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Appraisal on low cost and sustainable ECC using microfibers in hybridization at later age

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ABSTRACT

The addition of supplementary cementitious materials and fiber plays an important role in the mechanical and durability performance of ECC matrix. In the present research work, the assessment of the performance of ECC matrix with the utilization of iron industry waste and microfibers has been done. Three types of microfibers, i.e., polyvinyl alcohol (PVA) fiber, polyester (PET) fiber, and microsteel (MSE) fiber, were used at various percentages in hybridization to prepare total seven mixes. First, PVA was switched by PET fiber at dosages 5%, 10%, 15%, 20%, and 25% and afterwards another 25% by MSE fiber. The performance of various matrix proportions was judged based on the flexural response, electrical resistivity, air permeability, and sorptivity characteristics to introduce sustainable and cost effective ECC matrix. Test results revealed that hybridization of fibers enhanced the flexural and durability performance of ECC and also produced a cost effective and sustainable ECC matrix.

Keywords: Polyester fiber; Sorptivity; Permeability; Slag; Micro pores; Resistivity.

INTRODUCTION

Cement based materials are most commonly used in the structural application fields. The cracks and penetration of detrimental liquids reduce the durability performance and service life of the concrete structures. Therefore, most of the cement-based structures damage and require repairing in continuity during service life. To enhance the mechanical and durability performance of structures, few decades ago high strength concrete (HSC) was introduced in construction industry, because, of its unique characteristics. The nature of HSC is considered as brittle which affects the other parameters i.e. ductility and crack width. From last three decades, lots of efforts have been made by researchers to overcome these drawbacks. In present time, the material used in structural applications must satisfy the condition of high strength, tiny cracks and ductility. Engineered cementitious composite (ECC) is the novel class of high-performance fiber reinforced cementitious material (HPFRCM), which can be used to overcome above mentioned requirements. The most superb characteristics of ECC is the high energy absorption capacity (equal to 30 KJ/m^2), high tensile strain capacity (1%-8%) and controlled crack width (< 100 µm) (Singh *et al*., 2019[a]; Li *et al*., 1998[a]; Singh *et al*., 2019[b]; Li *et al*., 1998[b]; Said *et al*., 2015; Sahmaran *et al*., 2009). Design of ECC rely on the theory of microcracks and fracture mechanics and it presents a strain hardening behavior with multiple tiny cracks (Sahmaran *et al*., 2009; Ranade *et al*., 2014; Li *et al*., 1994). Literature reported several types of ECC matrix such as sprayable (shotcrete ECC), lightweight, self-compacting and extruded (Li *et al*., 1998[a]; Shao *et al*., 1997; Kong *et al*., 2003; Kim *et al*., 2003). Despite the abovementioned characteristics of ECC, its use in structural applications is limited due to higher cost. The usage of higher amount of cement and polymeric fiber (polyethylene (PE) and polyvinyl alcohol (PVA) play the main role in increasing the cost of ECC. Most of the researchers used PVA and PE fibers to develop the ECC. The cost of PE fiber is 6 to 7 times the cost of PVA fiber. The nature of PVA fibers is hydrophilic which makes a strong chemical bond with cement matrix, resulting into fibers rupture than pullout (Redon *et al*., 2001 & Pakravan *et al*., 2016). To decrease the bonding between matrix and fiber, oil treatment was applied on fiber surface, which increased the cost of fibers (Meng *et al*., 2017 & Li *et al*., 2017).

Hybridization of fibers and inclusion of waste was mainly employed to decrease the cost of ECC and improve the fiber-matrix interaction. Numerous investigations reported that hybridization of low and high modulus fiber promote not only the unique characteristic; but, also reduced the cost of ECC. Low modulus fiber promotes the ductile nature and also contribute in high absorption capacity; whereas, high modulus fiber contribute in higher bridging strength and modulus of elasticity (Li *et al*., 2016). Combined use of PE and steel fiber in ECC revealed the better shear strength and deflection capacity and also enhanced the fiber bridging strength (Alrefaei *et al*., 2018). The use of steel and PVA fiber in hybridization revealed better energy absorption capacity, impact resistance and also enhanced the tensile strength and fiber bridging capability (Soe *et al*., 2013[a] & Soe *et al*., 2013[b]). Ali *et al*., 2017 reported that the combination of PVA and SMA (shape memory alloy) fiber enhanced the tensile capacity, flexural strength and changed the failure mode of conventional cement matrix from brittle to ductile. The hybrid usage of PP (Polypropylene) and PVA fiber enhanced the tensile strain capacity with decrease in the cost of ECC (Pakravan *et al*., 2016). Most of the research works conducted on hybridization, with steel and PVA fiber. The combined use of steel-PVA leads to decrease in superb characteristics of ECC (tensile strain capacity and deflection capacity) and beneficial for flexural strength, toughness, fiber bridging capability improvement (Li *et al*., 1996 & Meng *et al*., 2018). However, previous studies reported that hybridization of fiber in ECC contribute in the enhancement of overall performance. Previous studies mainly focused on mechanical parameters and limited studies have been carried out on durability aspects of ECC matrix with the fiber combination. In past, lot of studies have been carried out on FRC (fiber reinforced concrete) with the use of various types of fibers such as steel, basalt, nylon, glass, textile, carbon, bagasse, PP, polyester (PET), PE, PVA etc., and the inclusion of these fibers in FRC enhanced the mechanical as well as durability performance of the matrix. The modulus of PET (polymeric) fibers is low and derived from virgin polyester. Utilization of PET fiber in cement-based products revealed better mechanical and durability performance than conventional concrete. Siddique *et al*., 2012 reported that the intrusion of PET fiber in HVFA (high volume fly ash concrete) concrete increased the abrasion resistance. The cost of PET fiber is very less as compared to PVA fiber. In present study mainly focus is on cost, sustainability and durability performance of ECC to promote its use in developing countries and hydraulic structures. PET fibers (polymeric nature) do not behave like hydrophobic or hydrophilic and distinctive features of PET make a very good bond between fiber and cement matrix (Rathod *et al*., 2010). Present research includes the hybrid proportion of PVA, PET, steel fiber and GGBFS (Ground granulated blast furnace slag) and performance of various mixes was evaluated based on flexural response, electrical resistivity, air permeability and sorptivity characteristics.

CONSTITUENTS AND METHODS

Constituents Used

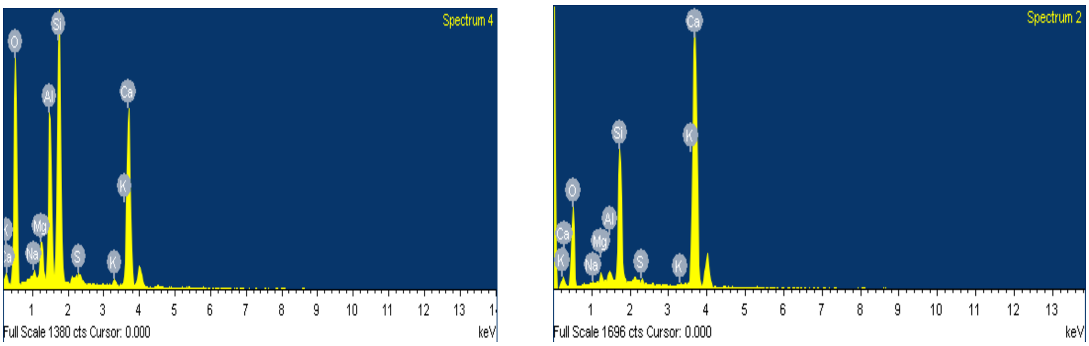
Proper selection of constituents is the prime factor in design of ECC matrix. Ordinary Portland (43 grade) cement (OPC) confirming to IS 8112 (2013) and ASTM C150 was used. GGBFS waste as a cementitious material and microsilica sand (MSS) with 175 micron maximum size was used as a fine aggregate. The chemical composition of solid constituents is presented in Table 1 and Energy dispersive X-ray spectroscopy (EDS) images illustrated in Figure 1. Polyvinyl alcohol (PVA) fiber coated by 1.2 % of engine oil, recron 3s polyester (PET) fiber and microsteel fiber (MSE) with brass coating were used as fibers reinforcement as shown in Figure 2. Typical properties of all the fibers used in this study are presented in Table 2. To achieve the proper flowability, master glenium SKY 8233 high performance plasticizer (SP) based on PCE (Polycarboxylic ether type) was used in all the ECC mixes.

Table 1. Chemical composition of solid constituents (EDS analysis).

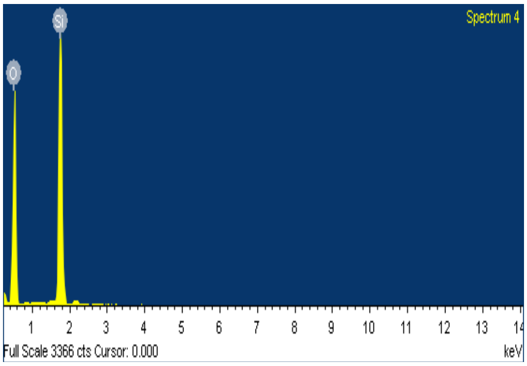
Chemical compounds (%)	GGBFS	OPC	MSS
CaO	33.47	61.56	-----
SiO_2	41.39	21.92	99.99
Al_2O_3	18.61	7.18	-----
MgO	3.82	5.37	-----
Na_2O	0.72	1.55	-----
K_2O	0.81	1.15	-----
SO_3	1.18	1.27	-----

Table 2. Physical characteristics of fibers.

Specifications	MSE	PET	PVA
Diameter (mm)	0.20	0.025-0.035	0.04
Length (mm)	13	12	12
Aspect ratio (L/D)	65	400	300
Tensile strength (MPa)	2000	480	1600
Elongation (%)	---	30	7
Young's modulus (GPa)	---	---	42.8
Density (g/cm^3)	---	1.31	1.3
Electrical conductivity	High	Low	Low



(a) (b)



(c)

Figure 1. EDS of (a) GGBFS, (b) PC, and (c) MSS.

(a) (b) (c)

Figure 2. Pictorial view of fibers: (a) MSE, (b) PET, and (c) PVA.

Matrix Proportions

In present investigation proportions of matrix were divided into seven groups with the intrusion of PVA, PET and MSE fiber as listed in Table 3. The performance of ECC mixture was evaluated with the use of all three fibers in various combinations.

Table 3. Matrix proportions with hybridization of microfibers.

Constituents	Mix Designation						
	HS1	HS2	HS3	HS4	HS5	HS6	HS7
OPC	1.0	1.0	1.0	1.0	1.0	1.0	1.0
GGBFS	1.2	1.2	1.2	1.2	1.2	1.2	1.2

MSS	0.8	0.8	0.8	0.8	0.8	0.8	0.8
PVA (%)	2.0	1.9	1.8	1.7	1.6	1.5	1.0
PET (%)	---	0.1	0.2	0.3	0.4	0.5	0.5
MSE (%)	---	---	---	---	---	---	0.5
w/b	0.27	0.27	0.27	0.27	0.27	0.27	0.27
SP (%)	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Sample Preparations and Methods

For making the cement matrix, mixer type and its rotation speed, mixing procedure and temperature are very important. In present research work electric type mortar mixture was used to prepare the cement matrix as shown in Figure 3. Firstly, all powdered constituents including OPC, GGBFS and MSS were mixed at low speed for approximately 2 to 3 min. Then two-third of water and SP was added into the dry mixture and rotated the mixer for another 2 to 3 min. Then remaining water and SP were added and mixed for 1 to 2 min to produce consistent and uniform mix. At last, fibers were dispersed slowly into the mixture and rotated until uniform mix was not achieved. To provide the required shape, uniform mix was poured into plates, prisms, and cubes of dimensions 250mm × 250mm × 75mm, 500mm × 100mm × 100mm and 70.6mm × 70.6mm ×70.6mm and placed inside the laboratory for 24 hours. All casted specimens were demoulded after 24 h and immersed into the water tank for curing. Plates, prisms and cubes specimens were taken out from water tank after 90d, 180d, and 365d to assess the air permeability and sorptivity index, flexural performance and electrical resistivity.

Figure 3. Pictorial view of mortar mixer during mixing.

TEST METHODS

Flexural Response

Prism specimens as shown in Figure 4 were used to assess the flexural performance of various matrix proportions. Four-point bending test was performed to evaluate the load-deflection performance as per IS 516:1959, 2006 and BS-EN-12390-5, 2009 specifications.

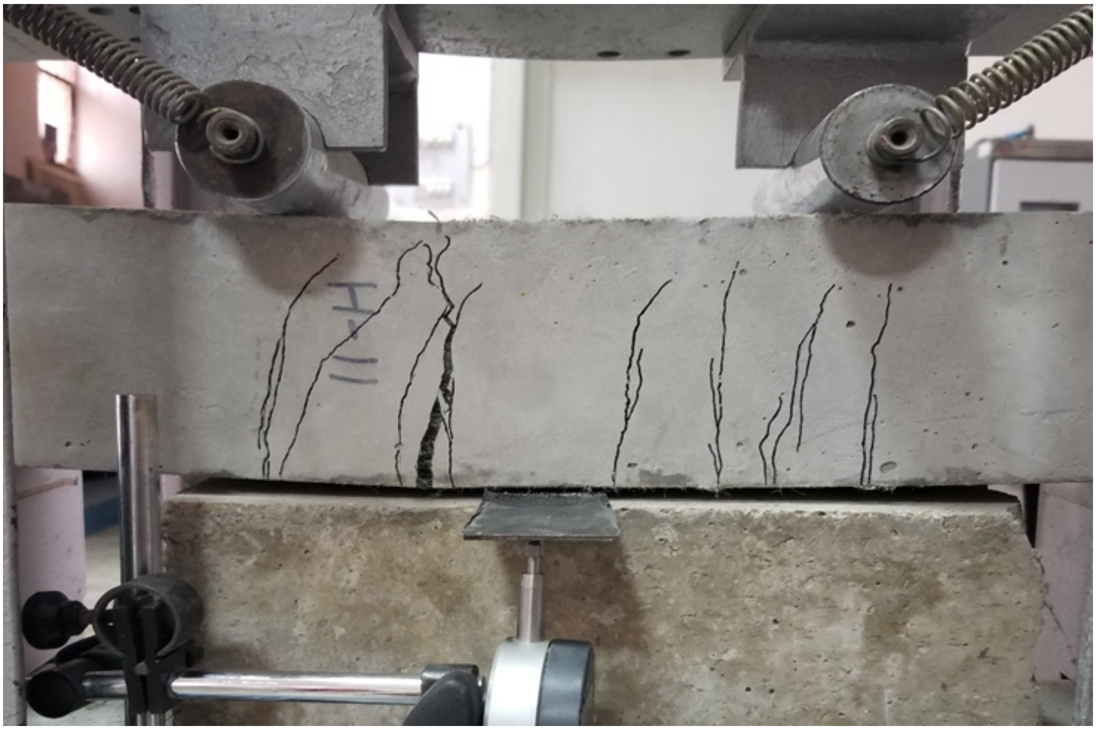


Figure 4. Four-point bending test setup.

Electrical Resistivity (ER)

ER performance can be used as durability indicator of cementitious material, which represents the movement and diffusion of ions inside the matrix. It is non-destructive technique and can be measured with various methods and indicates corrosion risk and chloride ion penetration into the matrix. In this research work the ER was measured on cubes specimens via a two-point method as shown in Figure 5. The ER (ρ) of the ECC matrix cubes was calculated by the following equation.

$$\rho = \mathrm{R}\frac{A}{L} k\Omega - cm \qquad (1)$$

where A is the area of the specimen (cm^2), L is the height of the specimen, and R ($k\Omega$) is the resistance of the specimen i.e. obtained from the multimeter. The recommended values for the correlation between ER, corrosion risk (CR) and chloride ion penetration have been given in Table 4.

Figure 5. Electrical resistivity setup.

Table 4. Correlation between ER, CR, and CIP (AASTHO T358-15,2015; ACI 222R-01,2010).

ER (kΩ-cm)	CIP	ER (kΩ-cm)	CR
< 12	High	< 5	Very High
12-21	Moderate	5-10	High
21-37	Low	10-20	Low to moderate
37-254	Very Low	> 20	Negligible
> 254	Negligible	---	---

Air Permeability and Sorptivity (water absorption)

Movement and diffusion of ions due to porosity is an excellent durability indicator of cement products and related to air permeability and sorptivity (water absorption). Air permeability and sorptivity (water absorption) tests were conducted on plates by using Autoclam permeability system, created by Queen's University, Belfast (United Kingdom). It is a non-destructive technique and also can be used on site for quality control. The assembly of Autoclam system comprises of (a) Base ring, (b) Autoclam body, and (c) electronic controller. The test setup of Autoclam permeability system was used to carry out the air permeability and sorptivity has been shown in Figure 6. In this investigation, the surface of the casted plates was isolated by taking standard base ring. To commence the air permeability test, the pressure was applied manually inside the Autoclam body with the syringe attached to the system. Test commenced automatically when desired pressure (500 mbar) reached, into the system and then decay in pressure was recorded for the next 15 minutes. The line of natural logarithm of measured pressure against time was plotted by regression, and the slope of the regressed line between 5th minute and 15th minute has been reported as the air permeability index (API) in units of Ln (mbar)/min. The scientific agency (Amphora) on the basis of API gives the criteria to classify the protective quality of cement-based products as presented in Table 5.

Table 5. API based criteria for protective quality of cement-based products (Autoclam manual, 1994).

Autoclam API, Ln (mbar)/min	Protective quality
> 0.9	Very poor
> 0.5 ≤0.9	Poor
> 0.1 ≤ 0.5	Good
≤ 0.1	Very Good

Sorptivity test (water absorption) was also conducted by the Autoclam permeability system, after the two hours of air permeability test completion at same location of specimens. The setup for sorptivity test was similar to that of air permeability test, but the upper channel of Autoclam body was filled with water. Internal priming pump of Autoclam body filled the test area with water and air escaped through bleed tube. After the selected test area was filled with water, priming pump automatically switched off and the micropump maintained the nominal pressure of 20 mbar and then sorptivity test started. The volume of water entering in specimen was recorded every minute for the next 15 minutes duration of test.

Figure 6. Test setup of Autoclam permeability system.

A plot of the amount of water entering against square root of time was plotted. The slope of plotted graph reported the sorptivity index in units of $m^3 \times 10^{-7}/min^{1/2}$. The criteria to classify the protective quality of cement mixes based-on sorptivity index has been given in Table 6.

Table 6. Sorptivity based criteria for protective quality of cement-based products (Autoclam manual, 1994).

Autoclam sorptivity index, ($m^3 \times 10^{-7}/min^{1/2}$)	Protective quality
> 3.40	Very poor
> 2.60 ≤ 3.40	Poor
> 1.30 ≤ 2.60	Good
≤ 1.30	Very Good

OUTCOMES AND DISCUSSION

Flexural Performance

The hybridizing impact of microfibers on the flexural performance of ECC matrix has been illustrated in Figure 7(a-c). Flexural strength capacity of ECC prisms ranges from 11.98 to 14.44 MPa and mid span deflection ranges from 4.68 to 6.28 mm between the ages of 90 to 365 days (d) depending on the various combinations of microfibers.

Hybridization of PVA and PET Fiber

Hybridization of PVA and PET fiber is a combination of high modulus and low modulus polymeric state fibers. Amalgam of these two fibers strongly influenced the flexural performance of ECC mixture. The literature of cementitious composite witnessed that low and high modulus fiber exhibited excellent behavior with several tiny cracks and also helps in minimizing the cost of fiber reinforced matrix (Pakravan *et al*., 2016 & Li *et al*., 2016). Subrogation of PVA with PET fiber at dosage 5%, 10%, 15%, 20%, and 25% enhanced the mid span defection capacity by 3.61%, 7.63%, 10.84%, 17.26% and 23.69%; 6.15%, 11.30%, 14.28%, 20.83% and 24.60%; 4.16%, 7.53%, 11.90%, 18.25% and 22.02% after 90d; 180d; 365d water curing. Flexural strength capacity of HS2 and HS3 mix proportions nearly similar to HS1 mix proportion. Increment in quantity of PET as PVA fiber subrogation decreased the flexural strength; but, increased the mid span deflection capacity. Flexural strength of HS4, HS5, HS6 mix proportion was decreased by 6.02%, 10.02%, 14.18%; 5.03%, 7.51%, 10.49%; 6.13%, 8.65%, 12.26% after 90d; 180d; 365d curing period as compared to HS1 mix proportion. Decrement in the flexural strength of PET fiber blended mix proportions was observed due to low modulus of PET as compared to PVA fiber, which reduced the fiber bridging strength in the matrix. On the other hand, deflection capacity of ECC matrix improved with PVA and PET fiber hybridization, better elongation capacity, slip hardening behavior, chemical bonding between PET fiber and cement matrix was responsible for this enhancement. Because the nature of PVA fiber is hydrophilic, which sustain a strong chemical bond between fiber and matrix i.e. responsible for fibers rupture than pull out. PET fiber lies in the middle state of hydrophobic or hydrophilic, which helps to sustain a very good bond between matrix and fiber surface (Rathod *et al*., 2010). This wacky nature of PET fiber contributes in the high absorption capacity and slip hardening behavior, which promote the ductile nature of the ECC. Minimum flexural strength was found 11.98 Mpa with 25% subrogation of PVA with PET fiber which is similar to fly ash PVA-ECC mixture (Pan *et al*., 2015 & Zhigang *et al*., 2014). The 25% utilization of PET fiber in ECC matrix as PVA fiber replacement reduced the total cost of ECC matrix by 20.72% for one cubic meter, which promote the use of ECC in developing countries or on large scale.

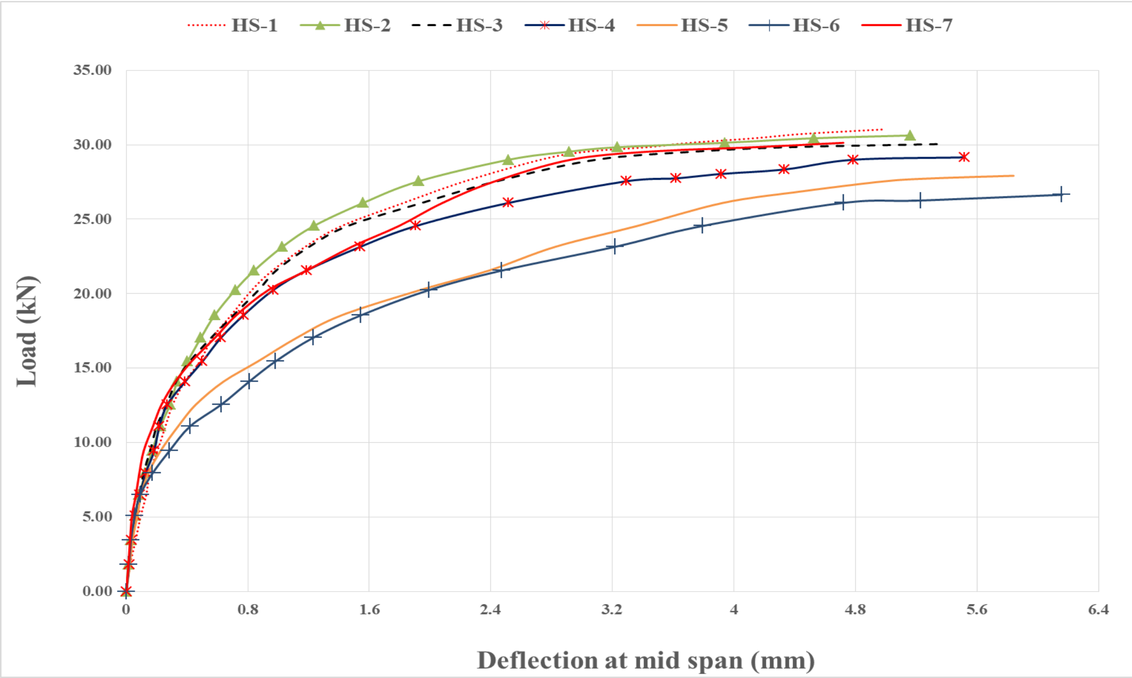


Figure 7 (a). Load deflection response of various mixes after 90d.

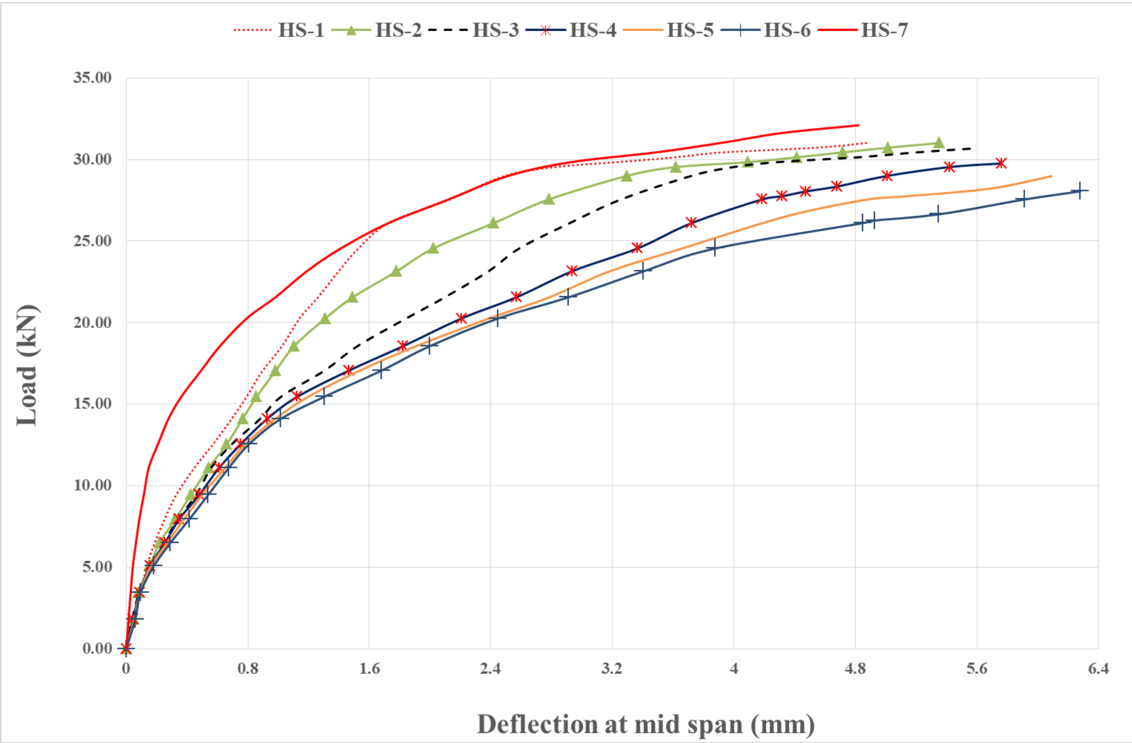


Figure 7 (b). Load deflection response of various mixes after 180d.

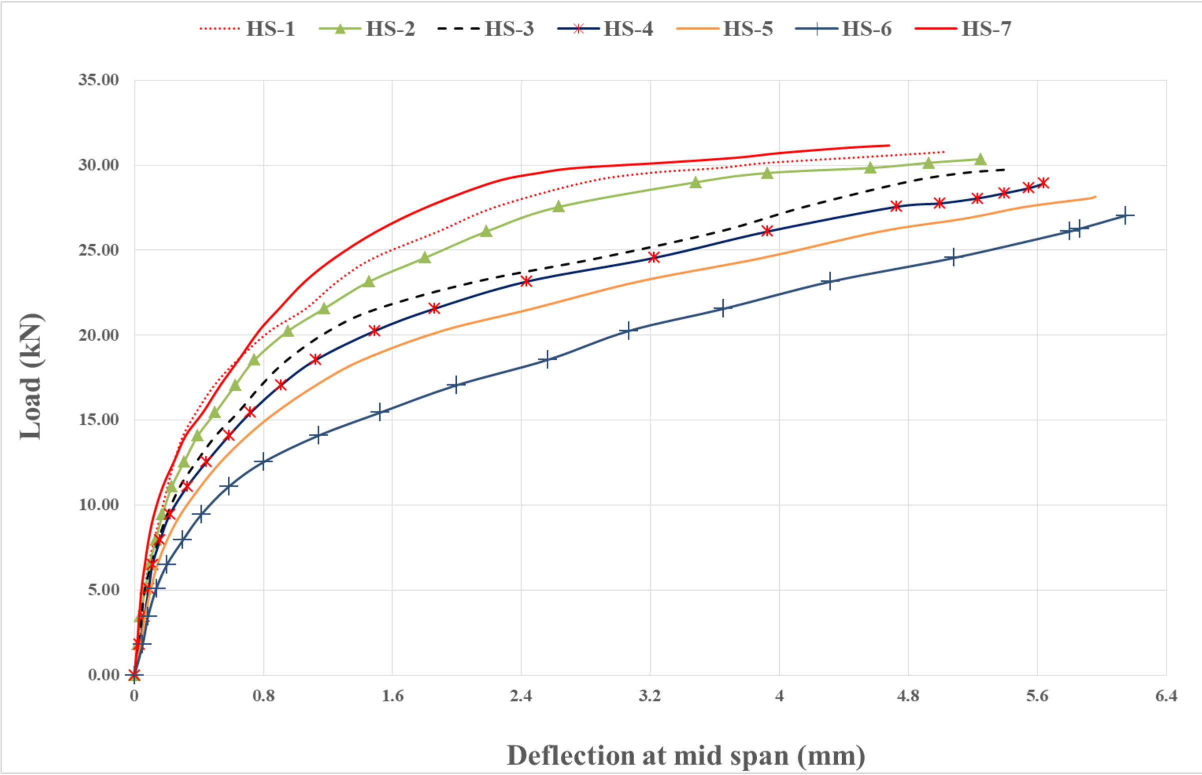


Figure 7 (c). Load deflection response of various mixes after 365d.

Hybridization of PVA, PET, and MSE Fiber

After the successful intrusion of PET fiber in ECC, further research work was carried out on combination of PVA, PET and MSE fiber at dosage of 50%, 25%, and 25%, respectively of the total fiber volume fraction. The PVA and MSE fibers used in this work lie in high modulus class, whereas PET fiber lies in the low modulus class. Previous research works reported that the hybridization of steel and PVA fiber exhibited excellent performance in terms of strength as well as strain parameters (Soe *et al*., 2013[a] & Soe *et al*., 2013[b]; Alhmead *et al*., 2003). In the present work aim was to reduce the cost of ECC with acceptable limit of various parameters by using PVA, MSE and PET fibers in combination. Amalgam of these three fibers not significantly affect the flexural strength of the matrix; whereas, mid span defection capacity decreased up to 7.14% as compared to HS1 mix proportion. In comparison to HS6 mix proportion the flexural strength of HS7 mix proportion enhanced by 15.30% and deflection capacity decreased by 23.90%. after final curing. Deflection capacity of all hybrid mix proportions developed in the opposite order of their flexural strength. MSE fiber sustain a perfect bond with matrix which was responsible for fiber rupture than pull out during loading, due to this the deflection capacity found to be reduced. On the other hand, high modulus of MSE fiber provided higher bridging strength during loading, which enhanced the flexural strength of the ECC prisms. Fiber bridging action and multiple microcracking behaviour of some prism specimens have been shown in Figure 8. Minimum flexural strength and mid span deflection was found 13.56 MPa and 4.68 mm in HS 7 mix proportion which was similar to other related works of PVA-ECC (Pakravan *et al*., 2016; Meng *et al*., 2017; Soe *et al*., 2013[a]). Therefore, the hybridization of PVA, PET and MSE fibers at dosage of 50%, 25% and 25% reduced the total cost of the ECC by 42.37% for one cubic meter without affecting the flexural performance.

Figure 8. Zoomed view of fiber bridging and multiple microcracks on prism specimens.

Electrical Resistivity

Electrical performance (resistivity or its reciprocal) of cement matrix has been utilized as a durability indicator, which represents the movement and diffusion of ions through the whole structure of matrix (Tsung *et al*., 2017; Ronaldo *et al*., 2016). The impact of various fiber combinations on ER performance has been shown in Figure 9. ER for all mix proportions ranges from 61.98 kΩ-cm to 146.70 kΩ-cm between the ages of 90 and 365 days (d) depending on the type and quantity of microfibers used.

Hybridization of PVA and PET Fiber

PVA and PET both are polymeric and low conductive nature fibers; however, analysis of their role in cement matrix is very important. To assess the electrical performance of fibers in ECC matrix, the ER with various fiber combinations has been investigated up to one-year curing age. The experimental observations depicted that ER of fully PVA blended mix (HS1) was less than hybrid mixes with PVA and PET fiber. Replacement of PVA with PET fiber at dosage of 5% and 10% had no considerable change in ER of cement matrix as compared to HS 1 mix proportion. Increment in the quantity of PET as PVA replacement enhanced the ER of the cement matrix. Inclusion of PET at 15%, 20% and 25% as PVA replacement increased the ER values of cement matrix by 5.36%, 7.93%, 11.75%; 4.12%, 5.83%, 8.37%; 5.32%, 9.18%, 12.93% after 90d; 180d; 365d water curing respectively. As the electrical conductivity of both the fibers is very low, despite that intrusion of PET fiber in cement matrix revealed better electrical resistivity. The character of PVA fibers was hydrophilic and it was also oil coated by 1.2% of engine oil used in this study. Presence of PVA fiber in the cementitious mix increased the porosity of the matrix around the fiber transition zone. The presence of pores promotes the movement of ions easily inside the cement matrix which is directly related to electrical performance, permeation, chloride ingress and corrosion. Similarly, Sakulich *et al*., 2011 & Suryanto *et al*., 2018 witnessed that the inclusion of PVA fiber in ECC matrix created the porosity around the fibers transition zone. The PET fibers used in this study had the ability to make a good bond with cement matrix. Inclusion of PET fiber decrease the micropores present on the transition zone of PVA fiber in cement matrix; because, PET fiber does not behave like hydrophobic or hydrophilic. Therefore, the hybridization of PVA fiber and PET fiber in ECC matrix enhanced the ER characteristic and also contributes in making the low cost ECC.

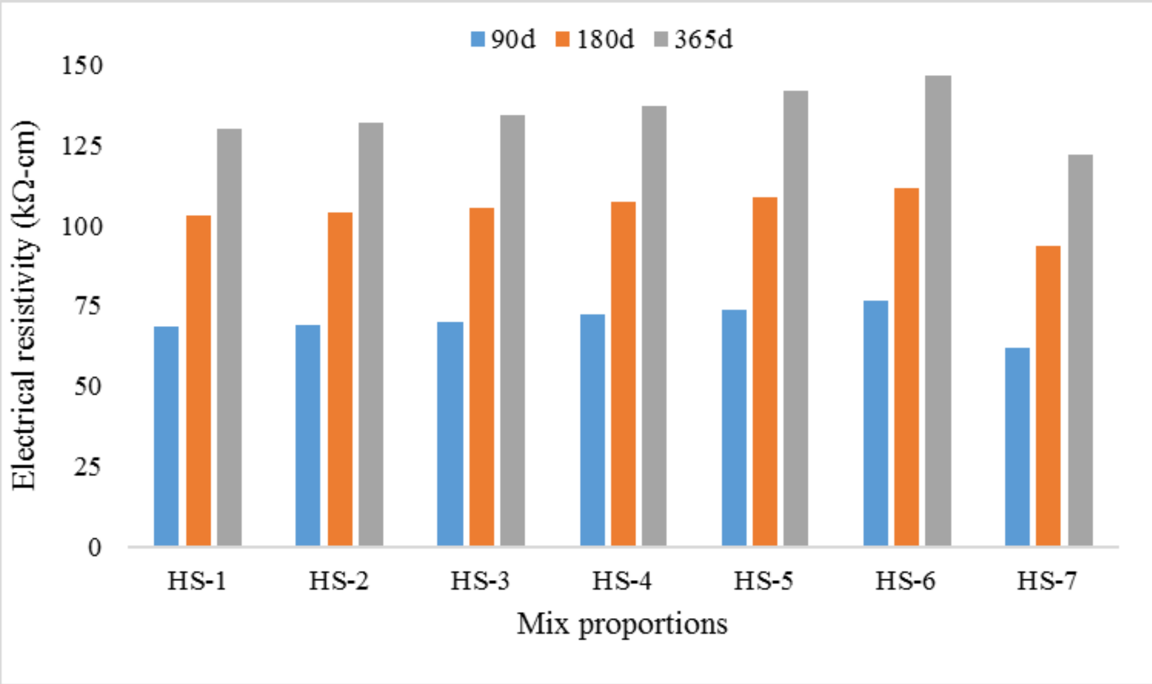


Figure 9. ER Performance of various mixes.

Hybridization of PVA, PET and MSE Fiber

After the successful utilization of PET fiber up to 25% as PVA substitution another 25% was substituted by MSE fiber. Combination of PVA, PET and MSE fiber at dosage of 50%, 25% and 25% of the total fiber volume fraction revealed lower electrical resistivity than HS1 and HS6 mix proportion. ER of HS7 cement matrix proportion decreased by 9.48%, 8.79%, 6.03% and 19.01%, 15.84%, 16.79% with reference to HS1 and HS6 mix proportion after 90d, 180d and 365d water curing respectively. Microsteel fiber was conductive in nature due to which the ER of HS7 mix proportion reduced. Numerous researchers reported the intrusion of steel fibers in cementitious mix increased the electrical conductivity of the matrix (Banthia *et al.*, 1992). With increasing the age of curing the change in ER percentage between HS1 and HS7 mix proportion was slightly reduced, it may be due to corrosive nature of steel. Because with increase in the time period the chances of corrosion on steel surface enhanced, which may defer the flow of current up to some limit. The values of ER for all mixes revealed that the chances of chloride ion penetration and corrosion risk were low and negligible for all cementitious matrix used in this research, as discussed in Table 3. Finally, from this non-destructive technique it has been observed that the hybridization of PVA, PET and MSE fiber enhanced the durability performance of ECC matrix with respect to chloride ingress, corrosive effect and electrical performance.

Air Permeability

To assess the permeation capacity of cement matrix the API was evaluated at the age of 90d, 180d and 365d with utilization of various fibers in combination and API performance has been illustrated in Figure 10.

Hybridization of PVA and PET Fiber

The observed values of API indicated that maximum and minimum air permeability was found in HS1 and HS7 mix proportion respectively. Due to the micropores present around the transition zone of PVA fiber in cement matrix, air permeability was found maximum in HS1 mix proportion. In ECC matrix the inclusion of PET as PVA fiber replacement decreased the API. Combination of PET and PVA fiber at rate of 25% and 75% revealed maximum reduction in API as compared to HS1 mix proportion, which was 18.20%, 20.37%, and 28.20% after 90d, 180d and 365d water curing respectively. The results of API revealed that intrusion of PET fiber in ECC matrix reduced the percentage of micropores as compared to the pores present in HS1 mix proportion. Reduction in porosity impaired the movement of ions through the whole structure of the ECC matrix, which was responsible for better air permeability performance of HS6 as compared to HS1 mix proportion. The continuation of hydration process of ECC matrix decreased the API values with increase in the time period. Numerous researchers witnessed that API decreased with increase in the water curing age (Pan *et al*., 2016). Therefore, the hybridization of PVA fiber and PET fiber in ECC matrix enhanced the API characteristic and also promote ECC matrix for sustainability.

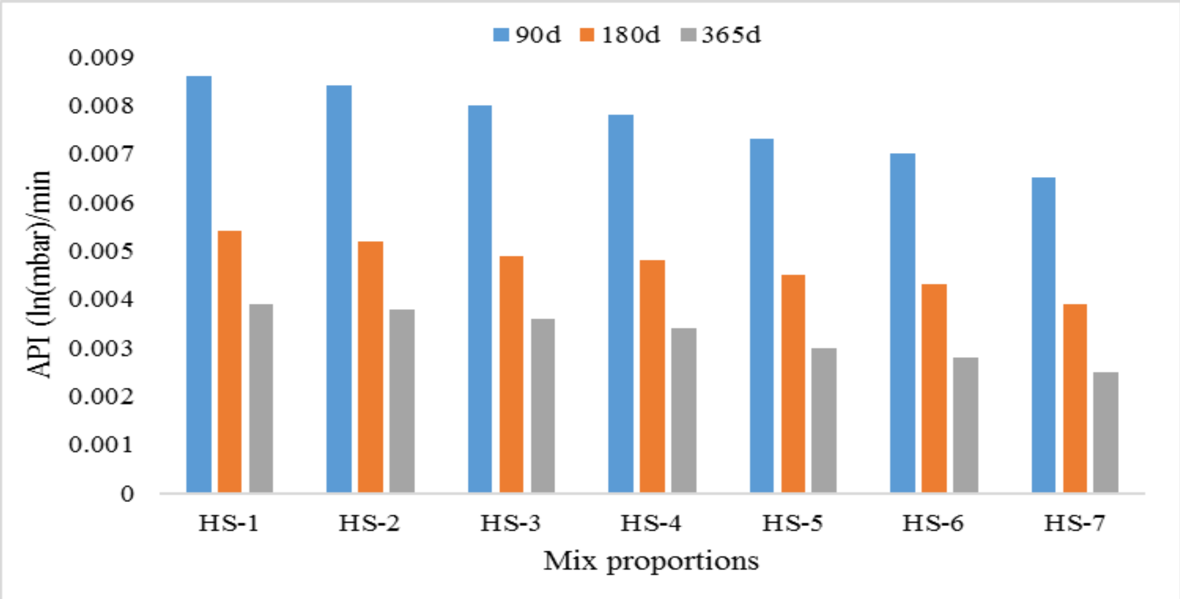


Figure 10. Air permeability index of various mixes.

Hybridization of PVA, PET and MSE Fiber

The assessed values of API depicted that air permeability of ECC matrix reduced with inclusion of PVA, PET and MSE fiber (at 50%, 25% and 25%) in hybridization. API of HS7 mix proportion reduced by 24.41%, 27.77%, 35.89%, and 7.14%, 9.30%, 10.71% as compared to HS1 and HS6 mix proportion after 90d, 180d, 365d time period respectively. Sticking of MSE fiber and matrix make a strong bond between them. Also, the bond between MSE fiber and matrix near the transition zone is strong, which results into reduction of micropores. Thus, the perfect bonding and packaging of particles with MSE fiber reduced the percentage of micropores present in ECC matrix, which was responsible for diffusion of ion through cementitious composite. The observed values of API range from 0.0086 to 0.0025 Ln(mbar)/min for all the mix proportions at various curing ages. According to the criteria for assessing the quality of cement matrix based on API as presented in Table 4, the quality of all ECC mixes was "very good" against air permeability. Finally, the combination of all three fibers (PVA, PET and MSE) reduced the air permeability of ECC matrix and contribute in making durable cement matrix.

Sorptivity (water absorption)

To assess the water absorption capacity of cement matrix the sorptivity index was evaluated at the age of 90d, 180d and 365d with combination of PVA, PET and MSE fibers and performance of all mixes has been illustrated in Figure 11.

Hybridization of PVA and PET Fiber

Maximum and minimum absorption capacity was found in HS1 and HS6 mix proportion. Inclusion of PET as PVA replacement reduced the water absorption capacity of ECC matrix. Hybridization of PVA and PET fiber marginally decreased the sorptivity index, the highest reduction was found as 14.64%, 19.40% and 16.23% after 90d, 180d and 365d curing respectively in HS6 mix proportion. As nature of both the fibers was same (polymeric), but with the inclusion of PVA alone and combination of PET and PVA in ECC matrix variation in values of various properties was observed. Grouping of PVA fiber revealed that presence of hydroxyl groups in large numbers made the nature of PVA fiber hydrophilic, which limits the water barrier properties of it. And as discussed earlier the utilization of PVA fiber in ECC matrix enhanced the porosity around the transition zone of fibers. All these properties and behavior of PVA fibers increases the chances of water absorption in HS1 mix proportion as compared to other compositions used in this research work (Redon et al., 2001; Sakulich *et al*., 2011 & Suryanto *et al*., 2018). Numerous researchers reported that the nature of PET fiber is hydrophobic, and it is water repellent material (Rathod et al., 2010 & U.S Patent, 1977). Due to these properties of the PET fiber, reduction in sorptivity index values of ECC matrix was observed. Therefore, the hybridization of PVA and PET fiber in ECC matrix contribute in the reduction of sorptivity index.

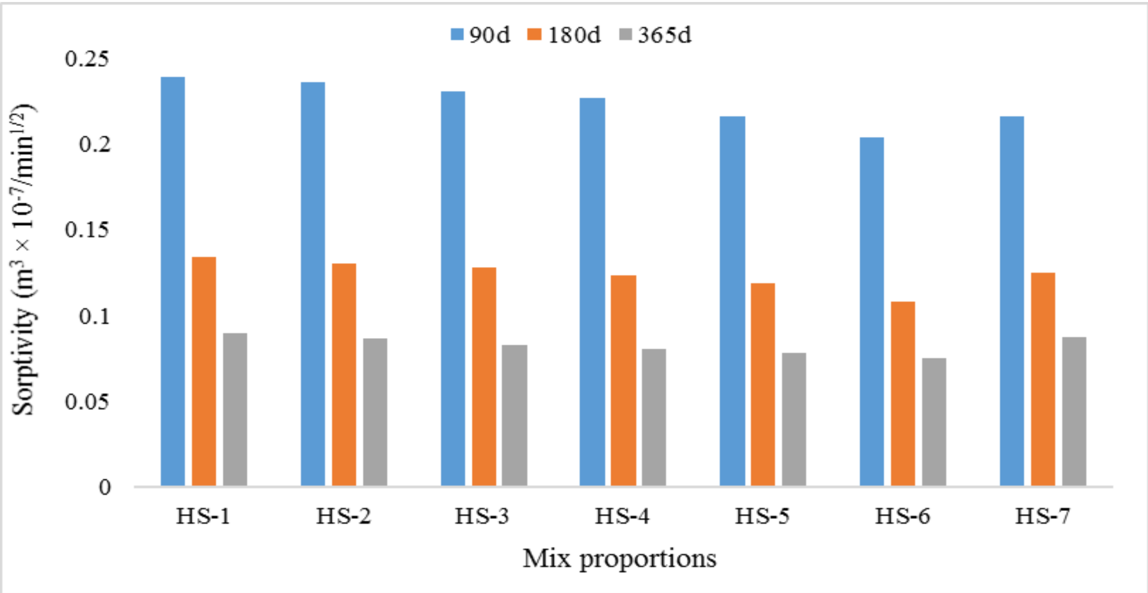


Figure 11. Sorptivity (water absorption) index of various mixes.

Hybridization of PVA, PET and MSE Fiber

The assessed values of sorptivity index depicted that water absorption of ECC matrix reduced with inclusion of PVA, PET, and MSE fiber (at 50%, 25% and 25%) in hybridization. Sorptivity index of HS7 mix proportion reduced by 9.63%, 6.71% and 2.35%, as compared to HS1 mix proportion after 90d, 180d, 365d curing time period respectively. Cement matrix behaves sticky and makes a strong bond with cementitious products due to presence of MSE fibers, which promote the diffusivity of ions in whole structure. The observed values of sorptivity ranges from 0.239 $m^3 \times 10^{-7}/min^{1/2}$ to 0.0748 $m^3 \times 10^{-7}/min^{1/2}$ for all the mix proportions at various curing ages. The values of sorptivity index for all the mixes was found less than 1.30 $m^3 \times 10^{-7}/min^{1/2}$, which demonstrate "very good" quality of ECC matrix against water absorption as per criteria given in Table 5. At the end, combination of all three fibers (PVA, PET and steel) reduced the water absorption (sorptivity) and promote the use of ECC matrix in hydraulic structures.

FINAL REMARKS

Sustainability of any material depends on the durability performance, energy and resources consumption, cost and life span of the material. As, the cement based construction materials consume energy and natural resources in lots of quantity and sometimes in harsh environmental conditions the durability performance of concrete structures is also affected. Recent scenario of making concrete structures revealed that the cost of the cement-based matrix increased with the enhancing quality. In the composition of reinforced concrete, aggregates, cement and steel are the basic raw materials. The manufacturing of these materials consumes natural resources and energy in very high quantity and the processing of these materials also extract various types of wastes which impact the environment. Therefore, all these things discussed above are very important in the composition of any material. In the present investigation 55% (of the total cementitious material) GGBFS (iron industry waste) and non-degradable plastic-based fibers (PVA and PET) have been utilized. The inclusion of GGBFS and fibers help in conserving the natural resources, contribute in making of eco-friendly sustainable cementitious product. Results obtained from present investigation revealed that the hybridization of fibers enhanced the mechanical and durability performance (enhance the life span) and also reduced the cost of cement matrix up to 42.37% for one cubic meter. Utilization of waste, lower cost and better performance of new formed cement matrix possesses very high sustainability, which promote the use of this material on large scale structural applications.

CONCLUSION

In the present investigation, the performance of ECC matrix with inclusion of microfibers (PVA, PET, and MSE) in hybridization has been carried out. Hybridizing effect of fibers was investigated through flexural strength, deflection capacity, electrical resistivity, air permeability, and sorptivity characteristics. The main conclusions from this experimental investigation can be summarized as follows:

Hybridization of PVA and PET Fiber

- Inclusion of 25% PET fiber as PVA replacement decreased the flexural strength of ECC matrix up to 14.18%. Low modulus of PET fiber diminished the fiber bridging strength which attributed to reduction in flexural strength of ECC matrix.

- The optimum deflection capacity was found in HS6 mix proportion 24.60% higher than HS1. Low modulus fibers can absorb high energy, which was responsible for better deflection capacity in HS6 mix proportion than other mixes. Finally, combination of PVA and PET fiber enhanced the ductile nature of ECC matrix.
- Optimum ER was found in HS6 mix proportion 12.93% higher than HS1 mix. Electrical conductivity of both the fibers was very low despite that the ER performance increased. PVA fibers are hydrophilic in nature due to which the percentage of micropores increased at the transition zone of fibers which promote the easy flow of the ions in the matrix structure. On the other hand, the PET fibers hydrophobic in nature, were able to reduce the micropores percentage in matrix due to better bonding between fiber and matrix.
- With the hybridization of PVA and PET, the maximum reduction in air permeability (28.20%) and water absorption (19.40%) was observed in HS6 mix proportion in comparison to mix. PET fibers are hydrophobic in nature, then inclusion reduced the water absorption capacity in ECC matrix.
- Finally, hybridization of PVA and PET not only enhanced the unique characteristics of ECC, but also reduced the cost of ECC up to 20.72%.

Hybridization of PVA, PET, and MSE Fiber

- The optimum flexural strength of ECC matrix was found with the inclusion of PVA, PET and MSE in combination. Hybridization of all three fibers enhanced flexural strength by 2.86% and 15.30% as compared to HS1 and HS6 mix proportion. The physical nature of MSE fiber i.e. high modulus, provide excellent fiber bridging strength with matrix which was responsible for increment in flexural strength of HS7 mix proportion.
- Deflection capacity, ER and API of HS7 mix proportion decreased by 7.14%, 9.48% and 35.9% as compared to HS1 mix proportion. MSE fiber was able to make a perfect bond due to sticking behavior with matrix. Due to the strong bonding, fibers ruptured than pullout. Packaging of the matrix particles at fiber surface was responsible for reduction in deflection capacity and API. The MSE fibers are conductive in nature which attributed to the lower ER in HS7 mix.
- The particle packaging behavior of MSE with matrix diffused the movement of ions in cement matrix which attributed lesser water absorption capacity (9.62%) of HS7 mix proportion than HS1 mix. Hybridization of all three fibers not only enhanced the strength and durability performance; but cut the total cost of ECC up to 42.37%.

Eventually, the present research recommends the use of hybrid ECC matrix in developing countries on large scale construction. The durability examination in this study promote the use of the low cost ECC in hydraulic structures. Low cost, superior performance and inclusion of waste and non-degradable materials in newly formed ECC matrix possesses high durability and strength properties and also promotes eco-friendly nature of mix.

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