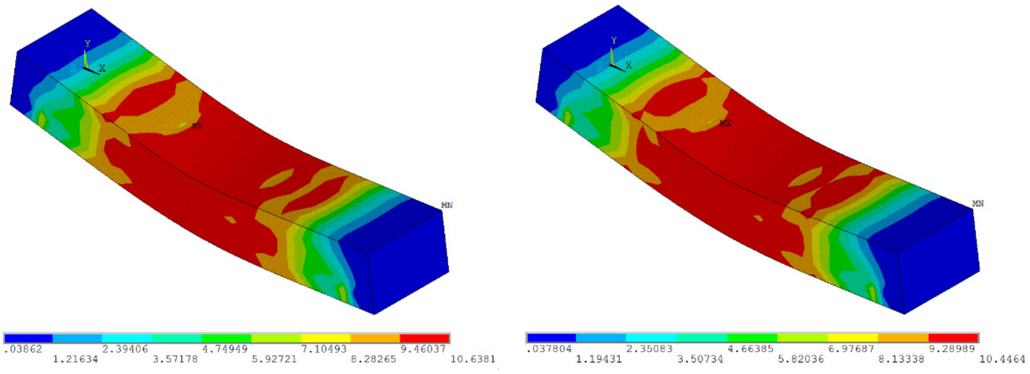
(a) AC=0.36, D_{max}=400

(b) AC=0.36, D_{max}=1000



(c) AC=0.45, D_{max}=400

(d) AC=0.45, D_{max}=1000



(e) AC=0.55, D_{max}=400 (f) AC=0.55, D_{max}=1000

Figure 7: Contour plots of flexural stress for ECC beams

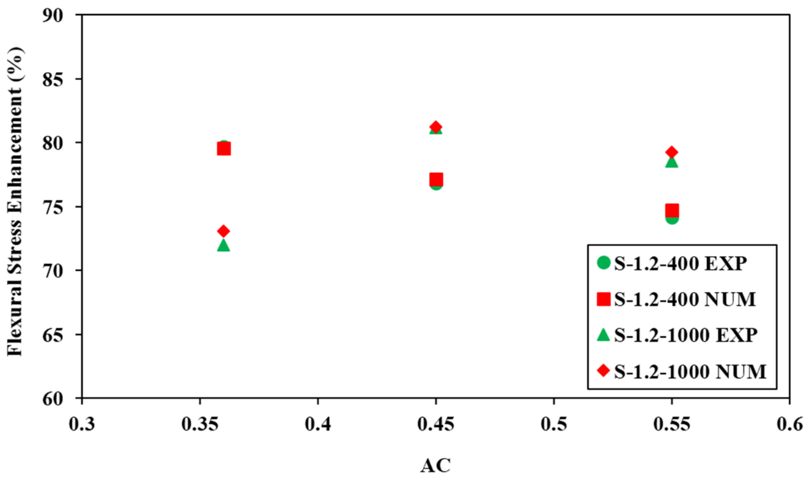


Figure 8: Flexural stress enhancement versus aggregate content of numerical and experimental results for ECC beams

3.3 Flexural strain

A normal numerical flexural stress– strain curve is shown in Fig. 9, which can be parted into two sections:

1. Elastic stage: This occurs along the first cracking process. The point of first cracking is analogous to the end of the initial linear section of the stress–strain curve. The strain at this stage is called first cracking strain.
2. Strain hardening stage: In this stage the flexural load-carrying ability increases to cause a consequent increase in strain which is accompanied by multiple cracking. The strain at this stage is called flexural strain.

The maximum strain for ECC beams having aggregate sizes of 400 and 1000 μm are 883% and 733%, respectively, which is higher than that of MSC beam. In Fig. 10 it has been shown that there occur a decrease in maximum strain and deflection by percentage of 60% and 47%, respectively when aggregate quantity of 400 μm maximum aggregate size of ECC beam is increased. In the same manner for 1000 μm maximum aggregate size ECC beams the respective percentages are 75% and 60%, respectively. As provided in Fig. 11, according to the simulation results of flexural strain for ECC beams, when the aggregate size is increased from 400 to 1000 μm there occurs a decrease in the flexural strain limit by percentage of 25%. Hence, this propose that the presence of high aggregate content and coarse aggregates in a cementitious paste may lead to increase the matrix (ECC without fibre) strength, which helps to reduce the initiation period of cracking process and averts the development of steady-state flat-cracking which may cause to decrease the tensile ductility of ECC [22, 24, 25]. Furthermore, employing aggregates having a particle size larger than the average fibre spacing may cause balling of fibres, leading to provide inadequate fibre dispersion uniformity [26, 27].

3.4 Mid-Span Beam Deflection

Fig. 12 illustrates the flexural deflection property of ECC beams, which signifies the material ductility. It has been provided that the type and amount of mineral admixture, significantly depends upon total deflection of the ECC beam. In comparison to the MSC beam, that of S-ECC exhibited better deflection abilities. This enhancement of deflection property in S-ECC beams can be justified by the fact that employing S is able to weaken the PVA fibre/matrix interface chemical linkage and reduce matrix (ECC without fibre) strength while strengthening the interface frictional bond [53]. Fig. 12 also demonstrates the correspondence between the numerical and experimental results providing that the average deflection from the numerical values for beams of aggregate size ranging from 400 and 1000 μm, are larger than those obtained from the experimental results having a variance of 2.1%.

In Fig. 12, the unwanted influence of enhanced size of aggregates on ductility performances can be easily observed. It is evident from the provided information that increases in aggregate size and quantity affects the ECC ductility and it decreases. The negative aspects of increasing aggregate may possibly be linked to the related poor dissipation of fibres. Required coating of fibres by the matrix is avoided by the balling of fibres supported by coarser aggregates at continuous aggregate content. Therefore, this affects a significant component that affects ductility i.e. effective fibre content [27]. In addition, a greater extent of aggregate interconnection is anticipated for ECCs with larger aggregate size and volume, giving out a greater matrix toughness, which results in the decrease in the margin to develop multiple cracking [22, 54].

It can be observed in Fig. 13 that when ECC beams are compared with MSC beam, development is demonstrated in terms of deflection. From experimental and numerical results, the average percentage deflection enhancement of 400 μm maximum aggregate size ECC beams whereas that of MSC beams were 882% and 928%, respectively. It is to be noted that the average enhancement percentage in deflection based on numerical and experiential outcomes for 1000 μm maximum aggregate size ECC beams were 799% and 755% respectively.

Other than ECC properties, characteristics and kinds of mineral admixture plus amount of the PVA fibres also determine the flexural behaviour of the beam specimens. Nonetheless, appropriate and suitable estimates of experimental outcomes can be provided by the simulation outcomes. It is to be noted that the techniques that are used to examine the flexural behaviour of the ECC are tested before they are implemented. The suggested numerical mechanism will be employed to evaluate the impacts of various parameters on the mechanical behaviour of the ECC beams.

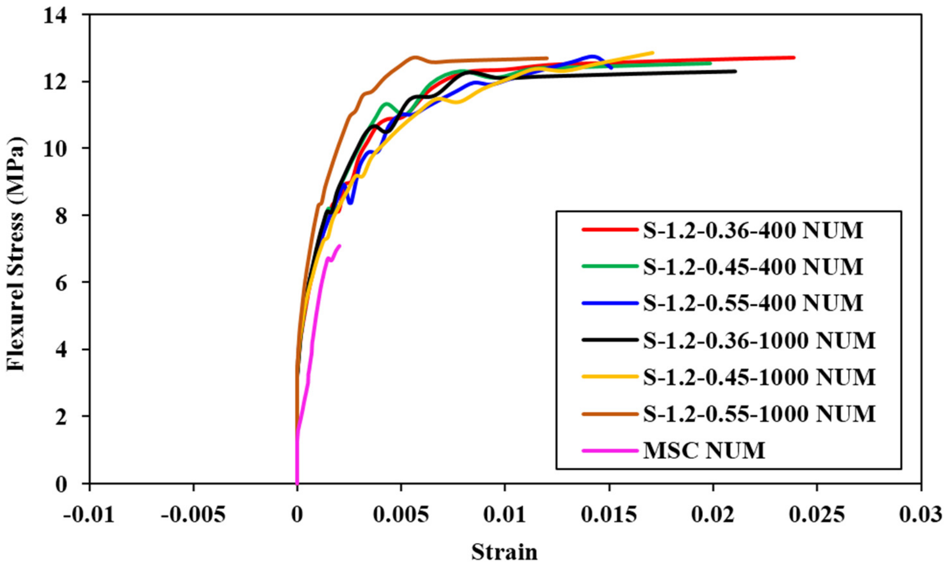


Figure 9: Numerical flexural stress-strain curves of ECC and MSC beams

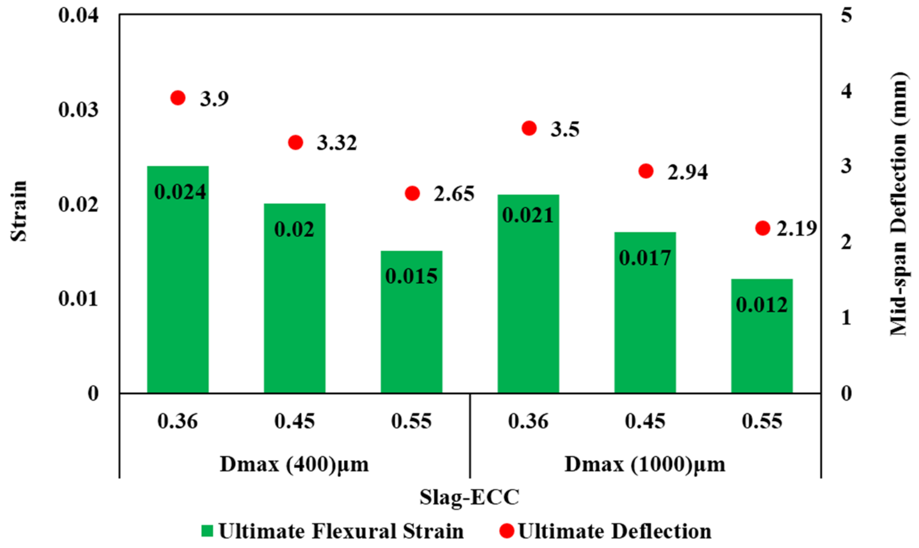


Figure 10: Influence of aggregate size and content on the flexural strain and deflection

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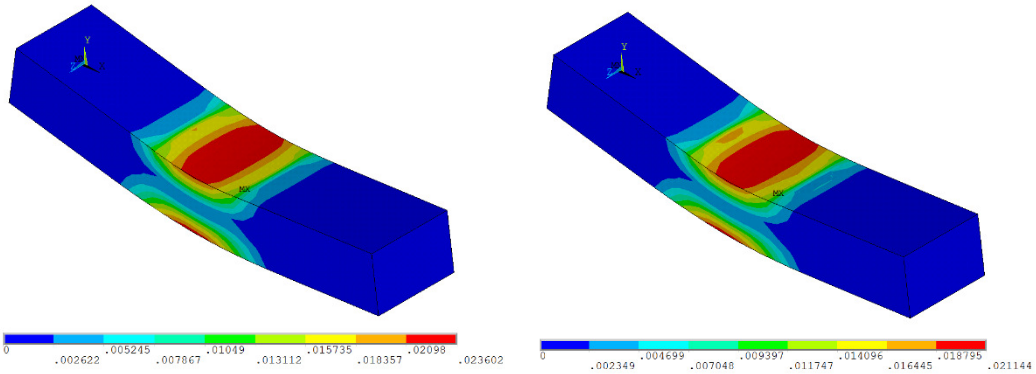
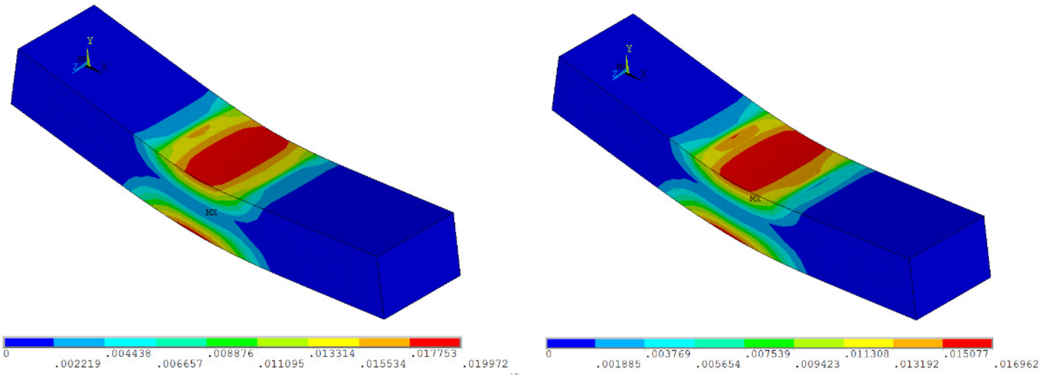
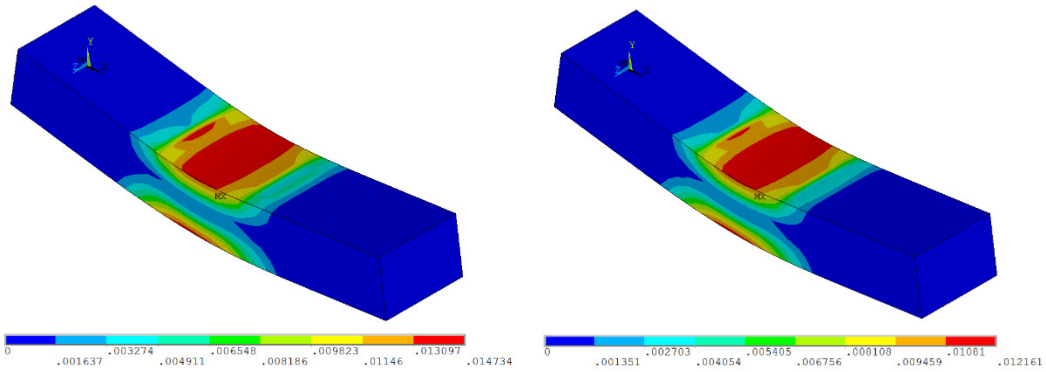


(a) AC=0.36, D_{max}=400 (b) AC=0.36, D_{max}=1000



(c) AC=0.45, D_{max}=400 (d) AC=0.45, D_{max}=1000



(e) AC=0.55, D_{max}=400 (f) AC=0.55, D_{max}=1000

Figure 11: Contour plots of flexural strain for ECC beams

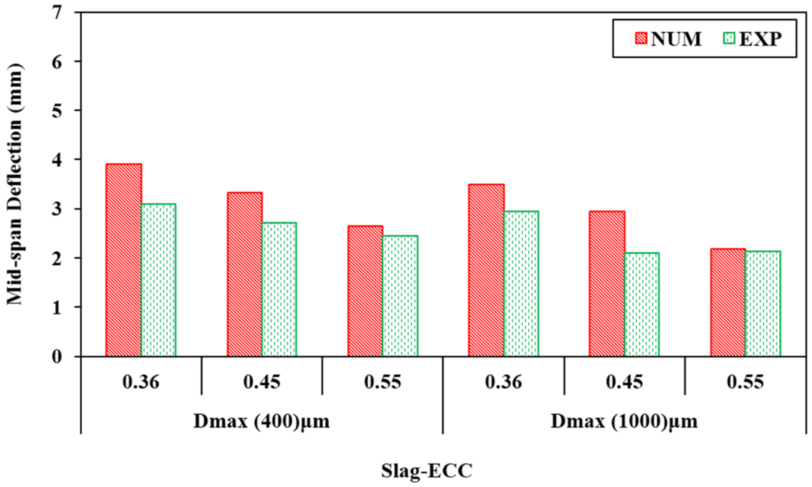


Figure 12: Comparison between numerical and experimental influence of aggregate size and amount on deformability in flexure

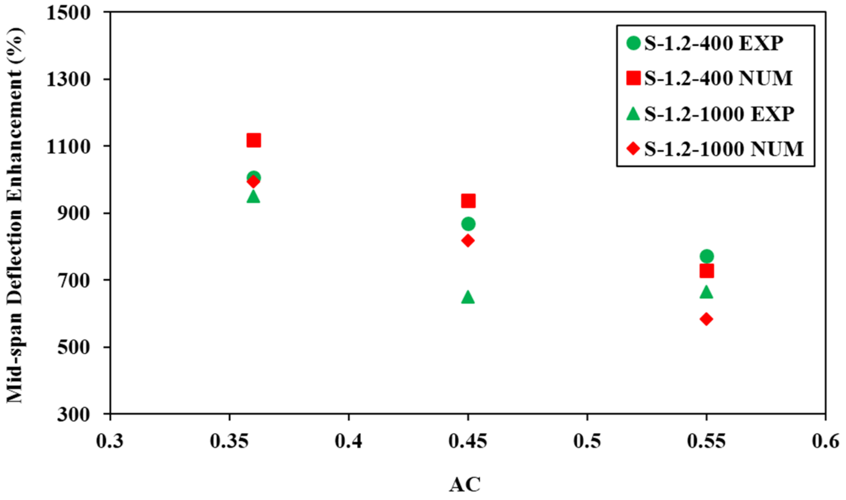


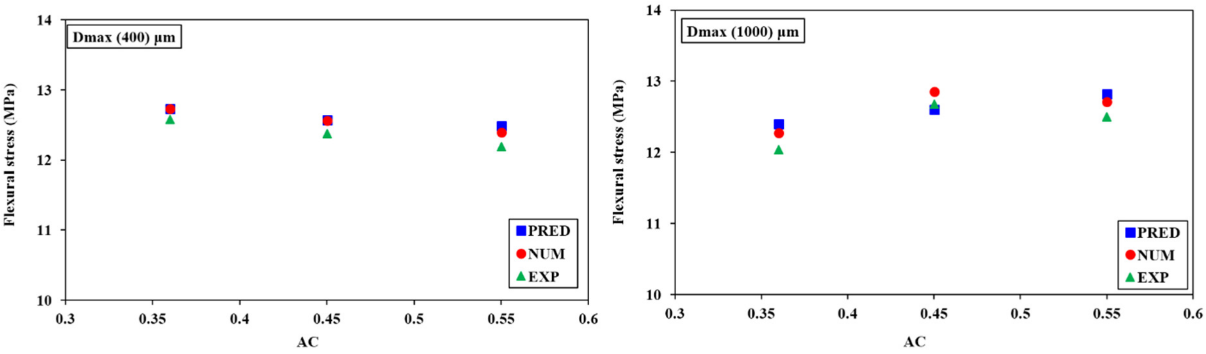
Figure13: Deflection enhancement versus aggregate content of numerical and experimental results for ECC beams

4.0 NONLINEAR PARAMETRIC STUDY

A nonlinear parametric study is carried out to evaluate the influence of parameters on the prediction of the flexural stress and flexural deflection of ECC beams in a 3D FE simulation, which comprises ECC aggregate content (*AC*), and ECC compressive strength (f_{ECC}) based on maximum aggregate size (D_{max}). These parameters have been obtained using an exponential regression line. The exponential regression analysis resulted in higher R^2 values (0.98) than other types of regression. This type of regression was used because it yielded a more realistic prediction of the flexural behavior of ECC beams.

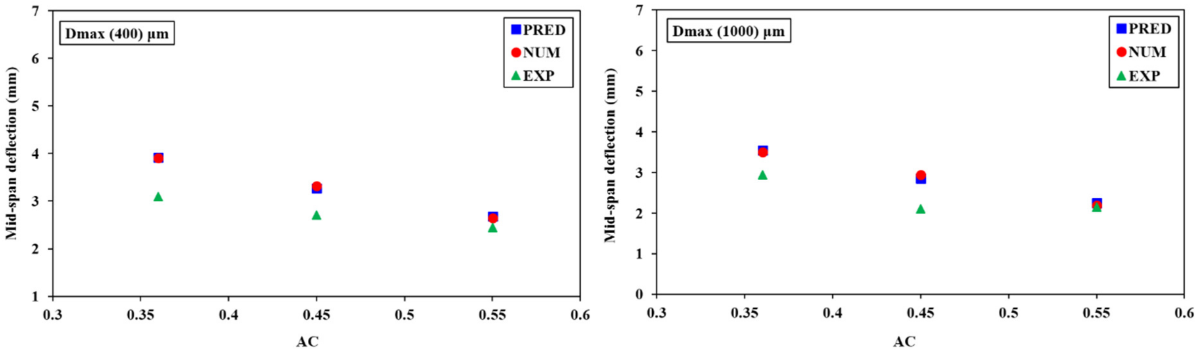
4.1 Influence of ECC aggregate content

The aggregate content is an important factor in the stiffness of the ECC beams. Fig. 14 illustrate the influence of the aggregate content on the likelihood of flexural stress, where, an increase in the aggregate content decreases the flexural stress of (400 and 1000) μm maximum aggregate size ECC beams by $13.397e^{-0.142AC}$ and $11.64e^{0.176AC}$, respectively. Furthermore, the flexural deflection of (400 and 1000) maximum aggregate size ECC beams decreases with an increase in aggregate content by $8.077e^{-2.008AC}$ and $8.385e^{-2.397AC}$, respectively, as shown in Fig. 15.



(a) (b)

Figure 14: Influence of aggregate content on the flexural stress by comparing experimental, numerical, and predicted results of ECC beams for: (a) 400 μm D_{max}; and (b) 1000 μm D_{max}.

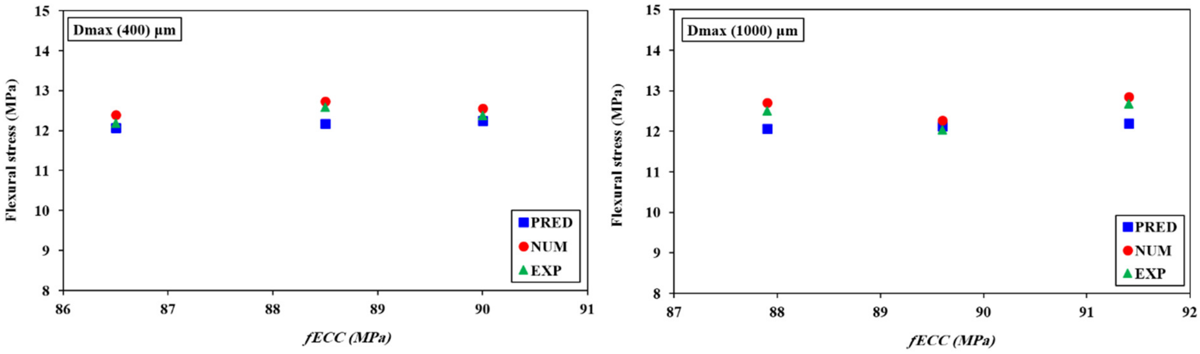


(a) (b)

Figure 15: Influence of aggregate content on the deformability in flexure by comparing experimental, numerical, and predicted results of ECC beams for: (a) 400 μm D_{max}; and (b) 1000 μm D_{max}

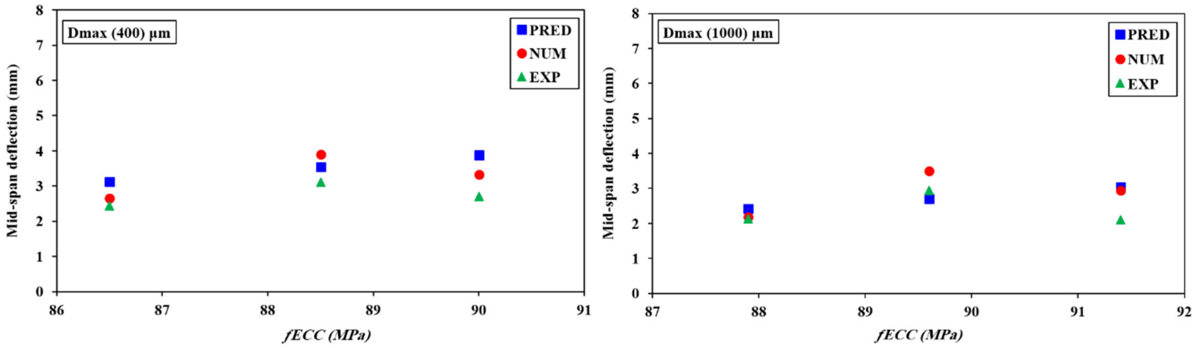
4.2 Influence of ECC compressive strength

The compressive strength is also an important factor in the stiffness of the ECC beams. Fig. 16 clarify the influence of the compressive strength on the likelihood of flexural stress, where, an increase in the compressive strength increases the flexural stress of (400 and 1000) μm maximum aggregate size ECC beams by $8.541e^{0.004f_{ECC}}$ and $9.266e^{0.003f_{ECC}}$, respectively. Furthermore, the flexural deflection of 400 μm maximum aggregate size ECC beams increases with an increase in compressive strength by $0.016e^{0.061f_{ECC}}$ and decreases with an increase in compressive strength by $0.008e^{0.065f_{ECC}}$ for 1000 μm maximum aggregate size ECC beams, as shown in Fig. 17.



(a) (b)

Figure 16: Influence of ECC compressive strength on the flexural stress by comparing experimental, numerical, and predicted results of ECC beams for: (a) 400 µm D_{max}; and (b) 1000 µm D_{max}



(a) (b)

Figure 17: Influence of ECC compressive strength on the deformability in flexure by comparing experimental, numerical, and predicted results of ECC beams for: (a) 400 µm D_{max}; and (b) 1000 µm D_{max}

5.0 CONCLUSIONS

This research aims to analyse the potential effect of aggregate size and amount upon the mechanical performances of ECC beams by means of employing nonlinear finite element model. To test the validity of models of the ECC beams operating under monotonic loading, experimental results were obtained. The results acquired from numerical evaluation were employed to conduct the nonlinear parametric study to investigate the aggregate content (AC), ECC compressive strength (f_{ECC}) parameters influencing the flexural stress and flexural deflection of ECC beams. These results can be summed up as:

- The model results showed that an increase in the aggregate size and quantity has no influence on the flexural strength, for the provided range of aggregate size. However, this change tends to reduce the ductility of ECC.
- When the ECC and MSC beams were subjected to comparative analysis, the ECC beams were observed to show an increase in flexural stress, strain, and mid-span

deflection, having an average improvement percentage of 77.51%, 800% and 863.5%, respectively.

- As per the finite element analysis, the flexural stress- deflection property of the beams was in agreement with the results obtained from experiments. Nonetheless, the numerical values for average ultimate strength and deflection obtained for the beams are 1.5% and 2.1% larger than those obtained from the experimental results, respectively. In addition to the ECC properties, the flexural behaviour of the beam can also be identified through properties and nature of mineral admixture, and quantity of the PVA fibres. The accuracy of experimental results can only be obtained through replication of results. Furthermore, the numerical method to identify the flexural behaviour of the ECC beams is validated through these results.
- The nonlinear parametric study demonstrated that the mid-span beam deflection properties, through which material ductility, and flexural stress of ECC beams is indicated, are subjected to considerable variations with respect to changes in AC and f_{ECC} parameters. The deflection ability and flexural stress of the beams are in a negative relation with both of these factors.

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