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Assessment of effect of chemical exposures on ECC containing micro fibers in hybridization

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Abstract. The present research emphasizes on the durability behaviour of hybrid fiber reinforced engineered cementitious composite (HFRECC) through exposure to chemicals environment for 12 months. The structural reinforcing micro-fibers used in this study were polyvinyl alcohol (PVA) fiber, polyester (PLY) fiber, and micro steel (MSE) fiber. Hybridization of micro-fibers was done in two stages; in the first stage, up to 25% of PVA fiber was switched by PLY fiber at a dosage of 5%, 10%, 15%, 20%, 25%. In further investigation, the amalgam of PVA, PLY (polymeric), and MSE (non-polymeric) fibers were used at dosages of 50%, 25% and 25% respectively. The performance of the matrix was assessed on the basis of compressive response, tensile strength, tensile strain capacity, and electrical resistivity (ER) characteristics. The results obtained revealed that the hybridization of micro-fibers enhanced the overall performance of ECC and provided resistance to the movement of detrimental ions through the matrix.

Keywords. Chemical exposure; polyester fiber; electrical resistivity; micro steel fiber; hybridization.

1. Introduction

Cement-based structures are highly brittle and easy to crack which leads to deterioration when exposed to aggressive environment (seawater, industrial wastewater, acid rain, etc.) conditions. In long term, the penetration of detrimental liquids into the cement matrix will deteriorate the mechanical and durability performance. The chemical reaction between the penetrated detrimental ions and the hydration product of cement-matrix affects the durability performance of the concrete structures [1–4]. Due to cracking the poor durability performance of cementitious materials is the main cause of hydraulic concrete structures deterioration [5]. Therefore, minimal crack width is desired to increase the life span and durability performance of concrete structures under aggressive environmental conditions. Over the last few decades, lots of efforts like the use of steel reinforcement, different types of constituents, and fibers have been made to overcome these drawbacks. Numerous researchers reported that the use of different types of fibers in cement matrix changed the failure mode from brittle to strain softening or strain hardening (ductile) and suppress the formation of wider cracks [6–9].

Engineered cementitious composite (ECC) is one of the fiber-reinforced high-performance cementitious composites. The novel tensile behaviour and minimal crack width differentiate it from other types of cement-based products. The superb characteristics of ECC are excellent tensile strain capacity (1–8%), high energy dissipation capacity (equal to 30 KJ/m^2), and constraint crack width (Avg. 60 μm) with the use of low volume fiber fraction (approximately 2% of the volume of cementitious materials). The design of ECC relies on the theory of micromechanics and fiber bridging, it represents extensive strain hardening behaviour with multiple tiny cracks [6–12]. The ranges of ECC parameters such as tensile strain capacity, flexural response, compression behaviour, toughness, density, etc. depend on the quantity and types of the constituents used. According to the available literature, the tight crack width of ECC suppresses the penetration of detrimental ions in cement-matrix and obstructs further deterioration, leading to improvement in the life span of hydraulic structures [13, 14].

Liu *et al* (2017) [15] evaluated the self-healing performance of ECC under sulphate and sulphate-chloride conditions. It has been reported that the use of ECC could improve the long-term performance of hydraulic structures under aggressive (sulphate and sulphate-chloride) environmental conditions owing to its durable nature. Sahmaran *et al* (2007) [16] recorded the transport properties of ECC and normal concrete (mortar) under chemical exposure. It was concluded that ECC demonstrated much higher durability performance than mortar mix due to tight crack width. Ozbay *et al* (2013) [17] assessed the durability

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performance of slag incorporated ECC under sulphate immersion and freeze-thaw (F-T) cycles. It has been reported that the incorporation of slag improved the ductility and durability performance with marginal reduction in strength parameters. The fine particles of slag fill the pores among cement particles which contributed in the enhancement of durability and ductility. Liu *et al* (2017) [18] investigated the durability performance of ECC under both sulphate and sulphate-chloride immersion. The experimental results showed that the compressive and tensile strength characteristics increased after long term exposure; while, tensile strain capacity slightly reduced. Li *et al* (2011) [19] studied the cracking and healing of ECC under a chloride environment. It has been reported that ECC demonstrated ductile nature and provides crack controlling capability to prevent cracking failure due to the extraordinary tensile performance of ECC matrix. Sahmaran *et al* (2008) [20], Li *et al* (2013) [21], and Li *et al* (2004) [22] assessed the durability, self-healing, and ductility characteristics of ECC under different environmental conditions. The experimental results showed that ECC matrices maintained ductile characteristics and remained durable under different aggressive environmental conditions.

The durability, ductility, and self-healing characteristics of ECC revealed that it was the most promising material to control the cracking and enhanced the service life of hydraulic structures. [15–22]. Despite the superior performance, the use of ECC is limited due to its higher cost. The usage of high-cost fibers and higher amounts of cement in matrix enhance the overall cost of ECC. Recently, various studies on ECC with the utilization of fibers in hybridization and different types of mineral admixture to decrease the cost of the ECC matrix have been reported [23–25]. The influence of fiber hybridization on cementitious composite variesfrom parameter to parameter and also depends on the type and percentage of fibers used in the matrix. The present investigation mainly focused on cost, fiber hybridization and durability performance of ECC to promote its applicability in developing countries and hydraulic structures. The polyvinyl alcohol (PVA), polyester (PLY), and micro steel (MSE) fibers were blended in HFRECC at various percentages. The cost of the PLY and MSE fibers is very low as compared to PVA fiber. The utilization of PLY fiber and MSE fiber in cement-based products exhibited better mechanical and durability performance than conventional concrete [26–28]. Rathod *et al* (2010) [27] reported that the distinctive nature (neither hydrophobic nor hydrophilic) of PLY fiber sustains a very good bond between cement and matrix. Most of the conducted studies with fiber hybridization reported fresh and mechanical behavior of HFRECC. There is still lack on durability performance of HFRECC.

Reported literature reveals that the PVA-ECC matrix remains durable under different environmental conditions such as F-T cycles, hot water immersion, chemicals immersion, alkali-silicate reaction, and de-icing salt exposures [13–18]. Most of the durability studies on ECC have been analysed with the use of fly ash (FA) and PVA. Fiber hybridization in a cementitious composite is the most attractive approach to decrease the overall cost; but, limited studies have been conducted on the durability performance of HFRECC so far. In the present experimental research investigation, the mechanical and durability properties of ground granulated blast furnace slag (GGBFS) incorporated HFRECC was evaluated under the chloride, sulphate, and sulphate-chloride exposure for up to one year.

2. Research significance

To make the cost-effective ECC, the utilization of low-cost fiber and a huge amount of mineral admixtures is required. In this research work, the by-product of the iron industry (GGBFS) and low-cost PLY and MSE were utilized to diversify the application of ECC. The objective of this research is to assess the influence of fiber hybridization on the durability performance of ECC under aggressive environmental conditions. The findings from the present work will highlight the durability performance of HFRECC under chemical exposures and provide guidelines for design in the future. The cost-effectiveness and durability performance of HFRECC also promote its use in large-scale structural applications and also in hydraulic concrete structures.

3. Constituents and methods

3.1 *Constituents and matrix proportions*

The powdered constituents used in this study consisted of 43-grade Portland cement (PC), GGBFS as supplementary cementitious material, and micro silica sand (MSS) as fine aggregate. The various types of fibers used in this research work were PVA, PLY and brass coated micro steel fiber (MSE) fiber. The PVA (polymeric) fibers have been used with a length of 12 mm, diameter of 40 µm, tensile strength (1600 MPa), elongation (7%), electrical conductivity (low), and alkali resistance (good). Recron 3s PLY (polymeric) fibers are neither hydrophobic nor hydrophilic (it presents itself in the middle state) and are designed especially for internal reinforcement in cementitious products have been used with a length of 12 mm, diameter of 25 µm to 35 µm, tensile strength (480 MPa), elongation (30%), electrical conductivity (low) and alkali resistance (very good). MSE (non-polymeric) fibers were brass coated and have been used with a length of 13 mm, a diameter of 0.20 mm, tensile strength (2000 MPa) and electrical conductivity (high). The water and PCE (Polycarboxylic ether) based admixture was poured to obtain the proper rheological performance. After selecting the constituents total 7 groups of ECC matrix were developed and designated as presented in table 1. BS1 is the control mix and in BS2, BS3, BS4, BS5, BS6 mix proportions the PVA fiber was switched by PLY fiber at dosages of 5%, 10%, 15%, 20%, 25% respectively. In BS7 mix proportion the PVA, PLY and MSE fibers were used at dosages of 50%, 25% and 25% respectively of the total quantity of fibers used in ECC matrix.

3.2 *Fabrication and curing process*

To mix all the constituents and achieve the stirring state of the ECC matrix automatic power-driven mortar mixer was used. First, MSS, GGBFS and PC were poured into the tank of mixer and rotated for 3 minutes. Then, premixed water with admixture was added gradually to the dry constituents while the mixer was spinning. After adding liquid constituents, the mixture achieved the stirring state within 4 to 5 minutes. Eventually, the mixed filaments of all three fibers were gradually dispersed into the mixture and rotated in the mixer till the fibers were evenly distributed. For assessing the electrical resistivity and compressive strength, the homogenous mixture was poured into 70.6 mm cube specimens; while the 310 mm × 100 mm × 20 mm dog-bone shaped specimens were prepared to assess the tensile parameters. All the specimens were placed at room temperature for 1 day and then demoulded and immersed into the water curing tank for the specified period. As per the testing, scheduled samples were removed from the water after 4 weeks of curing and immersed into the chemical solutions of 5% NaCl, 5% Na_2SO_4, and 5% Na_2SO_4 + 3% NaCl (by weight) for the next 28d, 62d, 152d and 337d and rest of the samples remained in water tank for reference.

3.3 *Testing programs*

3.3.1 *Compressive behaviour:* Mortar cube specimens were used to analyse the compression response of HFRECC. This test was conducted via compression testing machine (CTM) as per the specifications of BIS 516:1959 [29] and BS-EN-12390 [30] part 3.

3.3.2 *Electrical resistivity:* Electrical resistivity (ER) is one of the most predominant techniques to assess the durability of cement matrix [31]. ER mainly refers to the movement and diffusion of ions, corrosion risk and porosity of the matrix structure [32–34]. In the present research investigation, the influence of various types of fiber combinations on the durability performance of ECC was observed through ER measurement. The ER response of developed ECC mixes was recorded via a two-point method. The ER 'ρ' of constructed samples was calculated by using the following equation.

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

Where 'A', 'L', R represents the area of the sample (cm^2), length of the sample (cm), and resistance ($k\Omega$) respectively.

The recommended values of ER related to chloride ion penetration (CIP) and corrosion risk (CR) have been given in table 2.

3.3.3 *Tensile behaviour:* Dog-bone shaped samples were constructed to analyse the tensile response of developed mixes. The distance between the wedge faces (gauge length) of samples was used to record the tensile response and tested via universal testing machine (UTM) at a loading rate of 0.2 mm/minute.

3.3.4 *Chemical exposure:* To analyse the chemical exposure on various parameters of developed mixes, the casted specimens immersed in the chemical solutions. The change in compressive strength, electrical resistivity, tensile strength, and tensile strain was observed after 28d, 62d, 152d and 337d chemical immersion and compared with water-cured specimens of the same age. The resistance of the specimens against exposure to chemicals has been measured as per the recommendations of ASTM C1012/2012 [37].

Table 1. Proportions and mix designation details of all mixes.

	Constituents (kg/m^3)							
Mix ID	PC	GGBFS	MSS	PVA	PLY	MSE	W/B	SP (%)
BS1	570	684	456	26	0	–	0.27	0.45
BS2	570	684	456	24.7	1.3	–	0.27	0.45
BS3	570	684	456	23.4	2.6	–	0.27	0.45
BS4	570	684	456	22.1	3.9	–	0.27	0.45
BS5	570	684	456	20.8	5.2	–	0.27	0.45
BS6	570	684	456	19.5	6.5	–	0.27	0.45
BS7	570	684	456	13	6.5	6.5	0.27	0.45

Table 2. Correlation between ER, CR and CIP [35, 36].

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

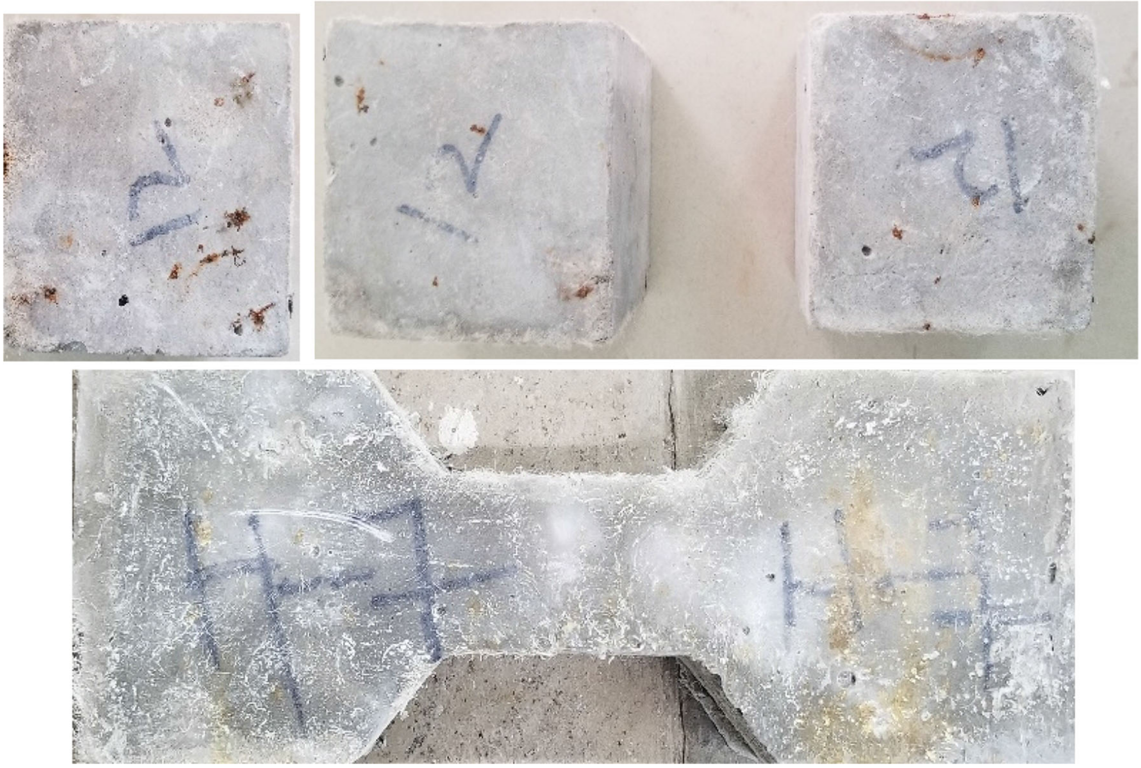


Figure 1. Surface of MSE blended specimens after 337 days of chemical exposure.

4. Outcomes and discussion

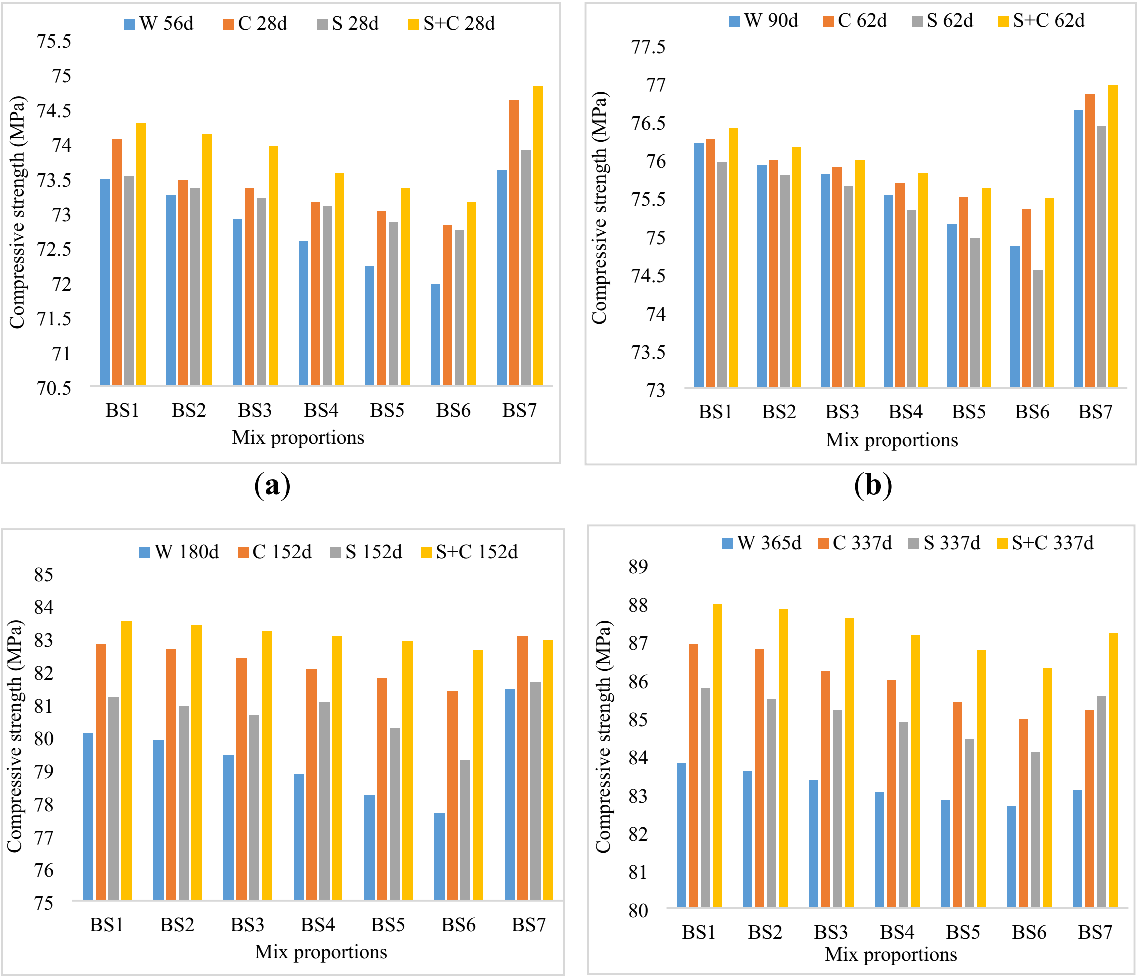
4.1 *Visual inspection*

The surface of the hardened ECC matrix specimens was smooth and well finished and no obvious change was found with the use of different types of fibers. At the age of 90d (28+62) immersion in different chemical solutions, no physical signs were visible on the surface of BS1 to BS6 matrix specimens; while, with the increase in the immersion period slight white covering was seen over it. However, on the surface of BS7 matrix specimens, some red dots of rust were visible with a slight white covering, it may be due to the presence of MSE fibers near the surface of the specimens. As shown in figure 1, the aesthetic performance of BS7 mix proportion was degraded due to the appearance of rust dots on the surface of the matrix.

4.2 *Compressive behaviour*

The influence of fibers amalgam on the compression behaviour of developed mixes was observed under water and chemical solution immersion at various ages. The behaviour of all ECC mixes in compression under various environmental conditions at respective ages has been shown in figures 2(a–d).

Recorded results revealed that the compression behaviour of developed mixes improved with an increase in the curing period; this may be happened due to pozzolanic

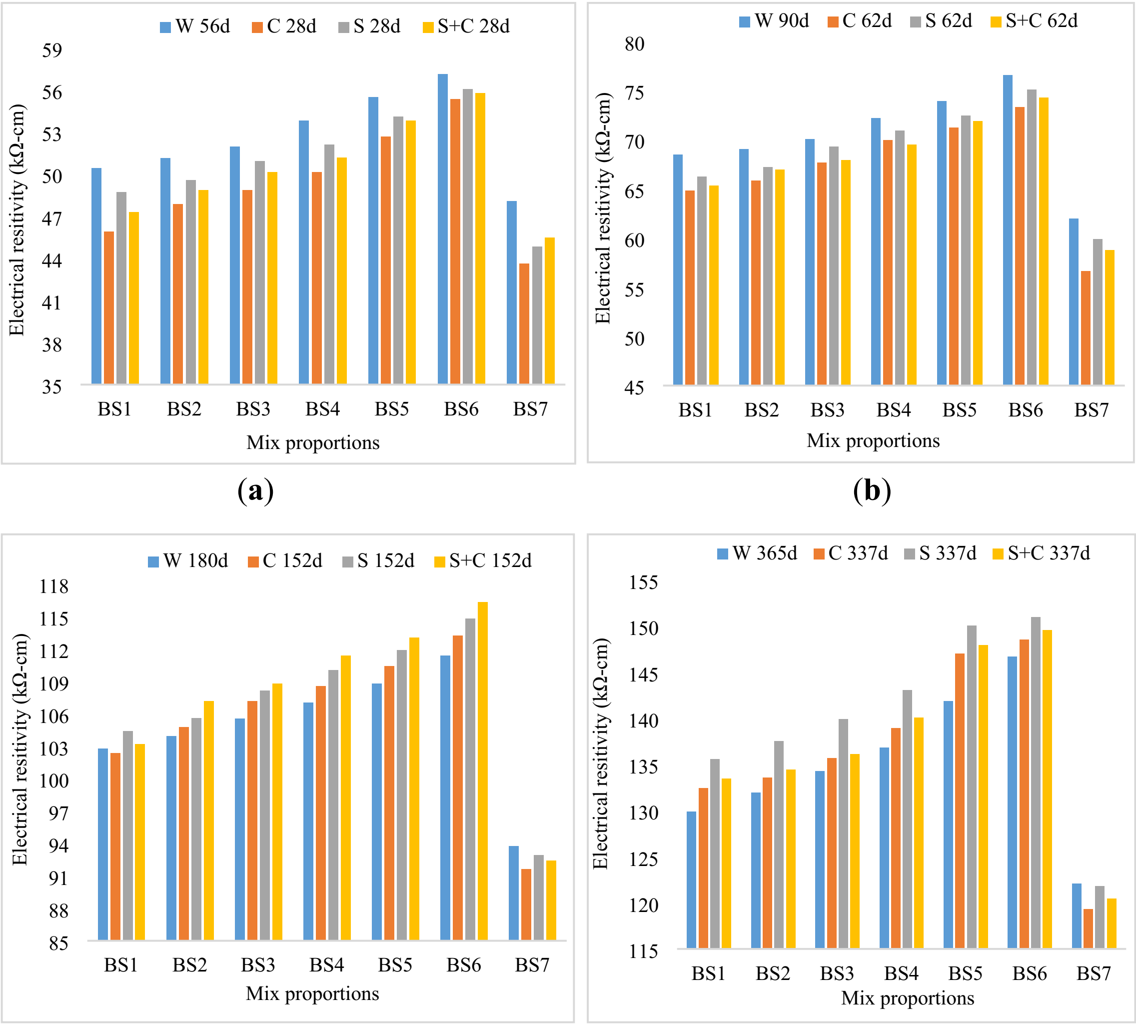


(a) **(b)** **(c)** **(d)**

Figure 2. CS of ECC mixes at various chemical exposures ages **(a)** 28d, **(b)** 62d, **(c)** 152d and **(d)** 337d.

activity of slag in the long term and continuous hydration process [17, 38]. The combined use of all three fibers in the BS7 mix proportion revealed maximum CS than followed by BS1 mix proportion after 56d, 90d and 180d water immersion; while, with an increase in the curing period (after 365d) the CS of BS7 mix proportion was found sight lesser as compared to BS1 mix proportion. The nature of steel is corrosive due to which slight reduction was found in CS after a long period of curing. The combined use of PVA and PLY fibers in ECC matrix revealed the decrement in the CS. Increment in the quantity of PLY fiber as PVA replacement in ECC matrix decreased the CS. The minimum CS was found in the BS6 mix proportion at all the curing ages. The modulus of PLY fibers is low as compared to PVA and steel fibers due to which decrement in CS was observed with the utilization of PLY fibers. The amalgam of PLY fibers decreased the CS up to 3.06% and 5.07% maximum as compared to BS1 and BS7 mix proportions. Moreover, the amalgam of MSE fiber enhanced the CS up to 3.46% maximum as compared to the BS1 mix proportion. From the compression behaviour findings, it has been observed that the variation in CS was marginal with the use of a different class of fibers. Similarly, the investigations related to FRCC confirmed that the addition of fibers improved the CS of cementitious mixes marginally [26, 39].

4.2 (a) *Chemical exposures on compression response:* From the measured CS of specimens exposed to Na_2SO_4, NaCl, and Na_2SO_4 + NaCl solution it can be seen that the CS of prepared mixes increased marginally at the beginning stage. However, after a long period of immersion (152d and 337d), the percentage increment in CS of all ECC mixes increased. Under various chemical exposures, the maximum improvement in CS was observed up to 6.38%. The diffusion of chemical ions into the micropores and contribution of GGBFS in pozzolanic activity in long run led to the formation of ettringite, responsible for strength



(a) **(b)**

(c) **(d)**

Figure 3. ER performance at various chemical exposures ages **(a)** 28d, **(b)** 62d, **(c)** 152d and **(d)** 337d.

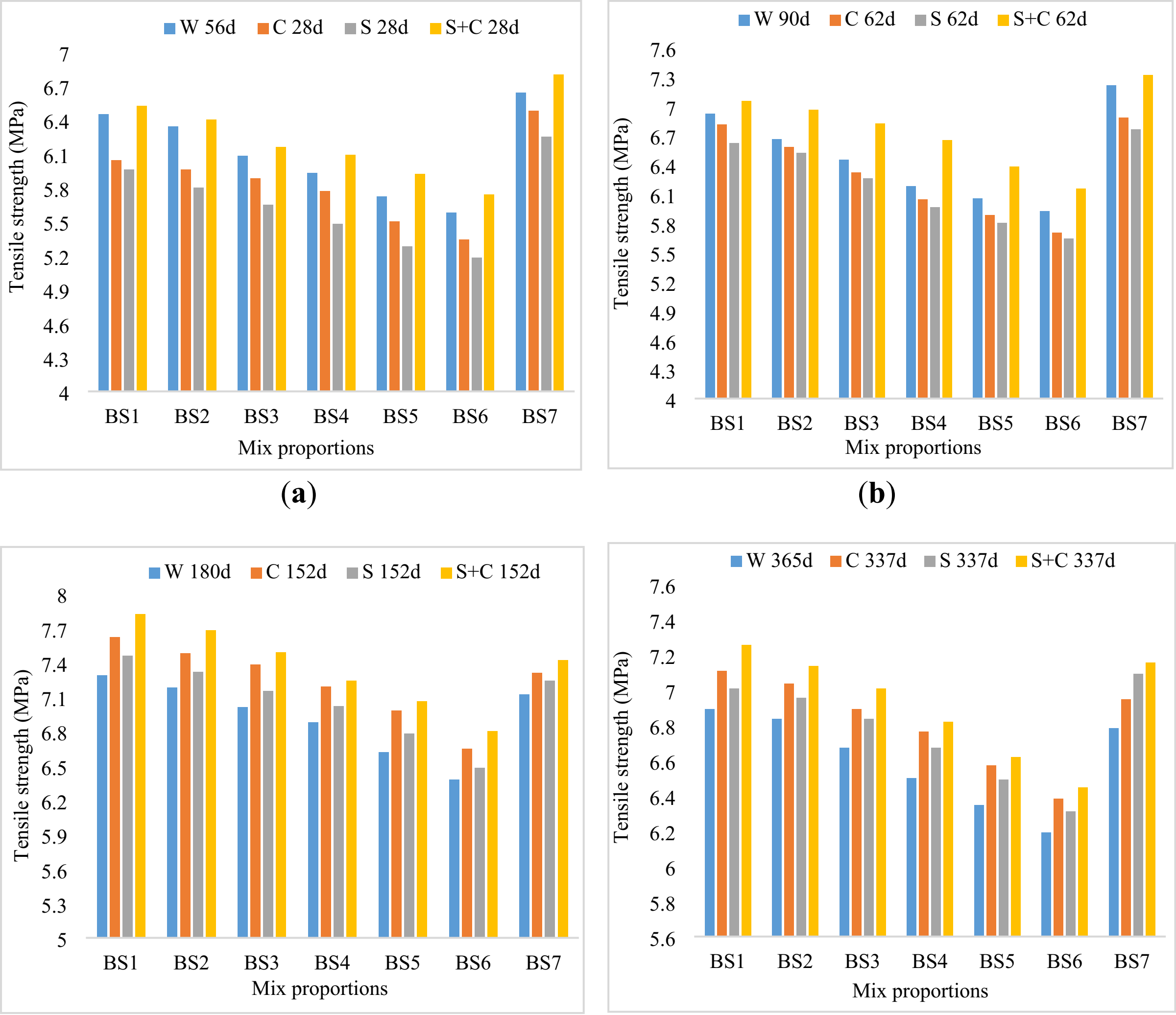
enhancement of ECC matrix under various chemical exposures. [17, 18]. The distinctive tensile characteristics of ECC delayed the surface cracking due to which the diffusion of the aggressive ion's reduced and resistance against a chemical-rich environment improved.

The percentage increment in CS for all the mixes under various chemical exposure was almost the same as compared to water immersed samples. The result of chemical immersion confirms that the intrusion of all three types of fibers provides resistance against chemical exposures. Moreover, no deterioration/strength loss was found due to corrosion of MSE fiber up to one year of immersion. As discussed earlier the inclusion of fiber marginally increased the CS of the matrix, therefore, the enhancement in CS was observed only due to the reaction of diffused ions with cement hydration products which produce ettringite and contribute in strength achievements. The present results indicated that maximum resistance was found against combined (Na_2SO_4 + NaCl) exposure and minimum for Na_2SO_4 solution. Eventually, the compression behaviour of various mixes revealed that the inclusion of polymeric and non-polymeric fibers had no adverse effect on ECC mixtures under various chemical exposures.

4.3 *Electrical resistivity (ER)*

Electrical resistivity (ER) is a lucid technique that has been utilized as a durability indicator in a cementitious matrix. The influence of fiber combinations on ER performance was observed under water and chemical solution immersion at various ages. The ER performance of various mixes has been illustrated in figures 3(a-d).

The ER performance of various mixes depicted that maximum resistivity was found in BS6 mix proportion; whereas, minimum in BS7. The intrusion of PLY as PVA



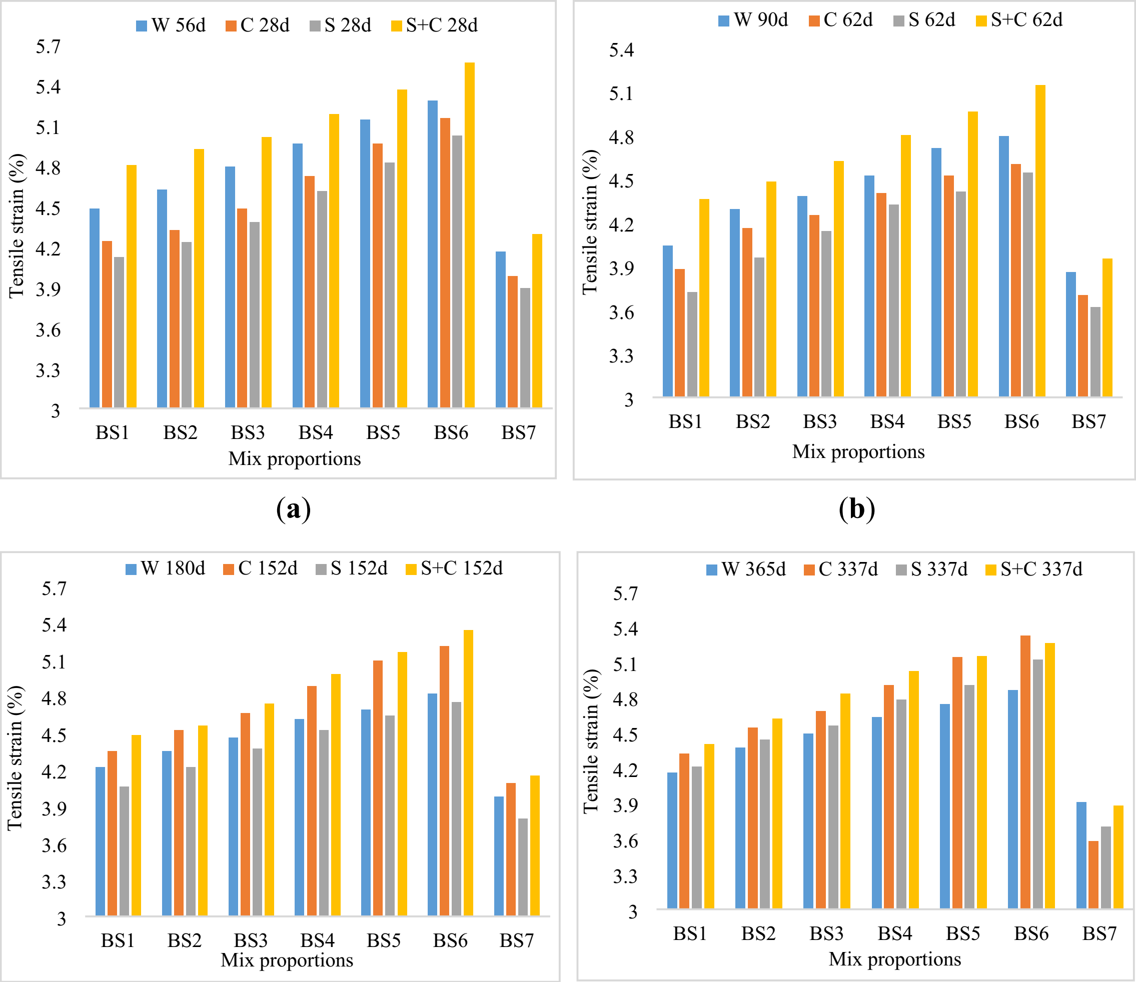
(a) **(b)**

(c) **(d)**

Figure 4. Tensile strength at various chemical exposures ages **(a)** 28d, **(b)** 62d, **(c)** 152d and **(d)** 337d.

fiber replacement enhanced the ER performance of cementitious mixes. The ER of ECC matrix increased up to 13.30% with an increase in the quantity of PLY fiber (at 25% replacement). The nature of both fibers is polymeric; whereas, both have different interaction characteristics with cement matrix. Hydrophilicity of PVA fibers increases the porosity in the matrix at the transition zone around the fibers [40, 41]. The presence of micro pores and moisture ions in the PVA blended ECC matrix results in the movement of ions through the whole structure which is directly related to resistivity, permeation, and corrosion. The distinctive nature of PLY fibers designed especially for cementitious products and sustaining a very good bond with matrix resulted inthe reduction of micropores at the transition zone around the fibers. Subsequently, the amalgam of PVA, PLY and MSE decreased the resistivity up to 9.48% and 19.01% as compared to BS1 and BS6 mix proportions respectively. The nature of MSE fibers is conductive due to which current ions easily flow through the matrix which results in ER decrement [42]. The percentage of ER decrement in BS7 mix proportion reduced with an increase in the curing period; because corrosion of MSE fibers after some period of water curing hindered the movement of current ions up to some limit in the cement matrix. The optimum ER was found in the BS6 mix proportion for all the water curing ages.

4.3 (a) *Chemical exposures on ER:* ER performance of various ECC mix proportions exposed to different chemical solutions revealed that the resistivity of all designated mixes reduced after 28d and 62d as compared to same age water cured specimens. The maximum reduction in ER was observed in NaCl solution immersed specimens; whereas, minimum in Na_2SO_4 solution immersed specimens. The maximum percentage in ER reduction was found in BS7



(a) **(b)**

(c) **(d)**

Figure 5. Tensile strain at various chemical exposures ages **(a)** 28d, **(b)** 62d, **(c)** 152d and **(d)** 337d.

mix proportion; whereas, minimum in BS6 mix proportion. Numerous researchers revealed that the hydrophicity of PVA fibers increased the porosity of the ECC matrix [40, 41] which allowed the movement of ions through the structure and resulted in resistivity decrement. However, after a long period of chemical exposure (152d and 337d), the ER of all mixes increased in comparison to water-cured specimens at the same age.

The continuous hydration process of cement, the pozzolanic activity of GGBFS in long term and the reaction between the diffused ions and hydration products were responsible for resistivity enhancement over a longer period. The whole process formed ettringite and contribute to densification at the interface between fiber and ECC matrix, which helped into obstructing the flow of ions and resulting in higher ER under various chemical immersion. The ER of BS7 mix proportion specimens under chemical immersion was found less as compared to specimens immersed in water at all the curing ages. The reduction in ER may be due to the corrosive nature of steel under chemical attacks. Finally, the ER values revealed that the chances of CR and CIP were very low and negligible for all designated ECC mixes, as discussed in table 2.

4.4 *Tensile response*

4.4.1 *Tensile strength:* The tensile response of cement-based structures is the most predominant parameter especially for the durability performance or service life of the structure. The impact of polymeric and non-polymeric fibers intrusion on tensile strength of ECC matrix was observed under water and chemical solution immersion for up to a year. The variation in tensile strength performance of designed mixes has been illustrated in figures 4(a-d).

The results obtained from the tensile response depicted that the strength of prepared mixes decreased with the combined use of PVA and PLY. The subrogation of PVA with PLY fiber at dosage of 5%, 10%, 15% 20% and 25% decreased the tensile strength by 1.70%, 5.73%, 8.06%, 11.31% and 13.48%; 3.75%, 6.79%, 10.69%, 12.57% and 14.45%; 1.50%, 3.84%, 5.62%, 9.19% and 12.48%; 2.40%, 5.21%, 6.95%, 10.02% and 13.37% after 56d, 90d, 180d and 337d water curing respectively. The decrement in tensile strength was found due to the low modulus of PLY fiber. The inclusion of high modulus fiber promotes the strength features; whereas, low modulus fiber enhanced the energy absorption capacity and ductile features [23–25]. The tensile behaviour of the BS7 mix proportion depicted that the strength of dog bone samples increased by 18.99%, 21.80%, 11.60% and 13.58% as compared to the BS6 mix proportion after 56d, 90d, 180d and 365d of water curing.

Moreover, the tensile strength results of the BS7 mix proportion increased by 2.94%, 4.19% and 2.60% after 56d, 90d and 180d water curing respectively as compared to the BS1 mix proportion. However, with an increase in the curing period the tensile strength of the BS7 mix proportion decreased by 1.60% as compared to the BS1 mix proportion after 365d water curing. The fiber bridging action of MSE fibers with cement matrix results in enhancement in load carrying capacity thus increasing strength achievement. The optimum tensile strength was found in BS7 mix proportion up to 180d water curing.

4.4.1 (a) *Chemical exposures on tensile strength:* Under NaCl and Na_2SO_4 solution immersion the tensile strength of designed samples decreased at the beginning stage (at 28d and 62d immersion). The percentage of reduction in tensile strength was found more under Na_2SO_4 solution. In combined chemical immersion no strength loss was observed for any mix proportion up to one year of exposure. Under combined exposure, the presence of chloride ions slowed down the rate of sulphate ions which resulted in strength achievement [18]. With the increase in immersion period (from 62d to 152d) no negative impact of chemicals was found on tensile strength. For better performance, long-term curing was required for GGBFS blended mix proportion [38]. Positive pozzolanic response of GGBFS in the long run and continuous hydration process in hardened cementitious samples diffused the chemical ions into the micropores, the reaction of these with hydration products contribute in densification at the interface between fiber and matrix, resulting in strength enhancement due to higher fiber bridging strength. As a result, marginal variation in tensile strength for all ECC mixes was observed. Therefore, no chemical effect was found on fiber hybridization in various ECC mixtures. The pozzolanic and non-pozzolanic constituents of ECC play mainly contribute to the variation in strength under the chemical immersion. From the results, it has been observed that the decrease in tensile strength due to the corrosion of MSE fibers was not found until one year of chemical immersion. Eventually, the influence of chemical immersion on tensile strength performance revealed that the combination of different fibers was not affected up to a year of immersion and provided resistance against chemical attacks.

4.4.2 *Tensile strain:* Figures 5(a-d) depict the influence of fibers amalgam on the tensile strain capacity of designed mixes. The experimental results obtained from tensile performance depicted that the hybridization of selected fibers in this study improved the tensile strain capacity. The subrogation of PVA with PLY fiber at dosage of 5%, 10%, 15% 20% and 25% enhanced the tensile strain capacity of ECC matrix by 3.12%, 5.13%, 9.82%, 11.83% and 15.62%; 5.19%, 8.17%, 10.89%, 14.35% and 17.57%; 3.08%, 5.68%, 9.24%, 11.13% and 14.21%; 5.04%, 7.93%, 11.29%, 13.94% and 16.82% after 56d, 90d, 180d and 337d water curing respectively. Scientific literature revealed that the combined use of low and high modulus fiber improved the tensile strength and strain response of cementitious mixes [24, 28]. Because the intrusion of low modulus fiber in cement matrix enhanced the energy absorption capacity which contributes to ductility achievement. The PVA and PLY fibers both are polymeric in nature; whereas, the mechanical properties of both fibers are different. The modulus of PLY fiber is less as compared to PVA fiber and is also graded in low-modulus fibers. The hydrophilicity of PVA fiber and their strong chemical bonding with cement paste is responsible for the fibers rupture than pull out. The distinctive nature (neither hydrophilic nor hydrophobic) of PLY fiber contributes to developing a very good bond between cement matrix and fiber surface [27]. The low modulus and some other unique parameters of PLY fiber are responsible for the improvement in the tensile strain capacity of HFRECC.

After the positive response from polymeric fibers hybridization, further investigation was carried out on the amalgam of PVA, PLY and MSE fibers at dosages of 50%, 25% and 25% respectively of the total fiber volume fraction. The tensile strain capacity of the BS7 mix proportion decreased by 7.14%, 4.45%, 6.63% and 10.09% after 56d, 90d, 180d and 365d water curing respectively as compared to the BS1 mix proportion. Moreover, the tensile strain capacity of the BS7 mix proportion decreased by 19.69%, 18.73%, 18.25% and 23.04% after 56d, 90d, 180d and 365d water curing respectively as compared to the BS6 mix proportion. The tensile strain capacity of the BS7 mix proportion decreased with the increase in the curing period, it may be due to the corroded nature of MSE fiber. The presence of corrosion may affect the slip-hardening behaviour of HFRECC. The optimum tensile strain capacity was recorded in BS6 mix proportion at all the water curing ages.

4.4.2 (a) *Chemical exposures on tensile strain:* Figure 5(a & b) depicted that the tensile strain capacity of all seven mixes decreased under NaCl and Na_2SO_4 solution immersion. The drop in strain capacity was observed due to a change in fiber/matrix interfacial properties. The strong influence of chemical immersion was observed on BS7 mix proportion due to the inclusion of MSE fiber. In the combination of PVA and PLY fibers no major effect was observed on tensile strain capacity under various chemical attacks. However, under combined solution immersion the tensile strain capacity of all the mixes was higher than water immersed specimens. In combined exposure, the presence of chloride ions slowed down the infiltration rate of sulphate ions due to which no strain loss was observed [43, 44]. With the increase in the immersion period, the effect of chemical ions on tensile strain reduced due to diffusion and their reaction with hydration products. After 337d chemical immersion the tensile strain capacity of BS1 to BS6 mix proportion slightly improved than water cured specimens; whereas, in BS7 mix proportion due to corrosion of MSE fiber the strain capacity was reduced. At this age (337d exposure), in the BS7 matrix the maximum reduction was observed under chloride immersion and minimum under combined exposure. The results indicated that due to corrosion of MSE fiber the interfacial properties between fiber and matrix were affected resulting in a loss in tensile strain capacity. Moreover, the interfacial properties of PVA and PLY fiber hybridization with matrix were not affected under a long period of chemical immersion. From all the mixes minimum tensile strain capacity was observed as 3.58%. The results indicated that the use of polymeric and non-polymeric fiber in ECC matrix improved the tensile performance under various environmental conditions. Therefore, the usage of present fiber hybridization in hydraulic structures can enhance durability performance.

5. Conclusions

This study evaluated the mechanical and durability performance of hybrid fiber reinforced engineered cementitious composite (HFRECC). In this investigation PVA, PLY and MSE fibers were used at various percentages in hybridization. To assess the influence of chemical exposure on HFRECC, three different (chloride, sulphate, and combined chloride-sulphate) solutions were used. The performance of HFRECC mixes was evaluated on the basis of compressive, tensile, and electrical resistivity (ER) response under different environmental conditions. The prominent conclusions from this experimental investigation have been summarized as follows:

(a) *Amalgam of PVA and PLY fiber*

- Amalgam of PVA and PLY fiber decreased the strength parameters; while, increased the tensile strain capacity and ER. The decrement in compressive strength was marginal; while, that in tensile strength was up to 14.45% (maximum).
- The combination of PVA and PLY enhanced the ER and tensile strain capacity maximum by 13.30% and 16.82%. As per various parameters, maximum enhancement or decrement was observed at 25% subrogation of PVA with PLY.
- The decrement in strength parameters was observed due to the low modulus of PLY fiber. However, utilization of low modulus fiber in ECC enhanced the energy absorption capacity which resulted in higher tensile strain capacity with the use of PLY fiber. The intrusion of PLY in ECC contributes in densification at the interface between fiber and matrix which results in hindering the flow of ions in the matrix. Thus, the utilization of PLY fiber in ECC enhanced the ER performance.
- Under chemical exposures, no deterioration was observed due to the amalgam of PVA and PLY fiber. The variation in various parameters was observed only due to pozzolanic and non-pozzolanic constituents of ECC matrix.
- The positive contribution of GGBFS in pozzolanic activities in the long run and continuous hydration process of cement paste diffused the ions into the micropores, the reaction of these with hydration products contributed to densifying the microstructure which resulted in strength and durability enhancement.
- In conclusion, the blending of PVA and PLY fiber in ECC provided resistance to the transport of detrimental ions and maintained the higher strength, tensile strain and ER under an aggressive environment for long period.

(b) Amalgam of PVA, PLY and MSE fiber

- The blending of MSE fiber with PVA and PLY marginally affect the compressive response; whereas, tensile strength increased up to 4.19% under water curing. The high modulus of MSE fiber contributes to taking more stresses and improved the fiber bridging capacity due to which enhancement in strength parameters was observed.
- In case of water curing, electrical resistivity, and tensile strain capacity of the BS7 mix proportion decreased up to 9.48% and 7.14% respectively as compared to the BS1 mix proportion. The intrusion of MSE fiber sustains a strong chemical bond with matrix due to which fibers ruptured than pull-out which resulted in a decrement in tensile strain capacity. The conductive nature of MSE fibers allowed the flow of current ions through the matrix which resulted in ER decrement.
- Under chemical exposure, no effect on strength and durability parameters was observed at the beginning stage; while, with the increase in the immersion period some rots were noted on the surface of the samples due to the corrosive nature of steel.

- After a long period of chemical immersion, no loss in strength parameters was observed; whereas, electrical resistivity and tensile strain capacity of BS7 mix proportion decreased marginally and 8.44% respectively as compared to water immersed samples.

The present research investigation demonstrated that the hybridization of micro-fibers enhanced the overall performance of the ECC. The lower cost and superior performance of ECC under an erosive environment promote its use in hydraulic structures and diversified applications.

Nomenclature

HFRECC	Hybrid engineered cementitious composite
PVA	Polyvinyl alcohol fiber
PLY	Polyester fiber
MSE	Micro steel fiber
MSS	Micro silica sand
GGBFS	Ground granulated blast furnace slag
ER	Electrical resistivity
CR	Corrosion risk
CIP	Chloride ion penetration
CTM	Compression testing machine

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