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FLEXURAL PERFORMANCE OF ENGINEERED CEMENTITIOUS COMPOSITELAYERED REINFORCED CONCRETE BEAMS

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This study focuses to develop a new hybrid Engineered Cementitious Composite (ECC) and assesses the performance of a new hybrid ECC based on the steel short random fiber reinforcement. This hybrid ECC aims to improve the tensile strength of cementitious material and enhance better flexural performance in an RC beam. In this study, four different mixes have been investigated. ECC with Poly Vinyl Alcohol (PVA) fiber and PolyPropylene (PP) fiber of 2.0% volume fraction are the two Mono fiber mixes; ECC mix with PVA fiber of 0.65% volume fraction hybridized with steel fiber of 1.35% volume fraction, PP fiber of 0.65% volume fraction hybridized with steel of 1.35%volume fraction are the two additional different hybrid mixes. The material properties of mono fiber ECC with 2.0 % of PVA is kept as the reference mix in this study. The hybridization with fibers has a notable achievement on the uniaxial tensile strength, compressive strength, Young's modulus, and flexural behavior in ECC layered RC beams. From the results, it has been observed that the mix with PVA fiber of 0.65% volume fraction hybrid with steel fiber of 1.35% volume fraction exhibitimprovements in tensile strength, flexural strength,andenergy absorption. ThePP fiber of 0.65% volume fraction hybridized with steel of 1.35%volume fraction mix has reasonable flexural performance and notable achievement in displacement ductility overthe reference mix.

Keywords: ECC, Fiber Hybridation,Young's Modulus, Flexural Strength, Composite Beam, Poly Vinyl Alcohol fiber, Polypropylene fiber and Steel Fiber

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1. INTRODUCTION

Engineered cementitious composite (ECC) is a material prepared based on a cement mortar matrix with short random fibers with a volume fraction of up to 2.0%. It belongs to the family ofUltraHighToughnessCementitious Composite (UHTCC) which displays outstanding mechanical properties in strain hardening, tensile strength, and ultimate strain capability. The type, geometry, volume fraction,and other strength characteristics of the fibers used in the mix decide the mechanical behaviours of ECC (1). ECC mixes are usually developed with polyvinyl alcohol (PVA) fibers, steel (SE) fibers, PolyPropylene (PP), and PolyEthylene (PE) fibers. The purpose of incorporating fibers is to improve the strain hardening nature, tensile strength, and energy absorption of the concrete, which facilitates damage reduction in the concrete structure subjected to dynamic and impact effects(2).

ECC obtains a better advantage in recent applications with excellent mechanical and multiple finecracking behaviour. Its performances in bridge decks, dampers, repair material for dams, irrigation channels, viaducts, and retaining walls are notable ones. ECC improves fatigue resistance and energy absorption; suppresses vibration control; resists against severe environmental exposures, and, furthermore, is maintenance free (3). The application of ECC in the strengthening of beams exhibits better performance than fiberreinforced polymers (FRP). The debonding failure appears due to normal stress and interfacial shear concentrations at crack points subjected to flexural loads in Reinforced Cement Concrete (RCC) beams. ECC placed at the ductile zone delayed deboning more so than the FRP material, whereas the ductility layer in the RCC beams improved the strength and minimized losses in deflection capacity (4).

The ECC introduced in the RCC beam which underwent flexural loading produces thinner cracks at the tensile face (rather than one extended crack). The finer cracks decrease the crack-induced stress concentration in the beam, thereby resulting in effective stress distribution in the bottom layer of the beam (5). Day by day application of ECC in construction is massive for a variety of infrastructure facilities. In the future, the scope of using ECC may augment various construction sectors. ECC with mono fiber reinforcement composites has few limitations in various applications, and thus there is a demand to improve the properties of conventional mono fiber ECC composites. Low elastic modulus fibers like PE, PVA, and PP have excellent ductility, strain hardening, and least amount tensile stress under tensile load (6). Glass fibers, steel fibers, and carbon fibers are the well known high elastic modulus fibers exhibiting soaring tensile strength, toughness of the concrete mix, and an intrinsic brittle nature that does not allow for ductility and strain hardening (7). The hybridation in the ECC with low modulus PVA fibers, PP fibers, and high modulus glass fibers exhibit notable improvement in the mechanical properties of the ECC mix (8,9).

The applications of ECC may be prolonged for different infrastructure divisions in the future. There are some limitations in different applications where mono fiber ECC is used, and so there is a demand to advance the properties of the ECC with mono fibers.In this study, the focus is predominantly laid to develop a new hybrid cementitious composite by introducing low modulus fibers such as PVA, PP, and SE as high modulus, with better mechanical properties, flexural behaviour, and ductility properties. For examining a variety ofbehaviours, PVA and PP fibres of 0.65%volume fraction are hybridized with steel fibers of 1.35%volume fraction. ECC with 2.0% volume fraction of PVA fibers is kept as a reference mix.

2. MATERIALS AND METHODS

2.1. MATERIALS AND MIX PROPORTIONS

The chemical compositions of OPC 53 grade and Class F fly ash are given in Table 1. In the same way, the physical and mechanical properties of PVA fibers, PP fibers, and SE are shown in Table 2. Various mixes used to develop the new fiberreinforced ECC are shown in Table 3. Table 4. displays the M30 grade mix design for concrete as per IS-10262(10) which is used for RCC beams under flexural performance, and Fe500 grade steel reinforcement used for RCC beams. A super plasticizer is added into the mix to meet the reliable mix in fresh state of ECC. Mixes are named as M1 for the ECC mix with PVA mono fiber reinforcement, and M2 for the PP fiber reinforced ECC mix. M3 ECC mix is made with a hybridation of PVA fibers and steel fibers of 0.65% and 1.35% volume fraction, respectively. Similarly, M4 ECC mix is a hybridation of PP fibers of 0.65 %volume fraction and steel fibers of 1.35%volume fraction of. The hybridation of steel fibers with PVA and PP is to improve the mechanical and ductility characteristics of ECC.

Table 1. Properties of cement and fly ash

	CaO (%)	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	MgO (%)	SO3 (%)	Alkalines (%)
Cement	63.71	22.30	4.51	3.39	1.77	2.59	1.73
Fly ash	5.31	55.37	29.74	7.88	1.48	0.22	--

Table 2. Physical and mechanical properties of fibers

Fibre	Diameter [μm]	Length [mm]	l/d ratio	Density (g/cm^3)	Nominal tensile strength [MPa]	Elongation at break [%]	Young's modulus [MPa]
PVA	39	12	308	1.3	1600	6	42.5
PP	37	10	270	0.91	400	23	2.5
Steel	300	12	40	7.9	2000	4.5	175

Table 3. Mix design of ECC

Mix ID	Cement	Fly ash	Sand	Water/Binder ratio	Super Plasticizer [%]	PVA Volume [%]	PP Volume [%]	Steel Volume [%]
M1	1	0.43	0.71	0.35	1.0	2.0	--	--
M2	1	0.43	0.71	0.35	1.0	--	2.0	--
M3	1	0.43	0.71	0.35	1.0	0.65	--	1.35
M4	1	0.43	0.71	0.35	1.0	--	0.65	1.35

Table 4. Mix design of conventional concrete (kg/m^3)

Cement	Fly ash	Sand	Course Aggregate	Water/Binder ratio	Super Plasticizer [%]
272.8	68.2	730	1235	0.4	0.9

2.2. MIX PREPARATION

A Mixer machine is used to mix the ECC ingredients (cement, fly ash, sand, fibers, water, and super plasticizer). Fine ingredients are first placed in the mixer and allowed to rotate for 5 to 8 minutes. Later, water and a super plasticizer are mixed together and added to the dry mix in the mixer machine and allowed to mix for another 5 minutes. The mix preparation shortly ends by adding fibers to the cement paste and allowing the mix to evenly distribute the fibers for another 3 to 5 minutes. The advantage in preparing the mix for more than 15 minutes is to reduce the thixotropy effect of the ECC (11). When fresh ECC is touched with the hand, no balling effects of the fibers are found. This specifies that the fibers are uniformly distributed within the cement mortar mix. The ECC mixture collected from the mixer machine ispouredinto various suitable moulds, and external vibration is not encouraged due to its self-compacting nature. The specimens are cured at room temperature for 24 hours,and afterwardsthey are demoulded and allowed to cure for 28 days. Later on, all the preferred tests are carried out over the respective specimens. For flexural behavior studies, ECC layered RCC concrete beams with an overall length and span of 2000 mm and 1800 mm of the beam are used,respectively.

2.3 TEST METHODSAND SPECIMEN DETAILS

2.3.1 UNIAXIAL COMPRESSION AND YOUNG'S MODULUS TESTS

Three 70.7 x 70.7 x 70.7 mm cube specimens were cast to determine the compressive strength of concrete ineach ECC mix at a range of 3, 7, 14, and 28 days according to IS 4031- Part 6 [12]. A cylinder 100 mm in diameter and 200 mm in length is used to determine Young's modulus. For each mix, 3 specimens are cast and tested after 3, 7, 14, and 28 days to determine the values**.**

2.3.2 DIRECT TENSILE TEST

A dog bone specimen of size 330 mm x 60 mm x 30 mm (13 and 14) has been used to determine the uniaxial tensile test of the ECC. The uniaxial tensile test is carried using the 100 kN capacity Universal Testing Machine, with specimens of a gauge length of 80 mm and a crosssection of 30 mm x 30 mm after 28 days of curing to determine the tensile strength of the various ECC mixes. Figure 1. Shows the test setup and specimen details for the direct tensile test.

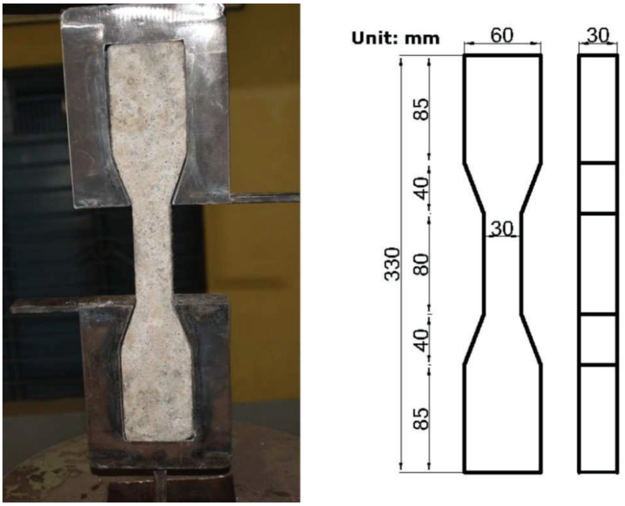

Figure 1. Test setup and specimen details for direct tensile test

2.3.3 Flexural Behavior of ECCLayered RC Beams

The third middle load is applied on the 1800 mm length of the RCC beams, and tests have been conducted at room temperature, as per standard. Figure 2. Shows the dimension parameters, reinforcement details, and position of the ECC layer. Top and bottom reinforcements are placed on a clear cover 15 mm from the top and bottom edges of the beam, respectively. The RCC beam is cast in such a way that the ECC mixes are placed inside the beam initially, and,one hour later, the conventional concrete is placed over the ECC to prevent debonding between two layers and to prevent the course aggregate from entering into the ECC layer. The ECC layer is about one-fifth of the total depth of the beam. Three LinearVariable Differential Transformers (LVDT) are placed at the bottom of the beam below the load acting point and the midspan. The Load cell is used to measure the load applied onto the beam; and is placed above the push-pull hydraulic jack of 100 kNcapacity, which is used to apply the load onto the beam. The Load cell and LVDTs are connected with a data acquisition system- via a computer and the readings are recorded and stored.

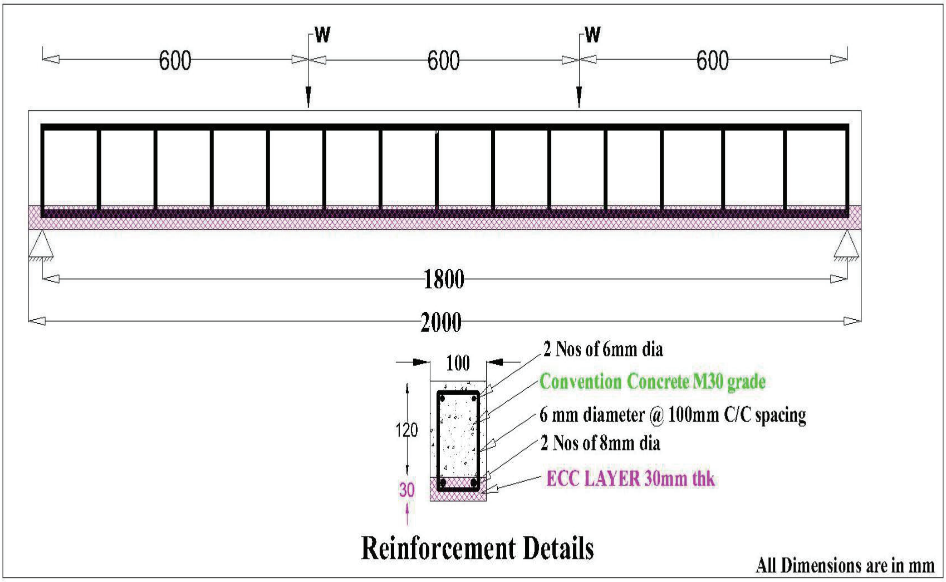

Figure 2. Dimension parameters, reinforcement details, and position of ECC layer

From the load deflection curve, seismic parameters such as the energy absorption of a section and displacement ductility have been evaluated. The area between the yield point and the breaking point under the load deflection curve is said to be energy absorption. The ductility of the reinforced concrete flexural system is defined as the ability to maintain excessive energy or deformation of the structural system after the steel reaches its yield stress. The structure should withstand sudden lateral loads and offer sufficient warning before it collapses. Therefore, a high ductility structural system is required. The displacement ductility is the ratio between the ultimate deflection and the first yield deflection (15).

3. RESULTS AND DISCUSSION

3.1 UNIAXIAL COMPRESSION AND YOUNG'S MODULUS TESTS

Mixes M1, M2, M3, and M4 have been tested to determine the compressive strength of the ECC after 3, 7, 14, and 21 days of curing. For each mix, three specimens were tested and an average uniaxial compressive strength was taken. Figure 3. shows the compressive strength of the mixes at different stages of curing. 51 MPa, 47.5 MPa, 53.2 MPa, and 52.2 MPa are the 28-day compressive strengths of M1, M2, M3, and M4, respectively. From the results it is observed that there is a significant difference between the compressive strengths for all the mixes. The compressive strength of the mixes after 3 days curing is 18.4%, 19.2%, 19.5%, and 19.3% of the 28-day compressive strengths of the M1, M2, M3, and M4 mixes, respectively. Similarly, after 14 days of curing, the compressive strengthsare observed as 74.9%, 78.9%, 73.9%, and 74.5 % of 28-day compressive strengths for M1, M2, M3, and M4. Hence, the results confirm that the hybridation of fibers in ECC mixes does not produce any major impact on the overall compressive strength. Figure 4. shows the failure pattern of ECC cubes after compressive strength testing. From the figure it can be observed that the hybrid ECC mixes are ductile; and due to the fiber bridging effect, the fragments are attached around the cubes (16).

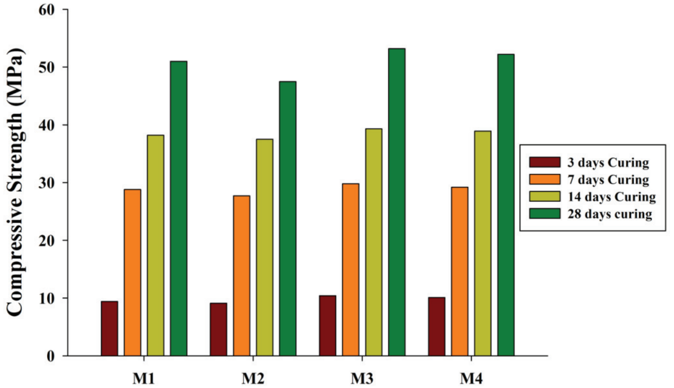

Figure 3. Compressive strength of ECC mixes

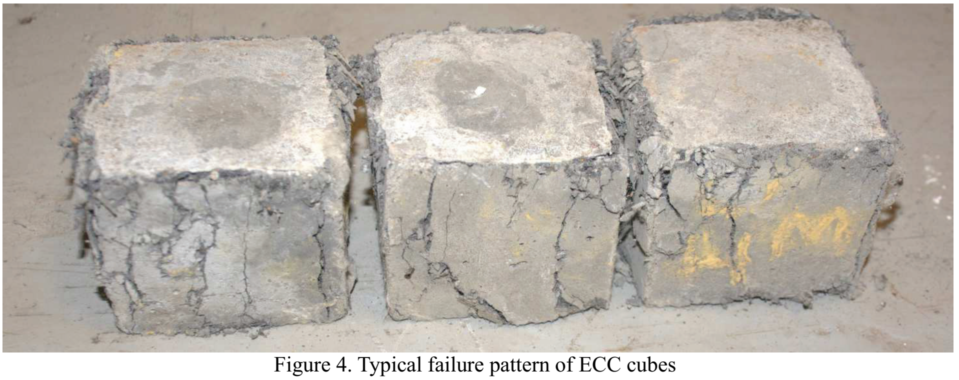

Figure 4. Typical failure pattern of ECC cubes

Figure 5. shows the average Young's modulus values of the ECC mixes after 3, 7, 14, and 28 days. From the figure it can be seen that Young's modulus values of the M1 and M2 mixes are similar at the periods of 3, 7,14, and 28 days, and the assessment of the M3 mix is 9.8%, 8.9%, 7.2%, and 8.4% greater than the M1 mix at the age of 3, 7, 21, and 28 days, respectively. Similarly, mix M4 is 7.7%, 6.1%, 7.2%, and 9.0% greater than mix M2 after 3, 7, 21, and 28 days of curing, respectively. Because of the absence of course aggregate in the ECC mixes, Young's modulus values obtained from the test are lower than those ofconventional concrete with corresponding compressive strength (17).

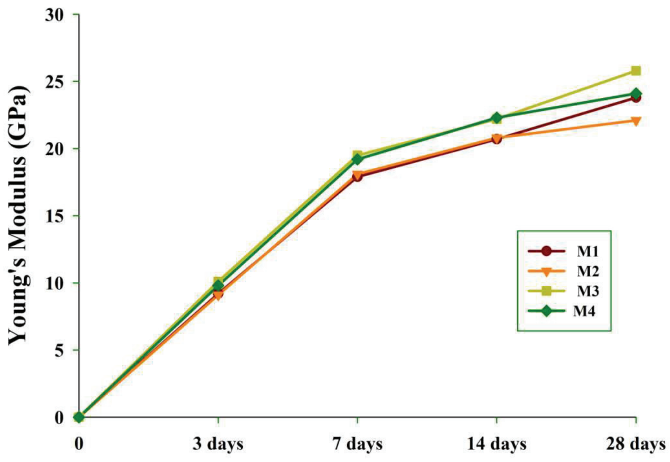

Figure 5. Young's modulus of ECC mixes

3.2 DIRECT TENSILE TEST

In the present scenario, the appliance applicationof ECC materials in the constructional field is extensive and is necessary to understand the role of ECC in each applications. The sustainable ECC compounddeveloped in this investigation is best indicated for repairing infrastructures and to improve crack-damage mitigation. Before introduction into practical applications, a direct tensile strength for the newly developed ECC mix needs to beperformed. Figure 6. shows the direct tensile strength of the various ECC mixes. The direct tensile strength tests have been carried out on 7, 14, and 28-day old specimen in which mix M3 performed better than all other cast mixes. The M3 mix exhibited 1.89 MPa, 3.95 MPa, and 7.45 MPa after 7, 14, and 28 days of curing, respectively, which is 36.7%, 35.2%, and 34.7% greater than the M1 mix. Mix M4 revealed tensile strengths of 1.84 MPa, 3.79 MPa, and

7.23 MPa for three different days of curing as mentioned, which is 33.1%, 29.8%, and 30.7% greater than the M2 mix. From the guidelines given by Victor Li (18) for the ECC mix, the value of the ultimate direct tensile strength is to be limited around 4-12 MPa, and the ultimate direct tensile strengths of all four different ECC mixes are within the specified range. In addition, the ultimate tensile failure crack pattern of the dog bone specimen occurred within the specified gauge length.

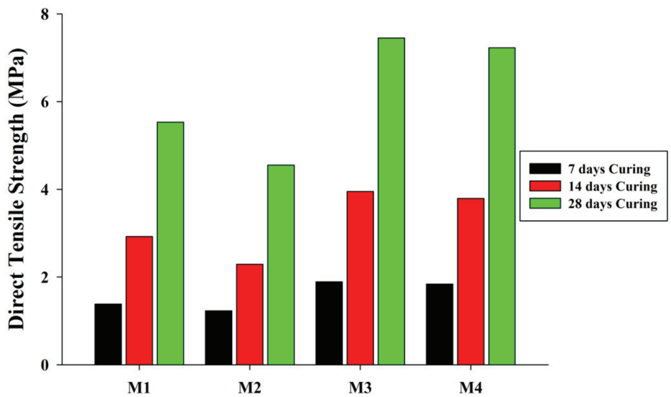

Figure 6. Direct tensile strength of ECC mixes

3.3 FLEXURAL BEHAVIOUR OF THE RCC BEAM

The typical fourpoint bending load deflection curves for all beams are exhibited by an initial crack in the concrete, yielding of reinforcement steel, and the ultimate and failure stages of beam behavior. Up to the yielding stage, all beams displayed the same flexural behavior. Within the yielding stage, the first crack load has occurred in all the beams and the values of the first cracking load have ranged from 3.72 kN to 4.38 kN.On the whole, due to loading nature, the first cracks have occurred between the point loads/midspan. Figure 7. shows the deflection behavior of an ECClayered beam under ultimate loading and Table 5. Shows the salient features of the load deflection values corresponding to the first crackin concrete, yielding of reinforcement steel, and the ultimate and failure stages of beam behavior. ECC is different from the brittle mode of failure, like concrete and noticeable strain. The hardening properties of ECC mixes under tensile/flexural loads ensured that the load does not decrease rapidly after the initial crack. The cracks which developed in the ECClayered beams are finer and multiple, which hasmarginal influence on the durability, strength, and performance of a structure (19 and 20). Due to the nature of ductility, the curves for ECClayered beams are wider than those of a conventional concrete beam. The number of flexural cracks increased withan increase in load but aftera particular stage, the development of new cracks in the beam ceased (21). Figure 8. shows the load deflection curve for the various beams.

Table 5. Salient features of the load deflection curve

Mix ID	First Crack Load (kN)	Deflection @ First Crack (mm)	Yield Load (kN)	Deflection @ Yield Load (mm)	Ultimate Load (kN)	Deflection @ Breaking Load (mm)
CC	4.07	0.19	9.6	1.8	18.1	25
M1	4.27	0.13	13.5	1.54	19.4	35.8
M2	3.72	0.34	10.3	1.49	19.6	48.1
M3	3.86	0.34	11.3	0.95	20.3	40.2
M4	4.38	0.39	13.9	0.81	19.55	40.9

After the yielding stage, the profile of the curve starts to vary and theydiffer from each other. At the ultimate stage, the developments of cracks in all specimen has been observed closely. In the conventional beam, only minor cracks have developed, whereas the depth of the cracks increased and extended to the compression zone before failure. In the case of the ECClayered beams, multiple cracks are developed in adjacent sides of the major cracks, owing to the transfer of the flexural load by fibere bridge effects (22). Fiber bridging effects in the ECC layer under flexural load are shown in Figure 9. The brittle matrix of the crack plane causes the formation of a crack near the major crack. Similar to conventional concrete, failure occurs on the ECClayered beam when the crack reaches the compression zone (23). The experimental results evidently indicate that there has been significant improvement in the ECClayered beams. In concern with the ultimate loadcarrying capacity, ECC with PVA and steel hybridation performed better among all other mixes: 1.12, 1.05, 1.04, and 1.04 times greater than the conventional concrete beam, M1, M2, and M4 ECClayered concrete beams, respectively.

Figure 7. Typical deflection behavior of an ECClayered beam under ultimate loading

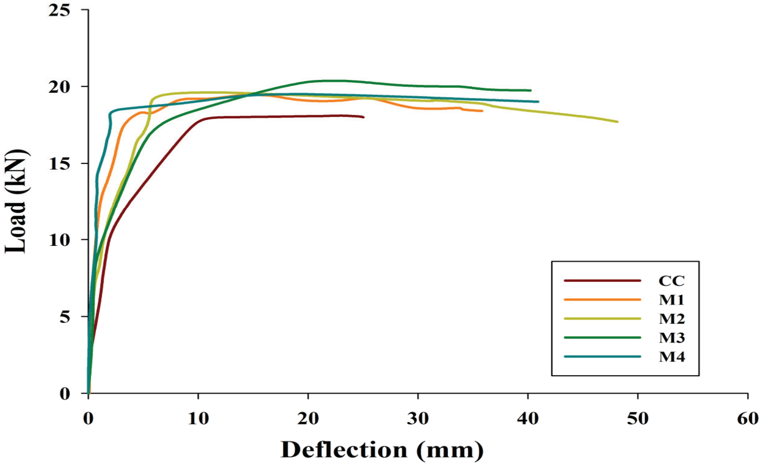

Figure 8. Load vs deflection curve for RCC beams

The energy absorption capacity is the area falling under the yield point up to the ultimate point in the load deflection curve. The comparison of the energy absorption between ECClayered beams and controlled specimens (a conventional mix generates 745.2 kN mm energy absorption) is less than the other ECClayered beam (M1, M2, M3, and M4 mixes exhibit 1.76, 1.71, 2.0, and 1.86 times greater). The presence of PVA fibers in the steel hybridation in the ECC mix makes a notable difference in the energy absorption. Table 6. shows the energy absorption and ductility of RCC Beams. On the other hand, the presence of PP fibers in hybridation exhibited admirable improvement in its ductility nature. This is 3.6 times greater than the conventional beam, 2.2 times greater than the M1 mix, 1.6 times greater than the M2 mix, and 1.2 times greater than the M3 mix.

Figure 9. Fiber bridging effects in ECC layer under flexural load

Table 6. Energy absorption and ductility of RCC beams

Mix ID	Energy Absorption (kN.mm)	Displacement Ductility
CC	745.2	13.9
M1	1318	23.2
M2	1276	32.3
M3	1490	42.3
M4	1390	50.5

4.0 CONCLUSIONS

The experimental investigation on the mechanical performance and flexural behavior of ECClayered RCC beams with PVA fibers, PP fibers, PVA fibers hybridized with steel fibers, and PP fibers hybridized with steel fiberswere carried out in the present work and the following conclusions have been collected:

The hybridation of steel fibers with PVA and PP fibers does not affect compressive strength. There is not much variation in the strength values, but the specimens are ductile, as the fragments are attached around the cubes with reasonable improvement in theirYoung's modulus values.

The direct tensile test proves that the addition of steel fibers exhibits better performance. This has increased up to 34.7% and 30.7 % over the ECC mix with PVA fibers. The failure of the specimen occurred within the designed 30 cm x 30 cm crosssection.

When compared with the reference conventional concrete beams, the beams with ECC layershaveshown better performance in the ultimate load, energy absorption, and ductility. It also helps control the deformation of the beam.

The failure of conventional concrete beams is abrupt with a minimum number of cracks and larger crack width. However, in ECClayered beams, multiple cracks are formed due to the bridging of the fibers before failure, and no spillage occurs during breaking load.

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LIST OF FIGURES AND TABLES:

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ZAPROJEKTOWANA FLEKSYJNA WYDAJNOŚĆ BELKI ŻELBETOWEJ POKRYTEJ KOMPOZYTEM CEMENTOWYM

Słowa kluczowe: zaprojektowane kompozyty cementowe, włókno polialkoholu winylowego (PVA), włókno polipropylenowe (PP) i włókno stalowe, hybrydyzacja włókna, moduł Younga, wytrzymałość na zginanie, belka kompozytowa.

Streszczenie:

Zaprojektowany kompozyt cementowy (ECC) jest materiałem przygotowywanym na bazie zaprawy cementowej z wykorzystaniem krótkiego włókna, z udziałem objętościowym do 2,0%. Należy do rodziny Kompozytu Cementowego o Bardzo Wysokiej Wytrzymałości (UHTCC), który wykazuje wyjątkowe właściwości mechaniczne w zakresie umocnienia odkształceniowego, wytrzymałości na rozciąganie i odporności na odkształcenia. Typ, geometria, udział objętościowy i inne właściwości wytrzymałościowe włókien stosowanych w mieszance decydują o mechanicznych zachowaniach ECC. Mieszanki ECC są zwykle opracowywane z wykorzystaniem włókna polialkoholu winylowego (PVA), włókna stalowego (SE), włókna polipropylenowego (PP) i włókna polietylenowego (PE). Celem zastosowania włókien jest poprawa umocnienia odkształceniowego, wytrzymałości na rozciąganie i pochłaniania energii betonu, co zmniejsza uszkodzenia w konstrukcji betonowej poddanej wpływom dynamicznym i uderzeniowym.

W celu zbadania zachowania ECC podczas testu ściskania, wykonano test modułu Younga, bezpośrednią próbę rozciągania oraz test zginania na belkach dla 4 różnych mieszanek. Mieszanka 1 (M1) zawiera 2% włókna PVA, mieszanka 2 (M2) zawiera 2% włókna PP, mieszanka 3 (M3) zawiera 0,65% PVA i 1,35% włókien stalowych, mieszanka 4 (M4) zawiera 0,65% PP i 1,35% włókien stalowych.

Wyniki 28-dniowych testów wytrzymałości na ściskanie wynoszą odpowiednio: 51 MPa, 47,5 MPa, 53,2 MPa i 52,2 MPa dla mieszanek ECC M1, M2, M3 i M4. W związku z powyższym, wyniki potwierdzają, że hybrydyzacja włókna w mieszankach ECC nie ma większego wpływu na wytrzymałość na ściskanie, ale hybrydowe mieszanki ECC są plastyczne; a dzięki efektowi łączenia włókien, fragmenty są przymocowane wokół kostek. Wyniki testu modułu Younga wykonanego na ECC pokazują brak kruszywa gruboziarnistego w mieszankach ECC, a wartości modułu Younga otrzymane podczas testu są niższe niż w przypadku betonu konwencjonalnego.

Zrównoważony materiał ECC opracowany w ramach tego badania służy do naprawy infrastruktur oraz do lepszego łagodzenia skutków uszkodzeń i pęknięć. Tak więc, przeprowadzono bezpośrednią próbę rozciągania na próbce kości psa. Wydajność mieszanek włókien hybrydowych M3 i M4 jest dobra w porównaniu z dwoma innymi mieszankami. Wszystkie wartości wyników bezpośredniej próby rozciągania wynoszą od 4 do 12 MPa, zgodnie z wytycznymi Wiktora Li, dotyczącymi mieszanki i wzorca ostatecznego pęknięcia próbki kości psa i występują na określonej długości pomiarowej.

Próby zginania wykonane na belkach pokazują, że maksymalna nośność ECC z hybrydyzacją PVA i stali (mieszanka M3) była lepsza wśród wszystkich innych mieszanek, co oznacza, że była o 1,12, 1,05, 1,04 i 1,04 razy większa niż w przypadku belki wykonanej z betonu konwencjonalnego, tj. odpowiednio belki betonowe M1, M2 i M3 pokryte ECC. Podobnie, mieszanka ECC M3 wykazuje zauważalną różnicę w pochłanianiu energii. Z drugiej strony, obecność włókna PP w hybrydyzacji wykazała godną podziwu poprawę w zakresie plastyczności. Wartość ta jest o 3,6, 2,2, 1,6 i 1,2 razy większa niż w przypadku konwencjonalnej belki, tj. mieszanki M1, mieszanki M2 i mieszanki M3.