Comparing the flexural behavior of ECC composite slab with reinforced concrete slabs

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Abstract. This study focuses on studying the impacts of applying various content of polypropylene fiber with (2,3,4%) volume fraction. In addition, 50% fly ash (F.A.), 50% silica fume (S.F.), and (25%F.A.+ 25%S.F.) as partial substitutes for cement were used in ECC. ECC specimens were evaluated based on their workability, compressive strength, and flexural strength. The best outcomes from the mixes were compared to steel reinforcement in slabs. Three slabs were constructed: (i) slab reinforcement with steel, (ii) slab with ECC only and (iii) slab reinforcement with ECC in the tension zone. Flexural tests were carried out on slabs to determine their mode of failure and ductility. The results showed that concrete with 3.0% V_f of fiber and 25%F.A. + 25%S.F. substitution of cement had higher results in compressive strength and flexural strength, which achieved 62 MPa and 2.49 MPa, respectively. Although this concrete mix reduces workability, it requires being cast in a slab. For the slabs, the R.C. slab had the highest load carrying capacity. The failure modes of the ECC composite slabs were more ductile than the R.C. slab.

Keywords: ECC composite slab, Polypropylene fiber, Flexural behavior

1. Introduction

One unique type of high-tensile-ductility concretes is known as engineered cementitious composites, or ECC. It displays a fiber volume percentage of no more than 2.0% and a tensile strain capacity of more than 3.0% [1]. To demonstrate that it can multiply fracture development and strain hardening, ECC particles must be very tiny. With equivalent or smaller particle sizes, it is possible to replace a portion of the cement with other pozzolanic or inert materials. The use of multi-sized cement replacements increases ECC's workability, strength, and wet packing density. A reduced cement composition reduces embodied carbon, making the ECC greener [2]. Because of its great tensile ductility and durability, ECC can be helpful in a variety of civil engineering applications. For example, high-rise buildings, pavement, and structural slabs have all used it [3]. Numerous investigations on fiber-reinforced cement composites have been conducted. (ECC). Yuan et al. [4] used ECC/concrete composite to investigate the effects of the thickness and location of the ECC concrete layer on the behavior of steel-reinforced specimens. Greater concrete compression was experienced by a greater area due to the stresses generated by ECC in the tension region. Consequently, the maximum moment capacity was enhanced. Martínez-Pérez et al. [5] analyzed the flexural behavior of eight beams having RC internal and SFRC exterior layers. SFRC beams have a 70% higher energy absorption than RC beams. Shanour et al. [6] and Liu, D. et al. [7] studied the application of ECC for beam strengthening. The results showed that ECC composite beams improved beam cracking load, yield load, ultimate load, stiffness, ductility, and energy absorption capacity when compared to a reference beam. Said, S et al.

[8] evaluates the behavior of ECC with different PVA fiber contents in terms of strain-hardening. According to the findings, compressive strength decreases with an increase in the reinforcing index. As the reinforcing index rises, there is a large increase in both the deflection at ultimate load and the deflection at failure. Sheta, A et al. [9] developed and evaluated composite CFS/ECC beams' shear and flexural behaviors. In the short-span Series, the load capacity of the composite beams increased to eight times that of the bare CFS members, while in the long-span Series, it reached to up to four times.
This study investigates into the possibility of using ECC as a substitute to steel reinforcement in slabs. Due to the high cost of steel reinforcement in Egypt, this approach provides an alternative for reducing steel in sections, hence lowering construction costs. The ECC's high tensile strength and strain capacity would improve the system's ductile behavior.

2. *Experimental mixing program*

2.1Engineered cementitious composites.

2.1.1 Materials

According to (E.S.S.47651-1/2013), Portland cement (CEM I 42.5 N) with a specific gravity of 3.15 t/m^3 was utilized for the cement [10]. Fly ash of class (F) with a specific gravity of 2.3 t/m^3 was used to fulfil (ASTM C618) [11] specifications. According to the manufacturer, 2.15 t/m^3 of silica fume was utilized as a pozzolanic admixture. The powdered silica content is approximately 97.8%, with a specific surface area of 19,800 m^2/kg. It is made by Egyptian Ferro Alloys Corporation. The silica fume utilized satisfied ASTM C 1240's primary criteria. The chemical composition of the used cement, fly ash, and silica fume is illustrated in Table 1.

Table 1. Silica fume, fly ash, and cement's chemical composition.

	Portland cement	fly ash	silica fume
SiO_2 %	20.45	55.71	97.80
Al_2O_3 %	4.08	22.56	0.34
Fe_2O_3 %	3.22	5.61	0.17
CaO %	63.01	10.44	0.27
MgO %	2.32	1.78	0.21
SO_3 %	2.46	0.54	-
Na_2O %	0.3	0.24	0.23
K_2O %	0.8	0.79	0.15

Graded siliceous sand accordance to the requirements of the Egyptian standard (E.S.S.1109/2008) [13]. With a fineness modulus of 2.61 and a specific gravity of 2.6 t/m^3. To meet the standards of ASTM C494 (type A and F), a high-range water reducer (HRWR) was used as a super plasticizer [14]. At room temperature, the admixture has a density of 1.18 kg/liter and is a brown liquid. Polypropylene fibers were used [15]. The properties of the used polypropylene fibers are illustrated in Table 2. Tap water was used for mixing and curing the specimens.

Table 2. Characteristic of the used Polypropylene fiber

Length range (mm)	6,12,20
Average diameter (mm)	0.034
Aspect ratio (L/d)	800
Tensile Strength (MPa)	500-700
Fiber elongation (%)	25%
Modulus of Elasticity	2800Mpa
Specific gravity (kg/m^3)	0.9

2.1.2 Mix proportion and mixing procedure.

The conducted experimental program had three groups of ECC with a total number of twelve mixes.

Each group was created based on different fiber volume fraction, and pozzolanic material (50%fly ash, 50%silica fume, and 25%fly ash with 25%silica fume) as a partial replacement of Portland cement. Polypropylene fiber was used with (2, 3, 4%) volume fraction of ECC mixes. Table 3 illustrates the proportions of concrete mixtures. For all ECC mixes the ratio of sand, HRWRA, and water was 80%, 1.5%, and 28 % of the binder weight, respectively.
To produce the ECC mixes, dry ingredients were combined with fly ash, cement, and fine sand and mixed for a minute to achieve homogeneity. After that, the dry mixture was mixed for three minutes while water and HRWR were added. Before adding the fibers, make sure the freshly mixed mortar is homogeneous and consistent. To ensure that the polypropylene fibers were evenly dispersed, they were introduced gradually and blended for two to three minutes.

Table 3. Components of mixes for concrete (kg/m³)

Mix ID	Cement	Poly Propylene	Fly ash	Silica Fume	Sand	Water	HRWRA
M_1	1085.93	18	-	-	868.744	304.06	10.85
M_1-50F.A.	542.96	18	542.96	-	868.744	304.06	10.85
M_1-50 S.F.	542.96	18	-	542.96	868.744	304.06	10.85
M_1-25(S.F.+F.A.)	542.9	18	271.48	271.48	868.744	304.06	10.85
M_2	1074.84	27	-	-	859.872	300.96	10.74
M_2-50F.A.	537.42	27	537.42	-	859.872	300.96	10.74
M_2-50 S.F.	537.42	27	-	537.42	859.872	300.96	10.74
M_2-25(S.F.+F.A.)	537.42	27	268.71	268.71	859.872	300.96	10.74
M_3	1063.76	36	-	-	851.008	297.85	10.637
M_3-50F.A.	531.88	36	531.88	-	851.008	297.85	10.64
M_3-50 S.F.	531.88	36	-	531.88	851.008	297.85	10.64
M_3-25(S.F.+F.A.)	531.88	36	265.94	265.94	851.008	297.85	10.64

2.1.3 Testing Method

Slump test

The consistency of ECC was measured using an inverted slump test. According to ASTM C143, the slump test was carried out.

Compressive strength

To find the compressive strength, cube specimens measuring 100 x 100 x 100 mm are constructed. In accordance with ASTM C-109, the compressive strength test was carried out. The compression testing apparatus has a capacity of 2000 KN. Three cubic specimens were used to calculate the average compressive strength.

Flexural strength

With this test technique, the flexural strength of a simply supported beam is determined. 300*100*30 mm (prism) under four-point loading at a universal testing machine according to ASTM C-78.

2.2 Test Results and analysis

2.2.1 Workability.

Figure 1 shows the relation between the slump value and volume fraction of fiber percentage. The result for 2.0% fiber showed that an improvement in workability for all replacements with cement, The value of the slump flow was 120mm for control mix M_1 without any cement replacement. While the cement was replaced by 50%F.A., 50%S.F., and 25% F.A. + 25% % S.F. slump flow values were recorded 160 mm, 125 mm, and 160mm, respectively.

For the mixes with 3.0% fiber the mix of 50% F.A. replacement with cement improved workability by 8.3%. Whereas the mixtures with replacement ratios of 50% S.F. and 25% F.A. + 25% S.F. were displayed decrease in workability by 96.4, and 94.5%, respectively compared to control mix M_2 without any cement replacement.

The same trend for mixes with 4.0% fiber, the workability showed increment for mix replacement with 50% F.A. while mixes with 50% SF and 25% F.A. + 25% S.F. replacement showed decrement. Their slump value was 70, 25, and 50mm, respectively. The increased surface areas and smaller particle sizes of combinations including S.F. or (F.A. + S.F.) materials may be the cause of the slump flow reduction. These ingredients produce more viscous alkaline solutions than water, which is why these mixtures were found to be stickier and more cohesive than the Ordinary Portland Concrete (OPC) mixture [16].

When compared groups together, it can be observed that the fiber volume fraction increased the workability decreased. This is due to the addition of fibers, which formed a network structure and prevented the mixture from flowing, maybe the cause of the declining trend in slump flow values. Additionally, some cement particles may absorb the fiber surfaces and wrap around the fibers, decreasing the quantity of paste that can effectively contribute to the flow of cementitious composite [17].

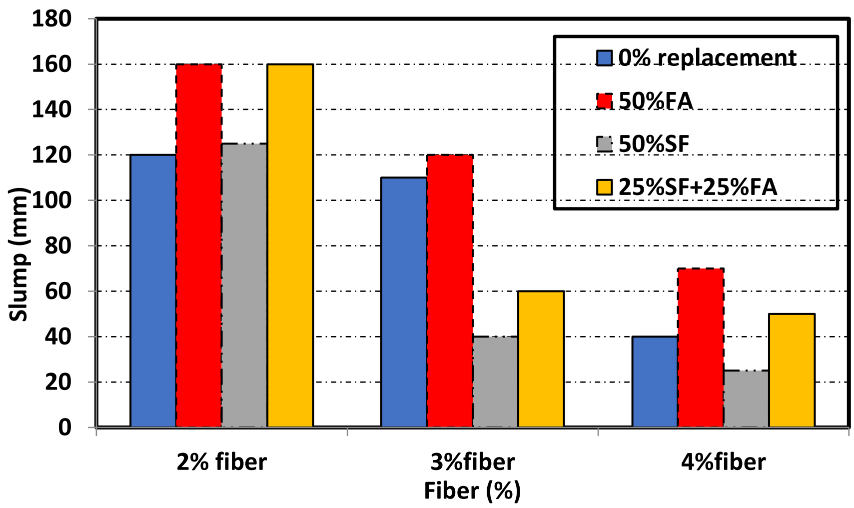

Figure 1. Slump values of ECC Mixes

2.2.2 Compressive Strength.

Figure 2 displays the compressive strength results at 28 days of age. For mixes with 2.0 % fiber the highest compressive strength has been found at 0% replacement and 25% (S.F and F.A) followed by 50% F.A. then50% S.F. The compressive strength was 47, 45, and 47 Mpa, respectively.

For mixes with 3.0% fiber slight decrement by 13, and 4.3% for 50% F.A., and 50% S.F., respectively and increment by 35% for 25% (S.F and F.A.) replacement with cement compared with control mix. For 4.0 % fiber the results indicated that an improvement in compressive strength by 72, 88, 124 % for mixes replacement with 50% F.A., 50% S.F., and 25% (S.F. and F.A.), respectively compared with control mix without any replacement.

Compared to the other groups, it is evident that the mixtures containing 3.0% fiber had the maximum compressive strength. Furthermore, it can be established that the addition of silica fume specifically when added with fly ash increased the positive effect of the fiber content which enhancing the compressive strength. In addition to densifying the interfacial transition zones (ITZ) and other microstructures of the concrete system, the S.F. fine particles also improve the particle packing in the aggregate paste interface and fill in the gaps between the relatively large OPC particles. Additionally, C-S-H gel is produced by the pozzolanic reaction of S.F. and Ca $(OH)_2$ and enhances the porosity and strength of the concrete mixture. The filler and pozzolanic Concrete's microstructure characteristics may provide insight into the effects of S.F. on the material [18-19].

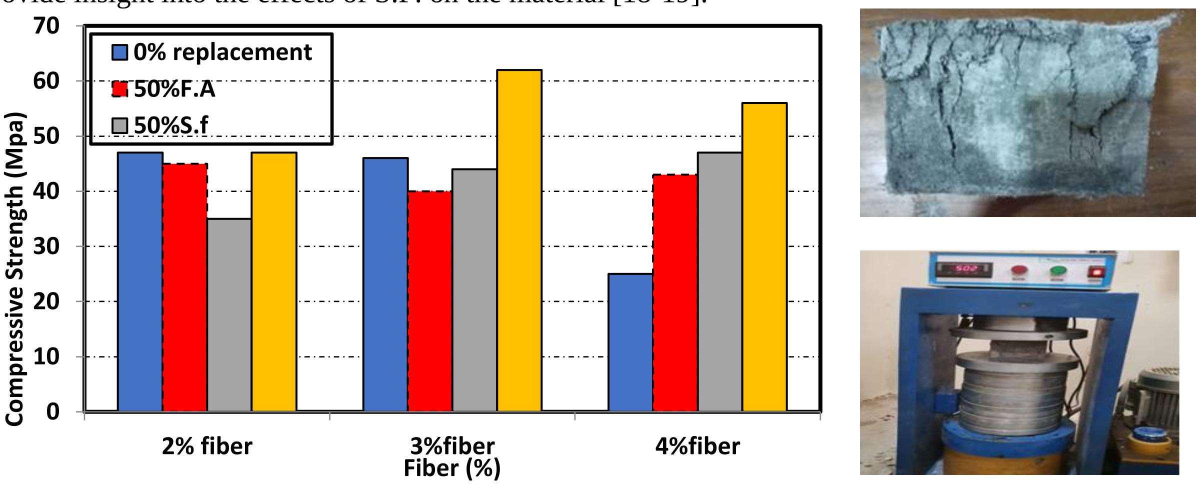

Figure 2. Compressive strength values of ECC Mixes

2.2.3 Flexural Strength.

Figure 3 presents the flexural strength results at the age of 28 days. The results generally indicated that using pozzolanic material as a replacement for cement had a slight effect on flexural strength. For example, at 2.0% fiber volume fraction, the flexural strength was decreased by (0, 2.5, and 13.7%) for 50% F.A., 50% S.F., and 25% (F.A.+S.F.), respectively, compared to the control mix without replacement. For 3.0% fiber volume fraction mix with 25% (F. A+S.F.), the maximum flexural strength was (2.42, 2.30, 2.16, 2.47) for 50% F.A., 50% S.F., and 25% (F. A+S.F.), respectively. On the other hand, the flexural strength had fluctuation between increasing and decreasing for mixes with a 4.0% volume fraction. The flexural strength was enhanced by (25, 26%) for mixes with 50% F.A. and 25% (F.A.+S.F.), respectively, while mixes with 50% S.F. was decreased by 9.7% compared to the control mix.

Like compressive strength, the group of mixes with 3.0% fiber achieved the maximum flexural strength compared to other groups. This is clarified by the fact that polymeric fiber has a lower modulus of elasticity, and that the interfacial bonding strength is reduced with a large volume of fiber. As a result, based on the workability, compressive strength, and flexural strength data, the following slab was cast with a 25% (F.A.+S.F.) cement replacement mix.

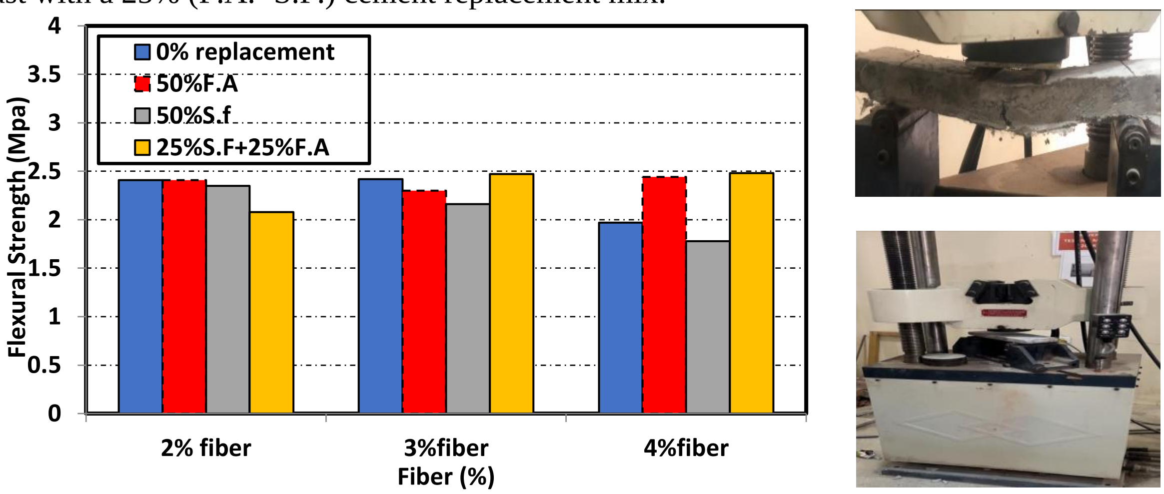

Figure 3. Flexural strength values of ECC Mixes

3. Experimental study program

3.1 Descriptions of the test specimen

Three slabs were constructed and evaluated under four-point concentrated loads in this experimental investigation. Each slab had a cross-section dimension of (80*1200*500) mm.

Slab (1): Reinforced concrete slab which contains of cement, gravel, sand (1: 3.60: 1.80), respectively water, 0.4% of the cement weight, and HRWRA, 0.5% of the cement weight. In addition, steel bars. 6ϕ10 and 3ϕ10 was applied in two directions.

Slab (2): The ECC slab, which consists of polypropylene fiber, was used with a 3.0% volume fraction of ECC mix (25% fly ash with 25% silica fume) as a partial replacement for Portland cement. The ratio of sand, HRWRA, and water were 80%, 1.5%, and 28% of the binder weight, respectively.

Slab (3): 50% plain concrete and 50% ECC the bottom of the slab was filled with ECC concrete, similar to the previous content. The top of the slab was cast in plain concrete without reinforcement.

3.2 Specimens preparation

For the slabs, plywood was used as the forms for the different slabs, as shown in Figure 4. For slab (1) plain concrete was placed with thickness 20mm then reinforcement Finally the rest of plain concrete was added to the edge of slab Figure 5. For slab (2) ECC was placed in all slabs. For slab (3) ECC was placed with thickness of 40mm. After 45minutes, the plain concrete was placed in the top of slab. The slabs were demolded and put in the curing room after a 24-hour period. Then, they were cured with water and covered with plastic sheets every day for a total of 28 days.

Figure 4. Formwork used to prepare the slabs

Figure 5. Cast of reinforced concrete slab

3.3 Test setup, and test methodology

The concentrated loads were placed vertically in a displacement control system with tested specimens oriented horizontally, at a rate of 0.5 mm/min until failure at the one-third positions for slabs. A spreader beam and 25-mm diameter rods were utilized to deliver the concentrated loads utilizing 1800-kN universal testing to uniformly distribute the applied loads over the top of the slab width.

4. Experimental study results and analysis

4.1 load versus mid span deflection

Figures 6 shows the relationship between the load, mid-span deflection. The load-capacities, deflections and ductility index for slabs are listed in Table 4. Similar behaviors were noted among the slabs. There were three stages to the slabs' load-deflection curve: (1) the pre-cracking stage, (2) the ultimate stage, and (3) the failure stage. During the pre-cracking stage, slabs exhibited similar behaviors. Slabs' rigidity decreased after the cracking point. However, the stiffness of ECC and 0.5P.C+0.5ECC decreased more significantly when compared to the R.C slab. This behavior can be explained by the decrease in tensile strength of the fiber compared to the reinforcement steel after cracking. However, after cracking, slabs exhibited tensile strain hardening behavior. The R.C. slab reached its maximal load capacity. There was no significant change in load during the slabs' ultimate stage, and the specimens reached their highest loads at this stage. R.C.'s peak load increased by 59.4 and 65.34% compared to ECC and 0.5ECC+0.5P.C. specimens, respectively. The ultimate deflection for R.C. increased by 20.67, or 48.22%, as compared to ECC and 0.5ECC+0.5P.C. On the other hand, ECC served to delay the collapse of the two slabs. This behavior occurred as a result of the ECC's greatly increased tensile strain capacity, which contributed to the slab's flexural strength while delaying concrete tension softening and slab failure. Larger deformation and material strain energy storage allowed for more energy dissipation.

Table 4: loads, deflections, and ductility index

Mix No	Yield load Py (KN)	Peak load P_U (KN)	Failure load P_f (KN)	Deflection at yield Δy (mm)	Deflection at Peak Δ_u (mm)	Deflection at Failure Δ_f (mm)	Ductility index (μ)
R.C	46.41	51.51	36.21	7.95	18	41.46	2.26
ECC	13.77	20.91	1.02	1.10	14.28	41.21	13
0.5ECC+0.5P.C	15.81	17.85	2.55	1.27	9.32	27.022	7.33

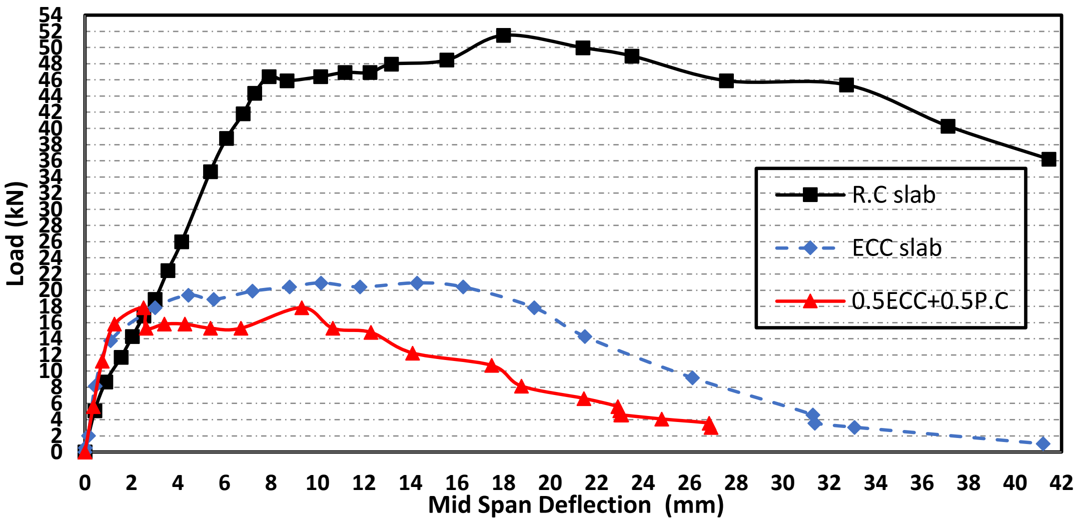

Figure 6. Relation between Load and mid-span deflection for different slabs

4.2 Failure Mode

Figures 8, 9, and 10 show the failure state of the tested slabs. Cracks on the tension face of the slabs indicate flexural deformation in RECC and RC specimens. The fracture shape ECC slab and 0.5ECC+0.5P.C were almost close. The tension face of the two slabs revealed that the development of multiple, finer cracks. indicates clearly that there are no balling effects and that the fibers in ECC mixtures are uniformly distributed. It also illustrates the fiber bridging in the ECC layer under flexural pressure Figure 8 and 9. Severe concrete crushing and spalling that was found in the RC slab.

Figure 8. R.C. Failure Modes

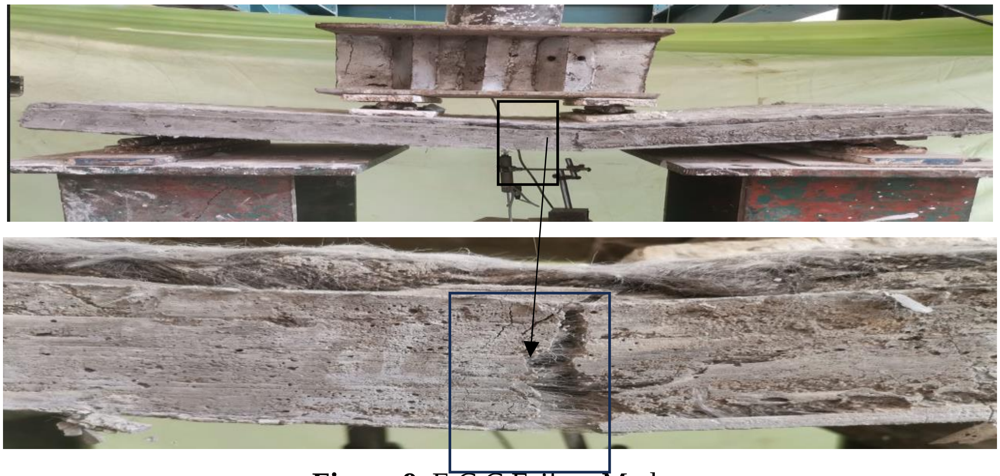

Figure 9. E.C.C Failure Modes

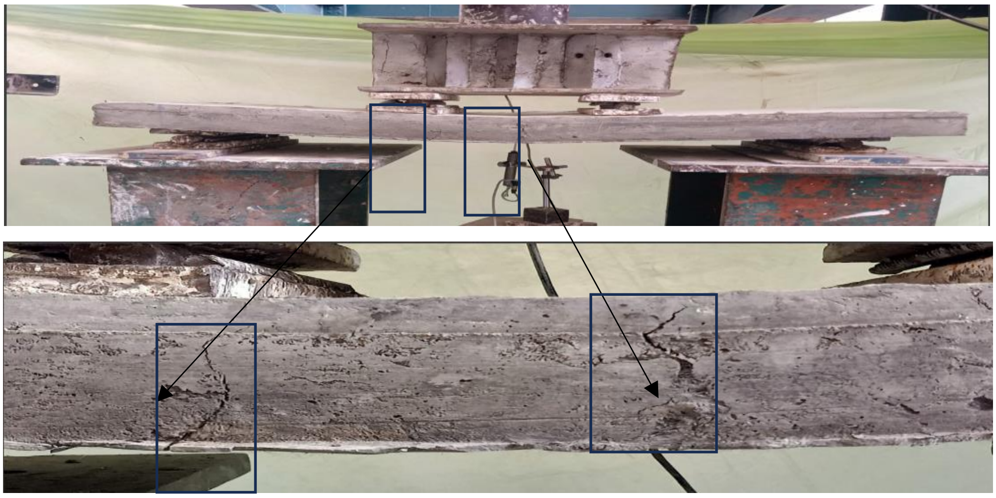

Figure 10. 0.5ECC+0.5P.C Failure Modes

4.3 Ductility Index

The expression of a member's ductility in limit and seismic design is often given as the ratio of the ultimate deformation (Δu) to the deformation at first yield (Δy). Deflection is a useful way to express member ductility. The following was the way ACI defined a deflection ductility index (μ):

$$\mu = \frac{\Delta u}{\Delta y}$$

According to figure 7, ECC and 0.5ECC+0.5P.C. slabs demonstrated ductile behavior more R.C slab with a ductility index μ = 34, and 7.33 respectively which are increased by 82.6% and 69.16% than R.C slab. The slab might continue to carry the tensile load before the main cracks appear because of the ECC in the tension region [22].

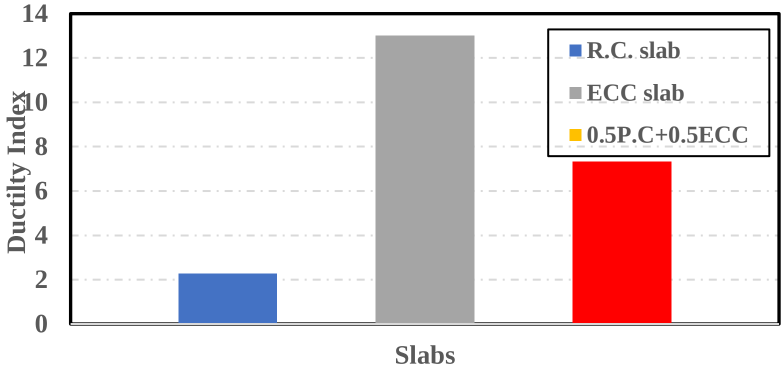

Figure 7. Ductility index of slabs

5. Conclusion

The following conclusions could be constructed:

1- Increasing fiber content impacted negative in the workability of fresh concrete.

2- The addition of 50% S.F. and 25% (F.A.+S.F.) as partial substitutes for cement lowered workability, while adding F.A. improved it.

3- Increased fiber content leads to increased compressive and flexural strengths. Among all fiber content, 3.0% V_f fiber had the maximum compressive and flexural strengths.

4- After 28 days of curing, the mix 25% (F.A.+S.F) with any fiber content resulted in the maximum compressive strength of 47, 62, and 56 Mpa, respectively.

5- The highest flexural strength was attained using a 25% (F.A.+S.F) mix and 3.0 and 4.0% V_f of fiber. However, employing it with 2.0% V_f of fiber showed a falling order of efficiency.

6- The slabs containing ECC were cast using a 25% (F.A.+S.F) and 3.0 fiber V_f mix based on workability, compressive, and flexural strength values.

7- Three slabs of R.C., ECC, and 0.5ECC+0.5P.C. displayed superior stress strain behavior.

8- The R.C. slab had the highest load among slabs. Whereas slabs reinforcement with ECC exhibited better ductility than it.

9- Cracks revealed excellent uniformity and did fiber bridging in slab reinforcement with ECC.

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