ARTICLE

JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)

مـــجلـة جـــامعة بـــــابـل للعلـــــوم الهندسية

Vol. 32, No. 2. \ 2024

ISSN: 2616 - 9916

The Development of Strain Hardening Behaviour of Engineered Cementitious Composite Reinforced by Carbon Fiber

Noor Al-Hayo[a], **Ali N. Al-Gemeel**[b]

[a] *Griffith School of Engineering/Griffith University/Brisbane/Australia*
Email: noor.al-hayo@griffithuni.edu.au; ORCID: https://orcid.org/0009-0007-5570-8849
[b] *College of Engineering/ University of Babylon/Babylon,Iraq*
Email: eng.ali.nassir@uobabylon.edu.iq; ORCID: https://orcid.org/0000-0001-9016-8525

Received:	**20/12/2023**	**Accepted:**	**31/12/2023**	**Published:**	**15/4/2024**

Abstract

Engineered cementitious composite (ECC) as one of the most promising types of strain-hardening cementitious composites (SHCC) has received worldwide attention. Polyvinyl alcohol (PVA) fibres have been proven as one of the more successful chopped reinforcement to achieve desired properties of ECC. Locally, this types of fibre is not available and still uneconomic choice to use. Research in this field, in Iraq, is still new although this composite has been under investigation in the last ten years in some countries such as the United States. This study points out the use of available discrete carbon fibre to reinforce cementitious matrix as an attempt to present ECC with locally available and economical components as composites with desirable strain-hardening performance that could help retrofitting and repairing existed deteriorating structures. Seven groups with volume fraction of carbon fibres ranging from 0% to 3% were considered to produce thin beams tested under bending conditions. The results showed an overwhelming performance of carbon fibres to add ductility to the cementitious composites with varied efficiency. Specimens with 2% volume fraction of fibres overcame the other groups when presented flexural strength 8 times more that of the control specimens and 8 mm mid-span deflection (vertical deflection), which represents notable ductility if compared with the control specimens that presents about 1mm. These results open up the opportunity to investigate and bring the research interests of future studies, locally, on this field.

Keywords: ECC, carbon, economic, strain hardening, fibre, composites.

1.INTRODUCTION

Fibre reinforced polymer (FRP) composites have been widely employed as an essential reinforcing material for weak reinforced concrete (RC) elements since 1980. FRP is widely used in many industries due to a number of important advantages, including as its high strength-to-weight ratio. As a result, handling will be simple, which will result in a quick application rate. As a result, there will be fewer construction and potential shutdown periods [1]. However, there are a few drawbacks to the FRP strengthening process. These include low performance at temperatures above the polymer's glass transition temperature, expensive polymer costs, and inapplicability on wet surfaces or at low temperatures [2,3].

High-performance fiber-reinforced concrete is known as engineered cementitious composites, or ECC for short. ECC can develop much better mechanical properties than regular concrete, including ultimate strain in uniaxial tension and excellent strain-hardening behaviour [4, 5]. Because of the bridging effect of the fibres in ECC, even after multiple cracks have developed, the material can still provide significant tension [6-8]. The crack widths in ECC are relatively small before the major crack is fully formed [9, 10].

When ECC is used with 2% fibre volume fraction, the ultimate tensile strain can reach up to 3%, and the average crack width under this strain stays at 100 µm [11]. Steel reinforcement and ECC can work together to maintain tension in the interim [12, 13].

Experimental research on the nonlinear performance of ECC cantilever beam structures was conducted by Fisher et al. [14]. It is shown that ECC material plays a fundamental role in the improved deflection capacity. Using an experimental program, Gencturk et al. [15] assessed the earth quick design parameters of ECC made columns under different loading conditions. It was found that all the design requirements could be enhanced at various aspects in ECC specimens. A numerical analysis of the column-slab performance in regard to cyclic vertical and horizontal load was conducted by Asdam et al. [16]. It is demonstrated that the PVA-ECC can greatly increase both mechanical performance and damage tolerance. Qin et al. [17] retrofitted reinforced concrete frames with glass fiber-reinforced polymer bars and an ECC layer, validating the strengthening scheme's efficacy in enhancing progressive collapse resistance.

One encouraging aspect of ECC is its strain-hardening performance. Dehghani and Aslani [18] examined the strain-hardening behaviour of ECC reinforced with steel and carbon fibres using uniaxial tensile tests. The strain-hardening behaviour and ductility of the ECC matrix were significantly improved, according to the results, by the addition of steel and carbon fibres. The impact of incorporating carbon fibre into the ECC matrix on its tensile characteristics, such as strain-hardening behaviour, was examined in a study in studies such as [19, 20]. According to the results, the tensile strength and strain-hardening performance were both enhanced by the addition of carbon nanotubes.

This research aims at further developing a ECC by using locally available low cost fibre. This investigation will therefore aim at developing ECC reinforced with carbon fibre as chopped firbres, in the hope that the composite is still capable of achieving stain-hardening whilst flexural strength of standard PVA-ECC are maintained and optimizing carbon fiber content with the new composites.

2.EXPERIMENTAL PROGRAM

Unlike traditional mortar or concrete. ECC can be described as a very component sensitive composites that can be affected negatively when using un-recommended component.

2.1.Materials

For the purpose of this research, standard sand was uses with grades ranging from 75 to 250 µm and 250 to 425 µm. Fig. 1 shows the sand aggregate that was used for the research project it was treated by sieve 0.6. This is such a new thing to be used with ECC, river sand is recommended in previous studies. Ordinary Portland Cement was used; the characteristic is shown in Table 1. The carbon fibre, shown in Fig. 2, used in this study is supplied by special trading company and the characteristics are presented in Table 2.

Figure 1: Standard Sand Separated by Sifting

Table 1: The Chemical and Mechanical Properties of the Used Cement.

Chemical test according to I.Q.S.472:1984		
Oxide	(%)	limits
CaO	62.21	………
SiO_2	19.40	……....
Fe_2O_3	4.96	………
Al_2O_3	4.00	………
MgO	3.24	≤ 5.0
SO_3	2.44	
Free Lime	1.68	
L.O.I	2.24	
I.R	0.87	
C_3S	53.09	………..
C_2S	15.57	………..
C_3A	6.38	……….
C_4AF	12.17	……….
L.S.F	0.94	0.66-1.02
Physical test according to I.Q.S.5:1984		
Fineness ,Blaine,cm^2/gm	3760	≥2300
Setting time ,Vicat's method Initial min Final hrs : min	1: 75 145 3:58	 ≥ 00 : 45 ≤ 10 : 00
Compressive strength (MPa 3 days 7 days	 30 24	 ≥ 15 ≥23

Figure 2: Carbon Fiber Used to produce The ECC Specimens.

Table 2: Properties of The ECC Fiber That Is Used for This Research, by OSCRETE Construction Products.

Typical properties	Amount
Fibre diameter (μm)	7
Fibre density (kg/m^3)	1800
Fibre length mm	6/12
Metal contamination (g/1000g)	Less than 0.1
Packaging kg	15
Tensile strength (MPa)	4150
Tensile modulus (GPa)	230-255

2.2.Specimens Moulding

Mould size of 20*100*400 mm was used for each sample. A set of three moulds was designed and crafted that made out of plywood, as shown in Fig. 3. This size is recommended in previous studies to investige the strain-gardening performance that is only possible for thin layer to be noticed [21].

Figure 3: Beam Mould (Length 400mm, Width 100mm, Thickness 2cm)

2.3.Mix Proportions

A total of six proportions (volume fraction) of fiber were investigated in this research (0%, 0.5%, 1%, 1.5%, 2%, 2.5%, to 3%) for optimal ECC design. This resulted in six groups of ECC that contained cement, sand and water. In this investigation the fly ash that is always recommended in literature to have a significant improvement to the composite was not used as a step to develop ECC with availed components to result is economically effective composites. The designed mixes and its proportions and number of samples are presented in Table 3. For each mix design, a total of three (3) rectangular cross section of 100 mm wide x 20 mm depth x 400 mm long. A total concrete volume of 0.003 m^3, which includes 10% surplus was required in order to create these samples.

Table 3: Mix Proportion for Specimens (kg/0.003 M3).

Type of Specimens	Number of Specimens	Cement kg/0.003 m3	Sand kg/0.003 m3	Water kg/0.003 m3	Nano-Carbon Fiber percentage %	Nano-Carbon Fiber kg/0.003 m3
C-0.0	3	2.475	0.900	0.675	0	---
C-0.5	3	2.475	0.900	0.675	0.5	0.027
C-1.0	3	2.475	0.900	0.675	1	0.054
C-1.5	3	2.438	0.880	0.665	1.5	0.081
C-2.0	3	2.425	0.880	0.660	2	0.108
C-2.5	3	2.409	0.875	0.657	2.5	0.135
C-3.0	3	2.392	0.870	0.650	3	0.162

.4.Mix procedure

Using standard sand and cement, according to the sizes mentioned the dry components were mixed for about two minutes, as shown in Fig. 4. Gradually, water was added to the mixture until it becomes well homogeneous and in the required quantity. Carbon fiber was added gradually according to the ratios 0.5%, 1%, 1.5%, 2%, 2.5%, 3% . The mixing continued for about three minutes and until the mix became homogenous. The moulds were oiled before pouring the mixture to facilitate the process of removing samples from the moulds. The moulds were hit using a rubber hummer to compact the specimens and release air bubbles, the procedure was used in [20,21]. The moulds were left for 24 hours, and then demolded and left in curing basin until the test day (28 days), as shown in Fig. 5.

Figure 4: Material Preparation.

Figure 5: Specimens Casting and Curing.

2.5.Testing setup

The flexural modulus or flexural strength of casted material is often ascertained by ureure tests. A flexure test yields slightly different results and is less expensive than a tensile test. A force is applied to the top of the material through one or two points of contact (upper loading span) until the sample fails. The material is laid horizontally over two points of contact (lower support span), as shown in Fig. 6. The maximum force recorded is the sample's flexural strength. The test was conducted in accordance with ASTM, C1609 [22].

Figure 6: Flexural Testing Machine.

3- RESULTS AND DISCUSSION

Table 4 displays the impact of carbon fibre usage on ECC flexural strength, maximum load, and mid-span deflection for each tested composition. The ensuing sections go into additional detail about the findings.

Table 4: Experimental Results

Mixture coed	Max L (kN)	Mid span* Deflection(mm)	Flexural strength (Ϭ) (N/mm^2)
C-0.0	0.200	0.93	2.000
C-0.5	1.070	3.312	10.70
C-1.0	1.074	1.826	10.74
C-1.5	1.170	3.086	11.70
C-2.0	1.700	8.020	17.00
C-2.5	1.420	4.260	14.20
C-3.0	1.450	3.152	14.50
*deflection was measured by LVDT			

3.1.Bending Strength

Flexural strength, which can also be referred to as bend toughness or modulus of rupture, is a property of materials that is defined as the stress in a material immediately prior to its cracking in a flexure test. The most common application of this bending test is to evaluate a beam's resistance to the moment of bending. A specimen with a rectangular cross-section that is bent until it fractures or yields can be investigated by applying a load through one or two places on the surface layer. The maximum stress that a material experiences at the point of yielding is represented by its flexural strength.

Table 4 and Fig. 7 report the bending strength of the beams tested under four-point bending. The bending strength of the ECC samples varies from 10.5 MPa to 14.5 MPa for groups with carbon fibres, while the control samples only exhibit 2 MPa. Out of all the mixes examined, the C-2 mixture produced the maximum flexural strength, according to the data. The flexural strength values are less affected by utilising a volume percentage of carbon fibre that is greater than or equal to 2% than with C-2. Strength gains differed throughout carbon fiber-based mixtures; for instance, group C-0.5's bending strength increased by roughly 5 times compared to C-0, whereas group C-0.8's increased by roughly 8 times.

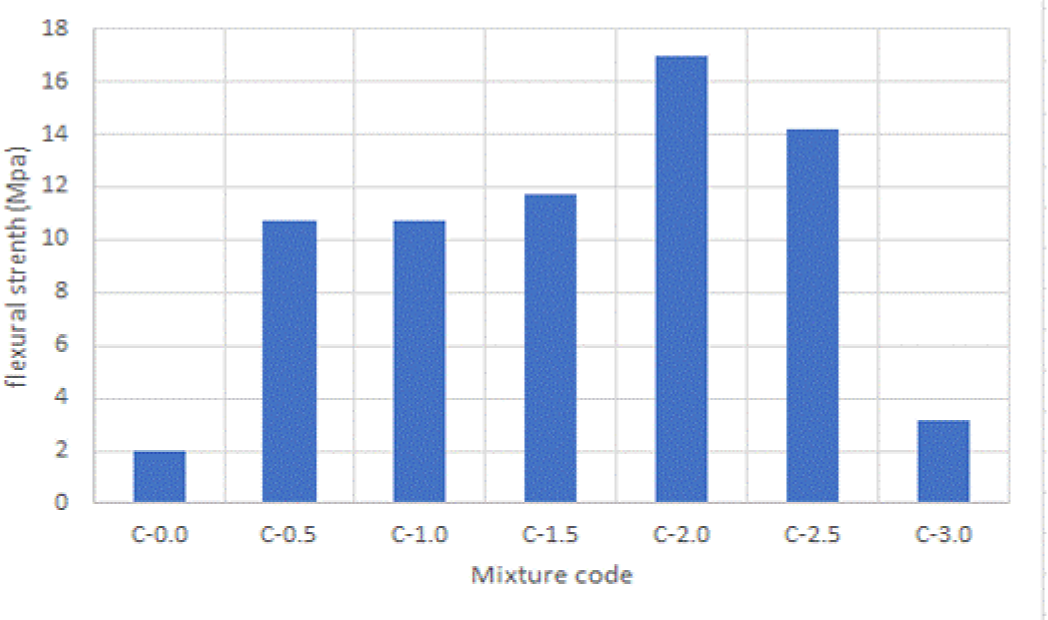


Figure 7: Flexural Strength.

3.2.Mid-Span Deflection

Average deflection for each group is presented in Table 3. Fig. 8 shows the results as a bar chart to compare the mixtures. This parameter is so important that it can reflect the ability of the beams to deform under bending and therefore the efficiency of the fibres to overcoming the brittleness of cementitious material. The capacity differed from one mixture to another due to the varied content of carbon fiber. The results showed that all tested samples presented a noticeable increment in their ability to deform compared to the control group. Specimens with 2% of fibre content produced the most developed deflection ability of about 8 mm that means eight times more than that of control specimens. Such a recognizable development can be caused by the ideal volume fraction of fibre. This content of fibre was also proven to be the most suited content in previous studies such as [23,24] when PVA fibre was used. Moreover, the other groups showed increase in the displacement ranging from 2 to 3 times compared to specimens of group C-0.

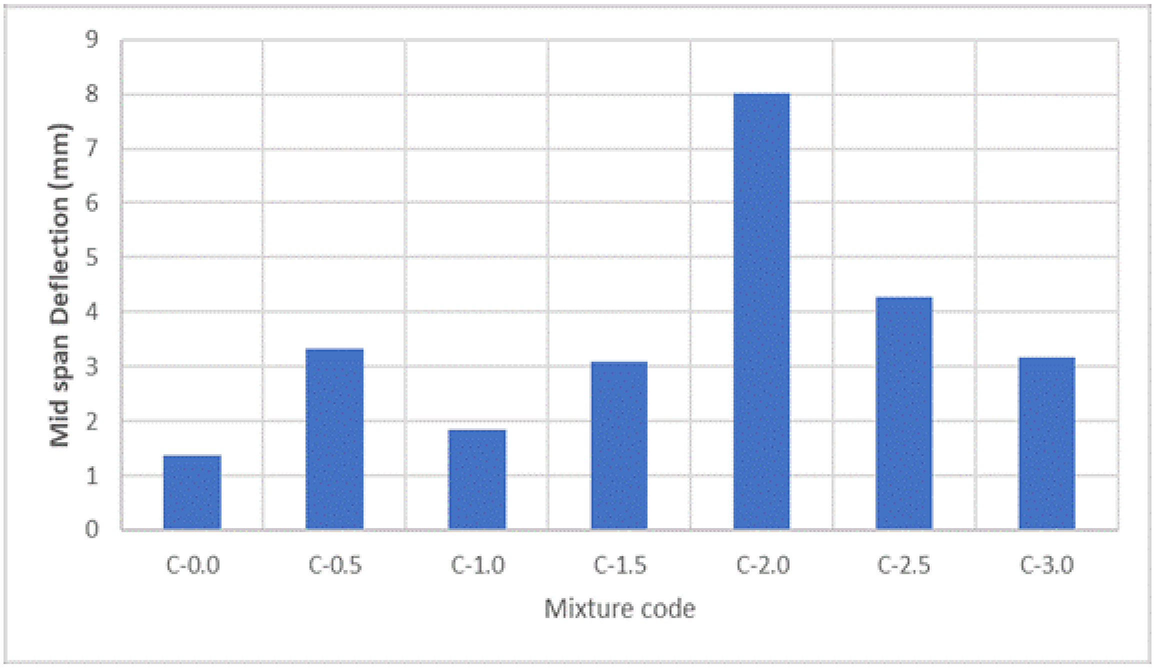


Figure 8: Mid-Span Deflection.

3.3.load Deflection behavior

The behavior of the specimens regarding load-deflection relationships is presented for the all groups in Fig. 9 and 10.

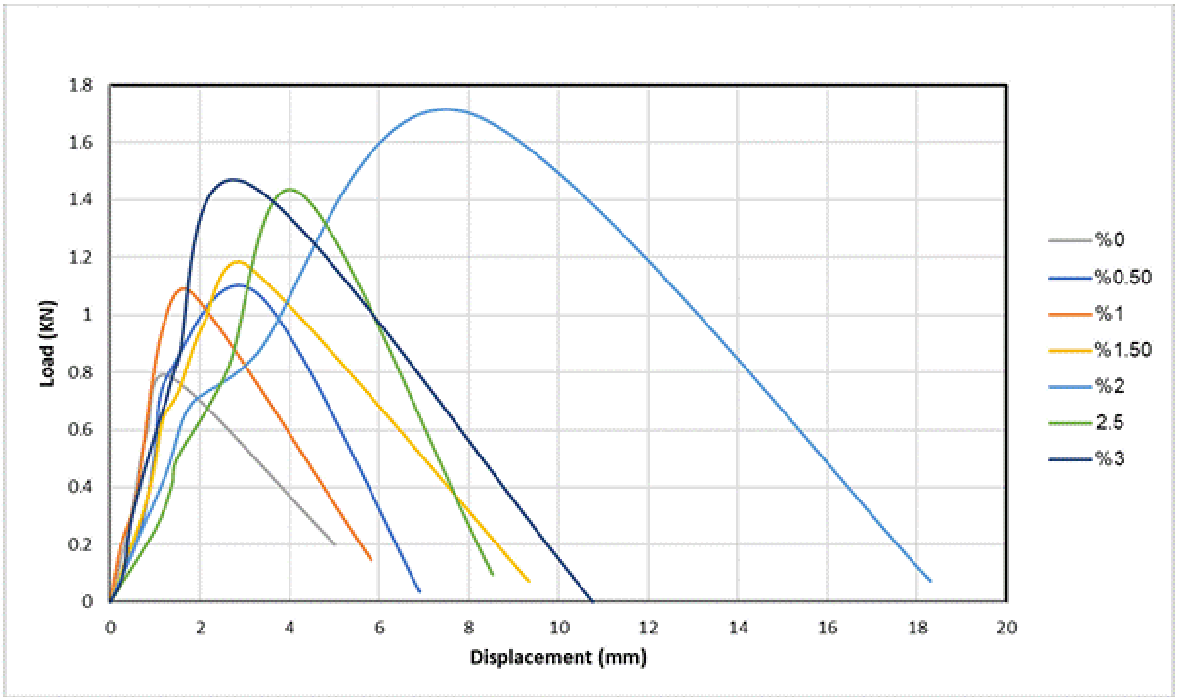


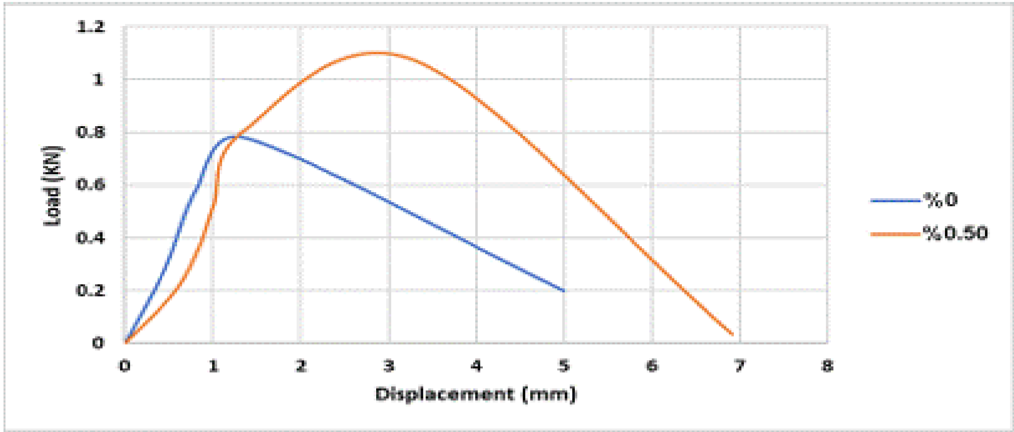
Figure 9 : Effect Of Different Fibers On ECC Flexural Behavior.

Two prominent phases are discernible in each curve, as illustrated in Figs. 9 and 10. The first stage began when the load was applied in a linear relationship and was succeeded by a nonlinear trend up to failure.

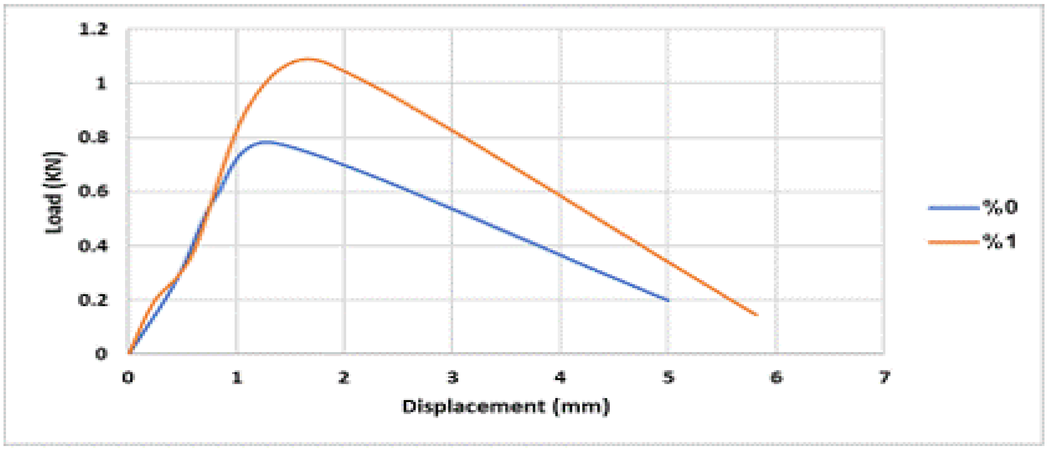
Despite variations in load carrying capability among mixtures resulting from variations in carbon fibre concentration, strain-hardening performance was demonstrated by all examined specimens. When a material induces peak stress that is greater than the initial crack stress, strain-hardening behaviour becomes apparent. In contrast to combinations containing fibres, control specimens performed poorly when it came to bearing weight following the initial stage of cracking.

It can be seen for Fig. 9 that the specimens of fibre based mortar presented smooth ascending trends after the first crack points that is more likely to be a non-liner until the ultimate stage. Then, the failure trend takes place is a smooth descending behavior. This behavior presents what is needed from the existing of such chopped fibres that can be a very successful outcome of the investigation when compared to the control specimens that showed a very sharp dropping with liner trends.

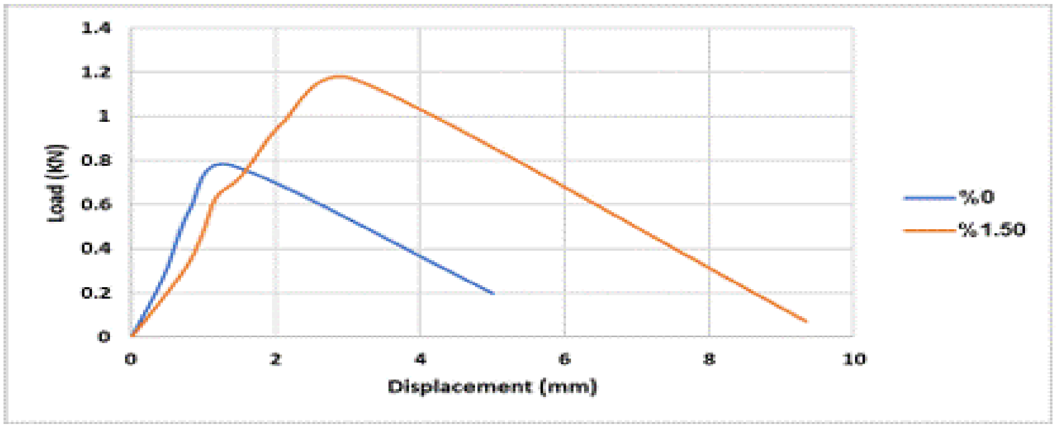
To closely zoom in the performance of each performance in comparison with the control specimens, Fig. 13 presented such defenses and the developed performance. From this point of view, there is a recognizable stage transitions and smooth cords of the relationships for specimens with 2% fibres as shown in Fig. 10 D. The first crack point is more noticeable indication the end of the linear stage after which the bridging effect of the fibre is activated indicating the non-linear stage of the curve. At this stage the specimens are still able to resist load resulting in an ascending non-linear trends until the ultimate load. After that the specimens presented gradual dropping trends indicating smooth failure.



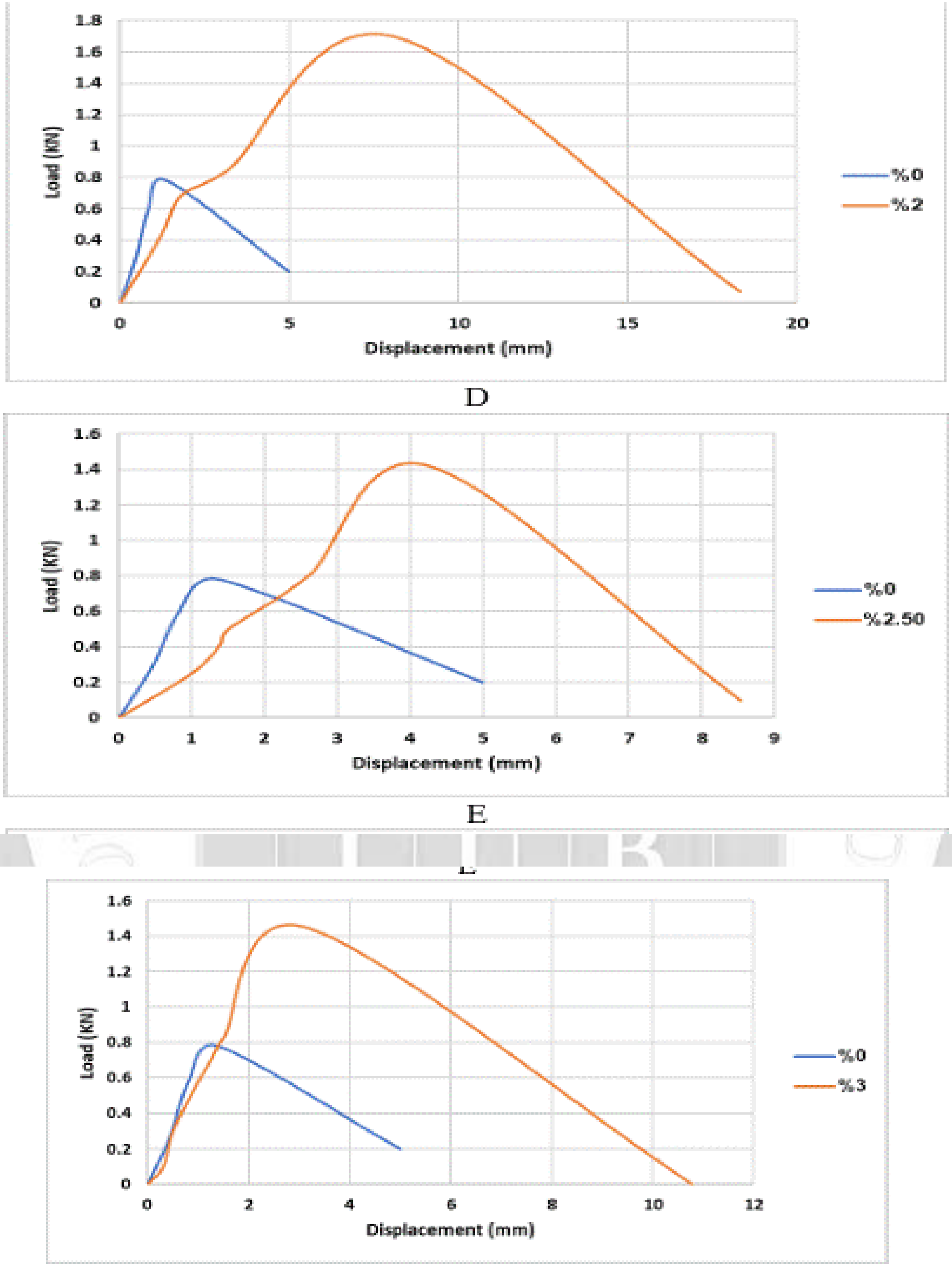
A



B



C



D

E

F

Figure 10: Shows The Relationship Between The Deflection And The Applied Load For Control Group C-0.5 In A Combination With: A (C-0.5), B(C-1), C(C-1.5), D(C-2), E(C-2.5), F(C-3).

3.4.Failure modes

In this investigation, two distinct failure modes were observed. Specimens that were reinforced with discrete fibers displayed multi-cracks that were uniformly distributed across the tension surface of the specimens, as illustrated in Fig. 11. Those cracks were formed as a result of the increase in tensile load, which was facilitated by the bridging effect of carbon fiber. As the specimens approached their maximum tensile strength, the carbon fibers progressively failed by being pulled out at multiple points. Despite the occurrence of multi-cracks, the specimens did not separate into segments, indicating the effectiveness of chopped fibers in evenly sustaining the tensile load. Specimens belonging to group C-2, which consisted of 2% of fibers with ECC mortar, exhibited a higher level of confinement efficiency due to the optimized volume fraction of fibers. That resulted in a much more comprehensive failure mode, characterized by the occurrence of numerous small cracks instead of a single major crack. As a consequence, the tensile applied load was uniformly distributed along the circumference of the specimen.

The second type of the failure was observed in the control specimens. The samples presented a typical brittle failure started with a major crack that progressed to widen and grow until the specimen reach its peak.

Figure. 11: Failure Mode of Group C-2.

4.CONCLUSION AND RECOMMENDATIONS

The performance of carbon reinforced ECC was investigated in this study that target to use locally available carbon fibre with ECC. Some key conclusions and recommendations are highlighted and presented in the following section.

- Notable increase in flexural strength were observed for specimens with carbon fibres ranging from 5 to 8 times higher than those of the control specimens.
- Carbon fibre is successfully and easily distributed within the mixture without need for more superplasticizer that could lead to more economic ECC.
- Specimens with 2% of fibre content produced the most developed load carrying capacity and deflection ability of about 17 MPa and 8 mm respectively, that means eight times more than that of control specimens.
- Strain-hardening performance was observed. where the composite induces peak stress higher that the first crack stress. This open up the hope of having such performance not necessarily when using PVA.
- Specimens reinforce with discrete fibres exhibited several cracks evenly spaced across the specimen rather than one major crack that was detected in control specimens.
- The volume fraction of fibre is optimized through the range of the contents used in the study. The content of 2% fibres presented the most suitable properties and needed hardening performance.
- This study opens up the door to further investigate locally available fibres and materials to reach needed features of ECC such as organic fibres.
- More contents are needed to be investigated.
- Combinations of carbon fibres with other types need to be investigated to study the hybrid effect of fibres.
- Universal tensile strength need to be investigated in the next stage of the research.
- Large scale specimens are recommended to investigate to understand the performance under real conditions.

REFERENCES

[1] ACI440.3R, "Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures," pp. 1–40, 2004.

[2] Y. A. Al-Salloum, N. A. Siddiqui, H. M. Elsanadedy, A. A. Abadel, and M. A. Aqel, "Textile-reinforced mortar versus FRP as strengthening material for seismically deficient RC beam-column joints," J. Compos. Constr., Vol. 15, No. 6, pp. 920–933, 2011.

[3] L. N. Koutas, Z. Tetta, D. A. Bournas, and T. C. Triantafillou, "Strengthening of Concrete Structures with Textile Reinforced Mortars: State-of-the-Art Review," J. Compos. Constr., Vol. 23, No. 1, pp. 1–20, 2019.

[4] Li. VC. On Engineered Cementitious Composites (ECC) A Review of the Material and Its Applications. Journal of Advanced Concrete Technology. 2003;1(3):215-30.

[5] Li VC, Mishra DK, Naaman AE, Wight JK, LaFave JM, Wu H-C, et al. On the Shear Behavior of Engineered Cementitious Composites. Journal of Advanced Cement-Based 405 Materials. 1994;1(3):142-9.

[6] Abrishami HH, Mitchell D. Influence of Steel Fibers on Tension Stiffening. ACI Structural Journal. 1997;94(6):769-76.

[7] Minelli F, Tiberti G, Plizzari G. Crack Control in RC Elements with Fiber Reinforcement. ACI Special Publication. 2011;280:1-18.

[8] Tiberti G, Minelli F, Plizzari G. Cracking behavior in reinforced concrete members with steel fibers: A comprehensive experimental study. Cement and Concrete Research. 2015; 68:24-34.

[9] Deluce JR, Vecchio FJ. Cracking Behavior of Steel Fiber-Reinforced Concrete Members Containing Conventional Reinforcement. ACI Structural Journal. 2013;110(3):481-90.

[10] Noghabai K. Behavior of Tie Elements of Plain and Fibrous Concrete and Varying Cross Sections. ACI Structural Journal. 2000;97(277-285).

[11] Li VC, Kanda T. INNOVATIONS FORUM: Engineered Cementitious Composites for Structural Applications. Journal of Materials in Civil Engineering. 1998;10(2):66-9.

[12] Fischer G, Li VC. Influence of Matrix Ductility on Tension-Stiffening Behavior of Steel Reinforced Engineered Cementitious Composites (ECC). ACI Structural Journal. 2002;99(1):104-11.

[13] Fischer G, Li VC. Effect of Matrix Ductility on Deformation Capacity Behavior of Steel Reinforced ECC Flexural Members under Reversed Cyclic Loading Conditions. ACI Structural Journal. 2002;99(6):781-90.

[14] G. Fischer, V.C. Li, Deformation behavior of fiber-reinforced polymer reinforced engineered cementitious composite (ECC) flexural members under reversed cyclic loading conditions, ACI Struct. J. 100 (1) (2003) 25-35.

[15] B. Gencturk, A.S. Elnashai, M.D. Lepech, S. Billington, Behavior of concrete and ECC structures under simulated earthquake motion, J. Struct. Eng. 139 (3) (2013) 389-399.

[16] Tambusay, P. Suprobo, Faimun, A. Amiruddin, Finite element analysis on the behavior of slab-column connections using PVA-ECC material, Jurnal. Teknologi. 79 (5) (2017) 23-32.

[17] W.H. Qin, Z. Xi, X.Y. Liu, P. Feng, X. Ou, J.X. Yang, Experimental and theoretical analyses of the progressive collapse resistance of NSM strengthening RC frames after the failure of a corner column, J. Build. Eng. 47 (2022) 103805.

[18] Dehghani, A., & Aslani, F. (2020). The synergistic effects of shape memory alloy, steel, and carbon fibres with polyvinyl alcohol fibres in hybrid strain-hardening cementitious composites. Construction and Building Materials, 252, 119061.
[19] Cui, X., Han, B., Zheng, Q., Yu, X., Dong, S., Zhang, L., & Ou, J. (2017). Mechanical properties and reinforcing mechanisms of cementitious composites with different types of multiwalled carbon nanotubes. Composites Part A: Applied Science and Manufacturing, 103, 131-147.
[20] Yıldırım, G., Öztürk, O., Al-Dahawi, A., Ulu, A. A., & Şahmaran, M. (2020). Self-sensing capability of Engineered Cementitious Composites: Effects of aging and loading conditions. Construction and Building Materials, 231, 117132.
[21] Al-Gemeel, A. N., Zhuge, Y., & Youssf, O. (2018). Use of hollow glass microspheres and hybrid fibres to improve the mechanical properties of engineered cementitious composite. Construction and Building Materials, 171, 858-870.
[22] ASTM, C1609 Standard Test Method for Flexural Performance of FiberReinforced Concrete (Using Beam With Third-Point Loading), Book of ASTM Standards, 2011.
[23] AL-Gemeel, A. N., & Zhuge, Y.(2017) STRENGTHENING SQUARE CONCRETE COLUMN WITH BASALT FIBRE TEXTILE REINFORCED ECC.APFIS2017 - 6th Asia-Pacific Conference on FRP in Structures.
[24] Al-Gemeel, A. N., & Zhuge, Y. (2019). Using textile reinforced engineered cementitious composite for concrete columns confinement. Composite Structures, 210, 695-706

تطوير سلوك الانفعال لمواد سمنتيه هندسيه مركبة مسلحه بالياف كاربونيه

نور اسعد الحيو   **علي ناصر حسين**

كلية الهندسه/ جامعة كرفث/ برزبن/استراليا   *كلية الهندسه/ جامعة بابل/ بابل/العراق*

الخلاصه

حظي المركب الأسمنتي المصمم هندسيًا (ECC) كواحد من أكثر الأنواع الواعدة من المركبات الأسمنتية المتصلبة باهتمام عالمي. لقد ثبت أن ألياف كحول البولي فينيل هي واحدة من أنجح الياف التسليح لتحقيق الخصائص الهندسيه المرغوبة ل ECC . هذا النوع من الألياف غير متوفر ولا يزال خيارًا غير اقتصادي للاستخدام. ولا تزال الأبحاث في هذا المجال في العراق جديدة على الرغم من أن هذا المركب قد تم التحقق فيه في السنوات العشر الأخيرة في بعض الدول مثل الولايات المتحدة. يهدف هذا البحث إلى استخدام ألياف الكربون الشعريه المتوفرة لتسليح االمركبات الأسمنتية كمحاولة لتقديم ECC بمكونات اقتصادية متاحة محليًا كمركبات ذات أداء انفعالي مطور يمكن أن يساعد في إصلاح الهياكل الخرسانيه المتضرره. تم اعتماد سبع مجموعات ذات نسبة حجمية من ألياف الكربون تتراوح من 0% إلى 3% لإنتاج نماذج مضلعه رقيقة تم اختبارها في تحت تاثير قوى الانحناء. أظهرت النتائج أداءً واعدا لألياف الكربون فيما يخص تطوير تحمل الانفعالات إلى المركبات الأسمنتية بكفاءة متباينه. تغلبت العينات التي تحتوي على جزء حجمي بنسبة 2% من الألياف على المجموعات الأخرى حيث اضهرت قوة انثناء أكبر بثمانية أضعاف من العينات الخاليه من الالياف واضهرت متوسط انحناء بمقدار 8 مم .وهو ما يمثل تطور ملحوظة في قابلية المركب على الانحناء إذا ما قورنت بالعينات الخاليه من الالياف والتي اضهرت حوالي 1 مم. وتفتح هذه النتائج المجال أمام التقصي واستقطاب الاهتمامات البحثية للدراسات المستقبلية محليا في هذا المجال.

الكلمات الداله: كاربون, اقتصادي, انفعالاتك, فايبر ,مركبات