Assessment of chemical exposures on ECC containing stone slurry powder

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ABSTRACT

Generation of solid waste materials from various industrial sources is becoming a challenging issue for safe disposal. Durability performance of hydraulic structures under environmental loadings (aggressive substances) is also a concerning issue. The present paper investigated the durability performance of engineered cementitious composite (ECC) mortar containing stone slurry powder (SSP). SSP was used as partial subrogation of micro silica sand (MSS) and fine sand (FS) by 25% and 50% for each type of sand. Electrical resistivity (ER), compressive and tensile behaviour of various mixes were studied experimentally under chloride, sulphate and chloride-sulphate combined environmental conditions. Results obtained from various properties revealed that performance of fully MSS and FS containing ECC mixes was affected under aggressive substances at initial stages. The observations demonstrate that ECC containing SSP was durable and maintains better mechanical performance over fully MSS and FS containing mixes. This improvement finds a place in construction of hydraulic structures under aggressive environments.

Keywords: Durability, electrical resistivity, chemical attack, stone slurry powder, micro pores

INTRODUCTION

Performance of cement-based composites not only depends on mechanical parameters but also durability parameters and are prime concerns during designing of structures. The durability parameters of cementitious composite are based on the permeation, expansion, resistance to freeze-thaw, surface layer spalling, electrical resistance and chemical attacks such as chloride and sulphate attack (Ozbay *et al.,* 2013). The presence of chloride ions and sulphate ions in marine and seawater affect the durability performance of concrete structures, due to the chemical reaction between high concentration of ions and hydration product of cement-matrix (Li *et al*., 2018; Taylor *et al.,* 2001; Al- Amoudi 2002; Santhanam *et al*., 2006; Al-Dulaijan *et al*., 2003; Neville 2012). Permeation of the ions into concrete structures leads to the poor durability performance and resulting into deterioration of structures (Sibbick *et al*., 2003; Salami *et al*., 2017; Skalny *et al*., 2002; Al-Amoudi 1998, Liu *et al*., 2017^{a}). Generally, the performance of conventional concrete is measured on the strength parameters. In last two decades the development of skyscrapers is going on, which triggers the use of high strength concrete (HSC) in concrete structures. The use of HSC increases the brittleness of concrete; but, propagate the cracks and their width. The growth of cracks resulting in poor durability performance of hydraulic concrete structures (Liu *et al.*, 2017^{b}). In cement-based structures thermal contraction, expansion, drying shrinkage, chemical attack, deformations and mechanical loads all are the possible reasons for cracking. These cracks in hydraulic concrete structures drastically accelerate the deterioration by connecting the pores and provide easy access for aggressive ions (chloride and sulphate ions) (ACI 224R, 2001; Sahmaran *et al.*, 2007). Wider crack width significantly increases the diffusivity of aggressive ions; whereas, in narrow crack width the influence of aggressive ions found negligible. The corrosion rate significantly increases, if the width of crack exceeds 100 µm. Therefore, controlled crack width is essential to enhance the life span and durability performance of hydraulic concrete structures under chloride, sulphate and chloride-sulphate conditions. In conventional concrete the controlled cracking is considered as a significant challenge. Numerous efforts like use of different types of materials, steel reinforcement and temperature control have been made to control crack width in cement matrix. Cracking in concrete is almost inevitable due to its highly brittle nature under mechanical loadings and environmental conditions (Li *et al.*, 2011; Sahmaran e*t al.*, 2008). Therefore, reliable control of crack width in concrete is tedious. However, to improve the durability performance of concrete structures under chemical attack and environmental conditions a material with controlled crack width is required. Numerous researchers reported that the use of different types of fibers in concrete enhanced the strength as well as strain parameters and arrest the micro and macro level cracks (Anandan *et al.*, 2019; Farooqi *et al.*, 2018; Zia *et al.*, 2017; Teng *et al*., 2018).

Cement based materials are typical porous materials and also have some electrical performance. The concrete properties have strong relationship with conductivity and pore structure. Electrical resistivity is a superb non-destructive technique (NDT), used in modelling the penetration of aggressive agents in cementitious materials and as an indication of electrical charge in cement-based materials. Several studies claim electrical resistivity as a key factor to indicate the permeability of concrete to aggressive substances, as resistivity is a function of concrete microstructure (Madani *et al*., 2014; Medeiros-Junior *et al*., 2016; Zivica *et al.*, 1994). Numerous supplementary cementitious materials (SCM) such as fly ash (FA), ground granulated blast furnace slag (GGBFS), palm oil fuel ash (POFA), rice husk ash (RHA) etc. have been used to reduce the pore size in cementitious paste, produce a highly resistive cementitious material and improve the durability performance of ECC under chemical attacks (Sahmaran *et al.*, 2009; Hussain 1994; Ramezanianpour *et al*., 2011).

ECC is one of cementitious material that contain fibers as well as high amount of supplementary cementitious material (SCM) in mix design. ECC is a superb class of high performance fiber reinforced cementitious composite (HPFRCC) featuring high strain capacity (1-8%) and constraint crack width (less than 100 µm). The low volume fiber fraction (approximately 2% of the volume of cementitious materials) has been used in ECC. The design of ECC rely on micromechanics of fiber bridging and crack extension. Under tensile loading ECC exhibits extensive strain hardening behaviour with multiple fine cracking (Singh *et al.*, 2019[a]; Li, V.C 1998; Singh *et al*., 2019[b]). The high energy absorption capacity (approximately 30KJ/m^2) and ductile nature of ECC made it unique from other types of cementitious materials. The performance of parameters such as flexural capacity, compressive, tensile, toughness, density etc. depend on the types of the constituents used in the mix design (Li *et al.,* 1998; Singh *et al*., 2019[c]). Minimal crack width of ECC arrests the penetration of aggressive ions in cement-matrix surface and also improve the durability performance and self-healing. Previous research studies on durability reported that the tight crack width of ECC greatly obstruct the further deterioration of structures as compared to conventional concrete structures (Liu *et al.,* 2017[b]; Abou-Zeid *et al*., 2001; Sahmaran *et al*., 2007). The standard ECC consists of Class-F fly ash, portland cement, micro silica sand, oiled polyvinyl alcohol fiber and polycarboxylic ether type (PCE) high range water reducing admixture (HRWRA). The durability performance of ECC under sulphate and chloride immersion has been investigated by various researchers.

Liu *et al.*, 2017[b] characterized the tensile and compressive behaviour of ECC under sulphate and sulphate-chloride immersion. The experimental results reported that ECC exhibits more durable behaviour than conventional concrete under sulphate and sulphate-chloride conditions. The findings demonstrated that ECC can be used as a protective layer to enhance the long-term durability performance of cement based hydraulic structures. Sahmaran *et al*., 2007 characterized the ECC properties under chloride exposure. It has been reported that ECC demonstrate low chloride diffusion coefficient and more durable behaviour than mortar mix. Li *et al.,* 2011 reported that ECC exhibits enhanced tensile ductility and durability under chloride immersion. Lepech *et al*., 2006 found that ECC more durable under freeze-thaw cycles. Sahmaran *et al*., 2008 and Li *et al*., 2011 demonstrated that the presence of high alkaline and chloride environment did not affect the self-healing characterization of ECC; whereas, improved the durability. Numerous investigations reported that durability performance of ECC significantly enhanced under exposure to aggressive ions, such as sulphate, chloride, sulphate-chloride immersion, freeze-thaw cycles, hot water immersion alkali- silicate reaction and de-icing salt exposures.

In this investigation, six ECC mixtures were prepared with the use of ground granulated blast furnace slag (GGBFS) as supplementary cementitious material and stone slurry powder (SSP) as substitution of fine aggregates (i.e. MSS and FS). Most of the durability investigations have been conducted with the use of fly ash till now. GGBFS is a by-product from iron and steel industries; whereas, SSP is being generated from stone industry during cutting and sawing process of stones. The utilization of slag in ECC enhanced the tensile strain and deflection capacity. The presence of slag in ECC mixture provides a driving force for fiber dispersion and also improved the durability performance under sulphate and chloride immersion (Zhou *et al*., 2010). Ozbay *et al*., 2013 reported that ductility, sorptivity, water absorption and porosity of ECC enhanced with the increase in quantity of slag. Ulubeyli *et al*., 2016 and Lakhani *et al*., 2014 reported that the use of stone waste in conventional concrete improved the durability performance of conventional concrete. The literature reported that limited studies have been carried out on ECC incorporating slag and SSP under chloride, sulphate, sulphate-chloride environment as well as electrical performance.

RESEARCH SIGNIFICANCE

Numerous research studies have been carried out on durability performance of conventional concrete with the use of various supplementary materials such as fly ash, slag, marble powder, silica fume, rice husk ash and many more. But the limited research works have been carried out on durability performance of ECC with these waste materials. To protect the environment from harmful impact, utilization of solid waste products in huge amount is required. In this research work industrial by products (GGBFS and SSP) were utilized in excess amount to make an eco-friendly ECC. The objective of this research is to assess the effect of SSP and GGBFS in combination on the durability performance of ECC under aggressive ions. The durability performance of different ECC mixes has been evaluated experimentally under immersion in chloride, sulphate and their combination. Present research provides a better platform for utilizing the GGBFS and SSP in construction industry. This work highlights the significance of GGBFS and SSP in durability performance of ECC under chemical exposures and also provide guidelines for design and applicability of ECC in hydraulic concrete structures.

MATERIALS AND METHODS

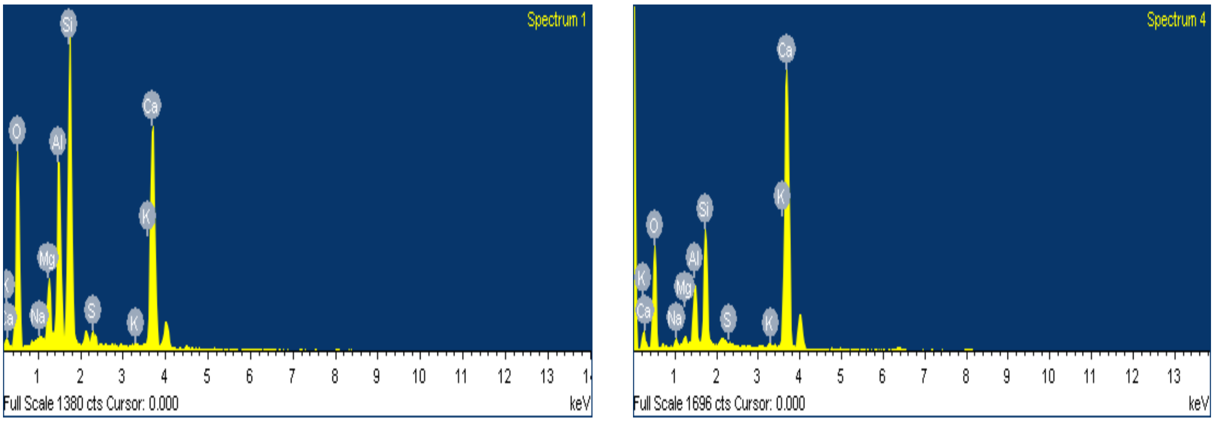
Characterization of materials

Constituents used in this research work were Portland cement (PC) of 43 grade, GGBFS and SSP. Chemical compositions and physical properties of PC, GGBFS and SSP have been given in table 1. Micro silica sand (MSS) and natural river fine sand (FS) with maximum size of 175 micron and 600 micron respectively have been used as fine aggregate in ECC mixtures. SSP was used as substitution of MSS and FS at levels 25% and 50% for each sand; whereas, GGBFS (55% of the total cementitious material) as cementitious material. Polycarboxylic-ether type high range water reducer (HRWRA) was added with water in solid content to achieve the proper rheological performance. The polyvinyl alcohol (PVA) fiber used in the present research was of 12 mm length, 39 µm diameter, density 1300 kg/m^3, tensile strength 1600 MPa, Young's modulus 42.8 GPa and elongation 7%. To reduce the chemical bond between fiber-matrix and friction, the oil coat (1.2 % by weight) was done on surface of the fibers. A constant fiber volume fraction (2% by weight of cementitious materials) was used in all the six mixes.

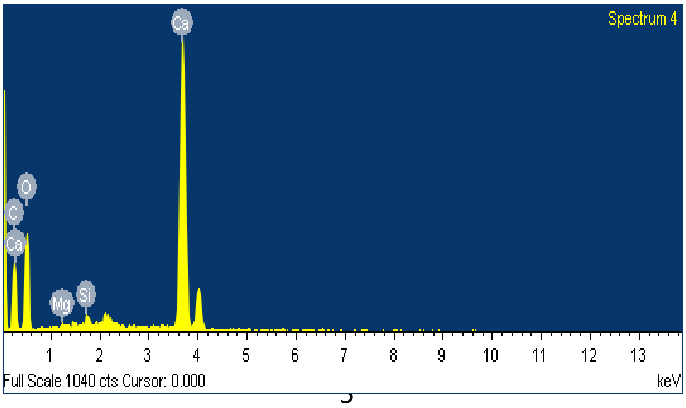
Table 1. Characteristics of PC, GGBFS, SSP.

Chemical analysis	GGBFS	PC	SSP
SiO_2	38.20	20.75	1.40
CaO	36.94	66.96	54.70
Al_2O_3	17.02	7.52	-----
MgO	5.24	1.03	0.24
Na_2O	0.29	1.22	-----
K_2O	0.19	0.41	-----
SO_3	2.12	2.12	-----
LOI*	-----	-----	43.66
Density	2.82	3.11	2.78

* Loss of ignition

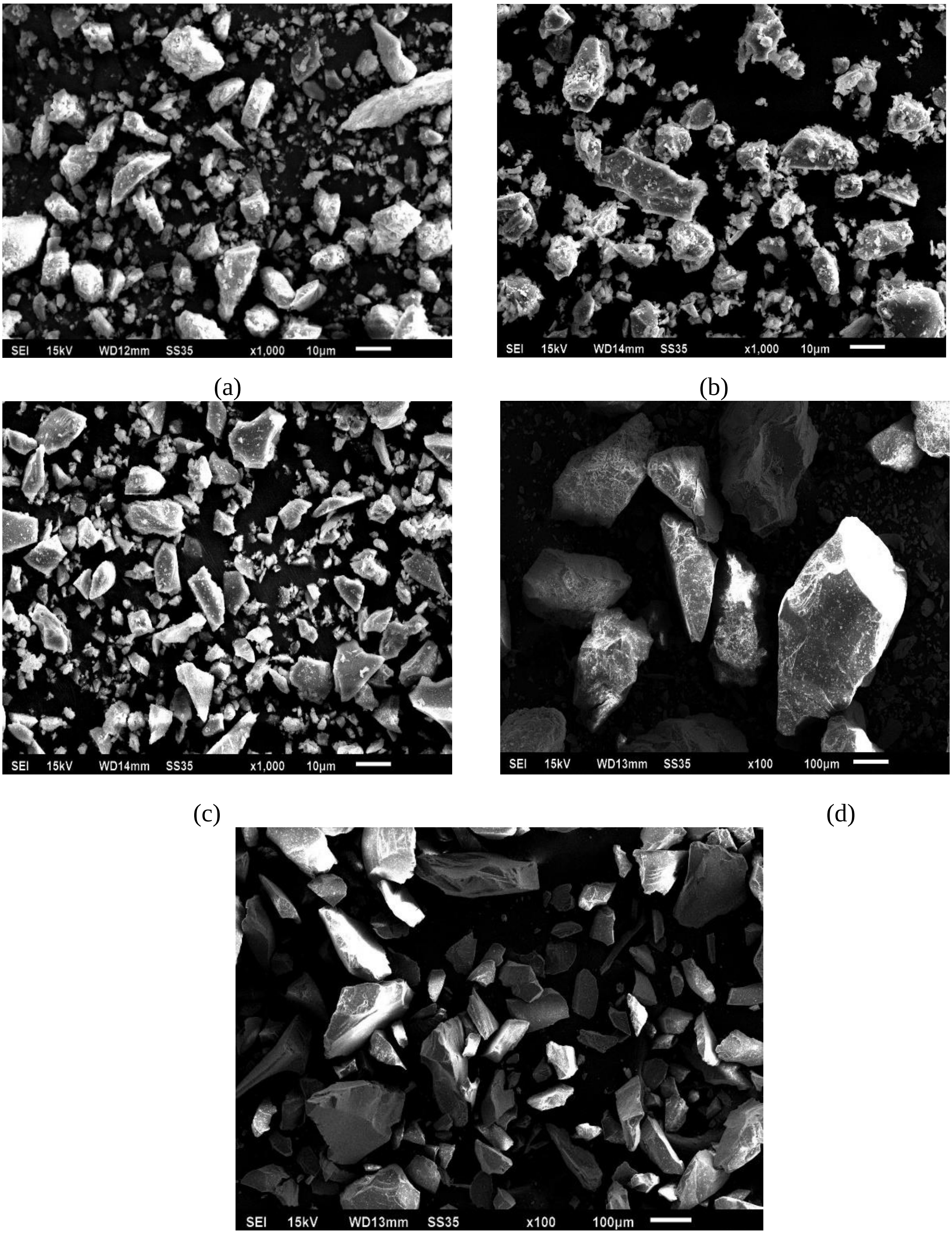


(a) (b)



(c)

Figure. 1(a) Energy dispersive X-ray spectroscopy analysis of (a) GGBFS (b) PC (c) SSP.



(a) (b)

(c) (d)

(e)

Figure. 1 (b) Micrographs of scanning electron microscopy (a) SSP (b) PC (c) GGBFS (d) FS (e) SS.

Mixture proportions

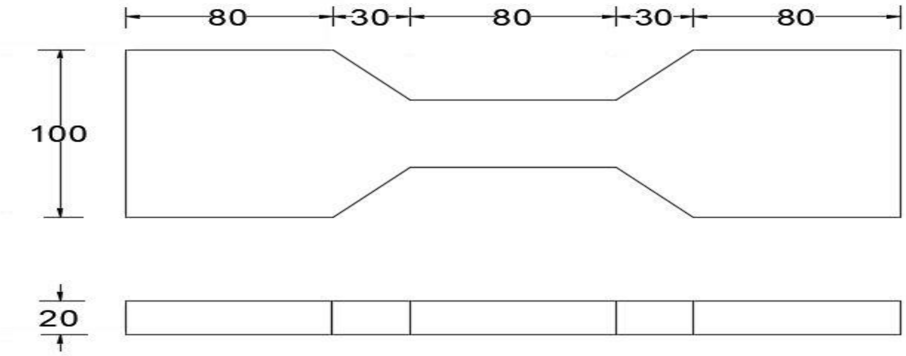
To analyse the effect of GGBFS and SSP in combination under different exposures, six cementitious mixes were prepared with the subrogation of MSS and FS as listed in table 2.

Table 2. Mix proportions of ECC incorporating industrial by products.

Constituents								
Mix Reference	PC	GGBFS	MSS	FS	SSP	w/b	PVA (%)	HRWRA (%)
MSS	1	1.2	0.8	------	-----	0.27	2	0.45
MSS_25 SSP	1	1.2	0.6	------	0.2	0.27	2	0.45
MSS_50 SSP	1	1.2	0.4	------	0.4	0.27	2	0.45
FS	1	1.2	-----	0.8	-----	0.27	2	0.45
FS_25 SSP	1	1.2	-----	0.6	0.2	0.27	2	0.45
FS_50 SSP	1	1.2	-----	0.4	0.4	0.27	2	0.45

Fabrication and curing process

Power driven mortar mixer was used in preparing all the cementitious mixtures. Ateriorly, all solid constituents were added into the drum in dry state and the mixer was rotated until adequately mixed. Then water and HRWRA were added slowly into the mixed constituents until stirred state was achieved. And at the last; fibers, were added slowly and the mixer was rotated until fibers were evenly distributed. The homogenous mix was poured into the moulds of 70.6mm × 70.6mm ×70.6mm cubes (for electrical resistivity and compressive strength) and 310 mm × 100 mm × 20 mm dog-bone shaped specimen (for tensile parameters), placed at room temperature for 24 h. Then all the casted specimens were demoulded and placed inside the water curing tank for required age. After 28 days water curing, as per testing requirements specimens were immersed into the solutions 5% (by weight) Na_2SO_4 solution, 5% (by weight) NaCl solution and 5% (by weight) Na_2SO_4 + 3% (by weight) NaCl for 28, 62 and 152 days and rest of the specimens remained in water curing tank for reference.



EA

All the dimensions in ‘mm’.

Figure 2. Schematic view of dog bone specimens.

PROCEDURE AND SETUP FOR TESTING

Compression behaviour

To study the compressive behaviour of various mixtures against exposure to chloride attack, sulphate attack, sulphate-chloride attack mortar cubes (ASTM C1012, 2012) of aforementioned dimensions were used and tested in compression testing machine as per IS 516:1959, 2006 and BS-EN-12390-3, 2009 specifications.

Tensile behaviour

In the present study dog bone shaped specimens shown in Fig. 2 were used to analyse the tensile behaviour of all six mixes, under different environmental conditions. The universal testing machine (UTM) at loading rate 0.2 mm/minute was used to analyse the tensile behaviour. The wedge face of specimen was gripped in the machine and gauge length was used to record the tensile strength and strain.

Electrical resistivity

During measurement of electrical resistivity of cement matrix, moving ions are taken as an indication of diffusion of ions. Electrical resistivity (ER) can be used as durability indicator, the correlation between ER and corrosion rate has been given in Table 3. The ER of ECC specimens was recorded via a two-point method. For measuring the movement of ions in various mixes cube specimens were used. The transport property of various mixes was recorded on cement matrix cubes. Moist sponge was used on top and bottom surface of cement matrix cubes to establish a stable electrical connection between two parallel plates. The alternating current was measured on set of three mortar cubes for each mix with help of True RMS multimeter, model number U1252B, manufactured by Keysight. The electrical resistivity of the cementitious composite, ρ, can then be calculated on mortar cubes by the following formula.

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

Where A is the area of the sample (cm^2), L is the length of the sample, and R ($k\Omega$) is the resistance of the sample which can be obtained from the multimeter.

Table 3. Co-relation between ER and corrosion rate (Broomfield, 2007; ACI 222R-01, 2010).

ER (kΩ-cm)	>20	10-20	5-10	<5
Corrosion Threat	Low	Low to moderate	High	Very High

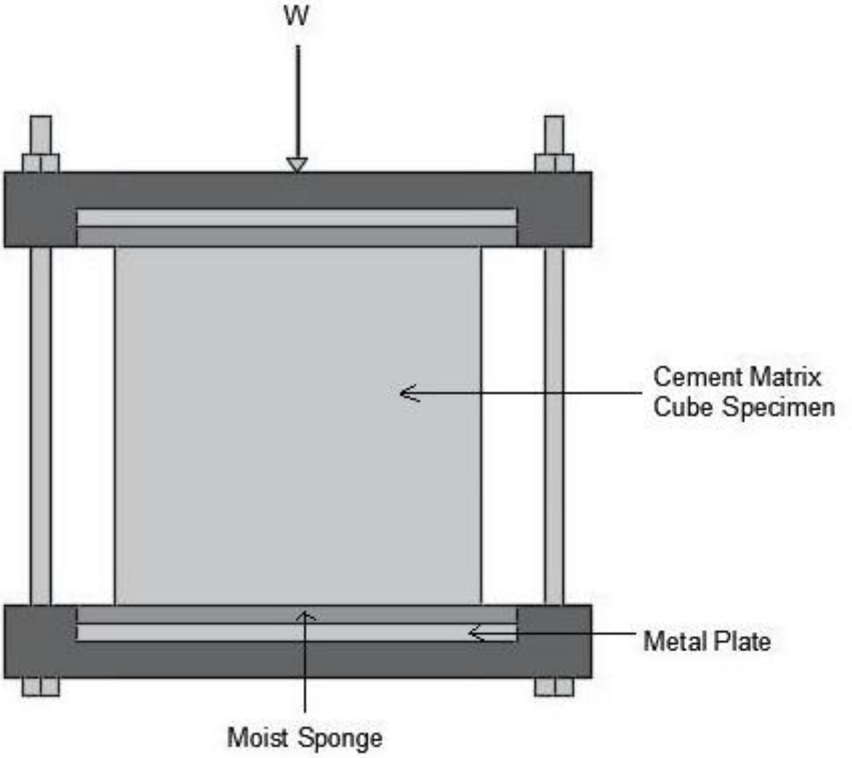


Figure 3. Electrical resistivity set up.

RESULTS AND DISCUSSION

Visual inspection

The surface of hardened ECC specimens containing SSP was smooth and better finished than fully MSS and FS blended mix. No physical signs were visible on hardened ECC specimens when exposed to different chemical solutions. At (28+62) and (28+152) day's exposure to aggressive environment (5% Na_2SO_4 solution, 5% NaCl solution, 5% Na_2SO_4 + 3% NaCl) white covering was observed on the surface of the specimens.

Compressive behaviour

The compressive strength (CS) of various ECC mixtures specimens stored under different exposure conditions i.e. (a) 5% NaCl solution (b) 5% Na_2SO_4 solution (c) 5% Na_2SO_4 + 3% NaCl solution for 28d, 62d and 152d was observed and compared with water cured specimens at 56d, 90d and 180d respectively. Figure 4 showed that the CS of all the six ECC mixtures increased under 56d, 90d and 180d water curing due to continuous hydration process of cement and pozzolanic activity of GGBFS that may be effective in long term and requires long period of curing (Ozbay *et al.*, 2013). The CS of fully MSS blended mix was observed higher than fully FS blended mix. Substitution of MSS at level 25% and 50% enhanced the CS by 7.17%; 7.41%; 6.86% and 4.92%; 5.64; 4.49% after 56d; 90d: 180d water curing respectively. Replacement of FS at 25% and 50% enhanced the CS by 9.37%; 8.43%; 9.52% and 7.03%; 6.13%; 7.49% after 56d; 90d; 180d water curing. Maximum enhancement in CS was observed in FS_25 SSP mix that was due to the finer pore structure of SSP. The optimum CS was found when 25% SSP was charged along with mix containing MSS and also mix containing FS under water curing at all curing ages.

In case of chloride attack, slight increase was observed in CS of fully MSS blended mix proportion; whereas, the slight decrease was observed in fully FS blended mix proportion at 28d and 62d exposure period. After 152d chloride exposure increased the CS of fully MSS and FS blended mix proportion by 3.37% and 1.84% respectively. Replacement of MSS with SSP at level 25% and 50% increased the CS by 1.27%; 2.55%; 2.34% and 2.23%; 3.75%; 3.22% after 28d, 62d and 152d chloride exposure respectively. FS substitution with SSP at 25% and 50% increased the CS by 1.62%; 3.02%; 2.57% and 1.16%; 4.05%; 3.73% after 28d, 62d and 152d chloride exposure respectively. The highest CS was observed for mix proportion FS_25 SSP; whereas, the higher percentage increase in CS was observed in mix proportion FS_SSP 50 after 62d exposure.

In case of sulphate exposure at 28d and 62d no slight change was observed in CS of fully MSS blended mix; whereas, the CS of fully FS blended mix showed slightly decreasing trend i.e. 1.17% and 2.73% after 28d and 62d exposure respectively. Utilization of SSP as both type of sand replacement at 25% and 50% in cementitious mix enhanced the CS. Highest value of CS was observed in mix proportion FS_25 SSP; whereas, the higher percentage increase in CS was observed in mix proportion MSS_SSP 50 i.e. 1.36% at 28d exposure. And at 62d exposure highest value of CS was observed in mix proportion FS_25 SSP; whereas, the higher percentage increase in CS was observed in mix proportion FS_SSP 50 i.e. 3.03%. After a 152d sulphate attack the enhancement in CS of all the six mix proportions was observed. The optimum CS in both cases i.e. MSS and FS blended mix proportions was found when 25% SSP was charged along with; whereas, the higher percentage increase in CS was observed in mix proportion FS_SSP 50 i.e. 2.65%.

In case of combined chloride and sulphate attack, slight increase was observed in CS of fully MSS blended mix proportion; whereas, no obvious change was observed in fully FS blended mix proportion after 28d and 62d exposure period. After 152d combined chemicals exposure increased the CS of fully MSS and FS blended mix by 4.24% and 2.64% respectively. Utilization of SSP as MSS replacement at 25% and 50% increased the CS by 1.65%; 3.14%; 3.39% and 2.79%; 4.78%; 5.02% after 28d, 62d and 152d exposure respectively. Substitution of FS with SSP at 25% and 50% increased the CS by 2.12%; 3.98%; 4.08% and 2.05%; 4.66%; 4.90% after 28d, 62d and 152d combined exposure respectively. The highest CS was observed for mix proportion FS_25 SSP; whereas, the higher percentage increase in CS was observed in mix proportion MSS_SSP 50 after 152 days combined exposure i.e. 5.02%.

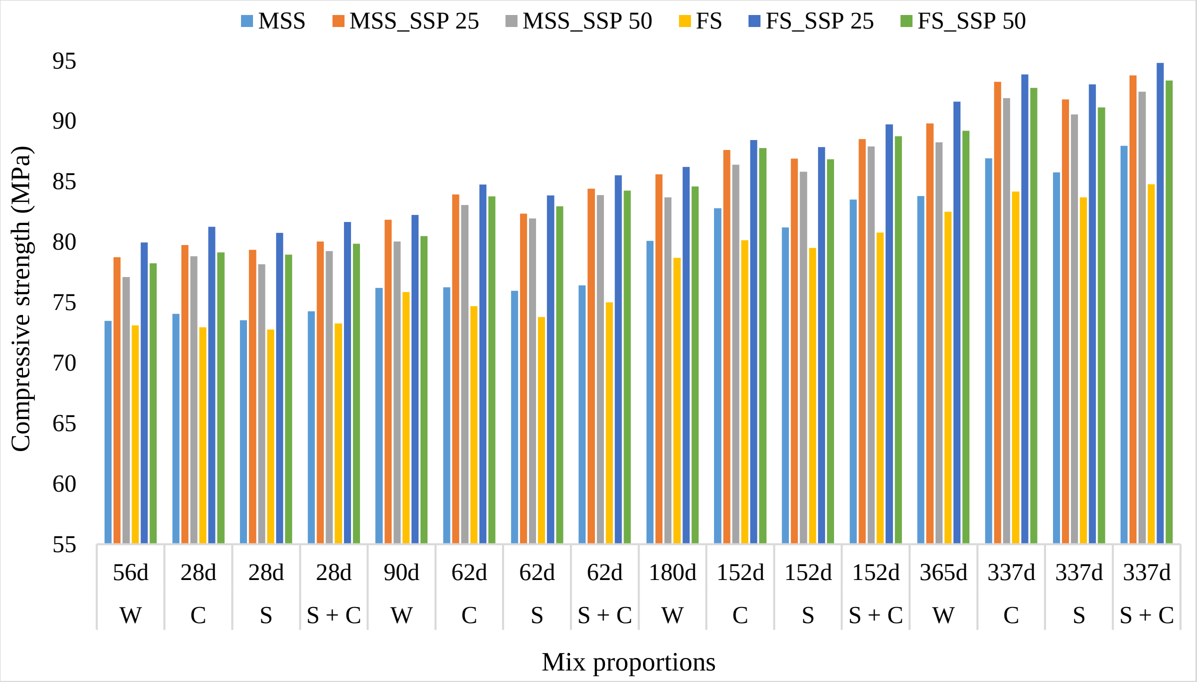


Figure 4. CS behaviour under different environmental conditions at various ages

The optimum mix proportion was found FS_25 SSP in terms of resistance against various chemical attacks. The CS results of various mixes showed that the utilization of SSP waste in ECC fill the micro pores and provide resistance against various chemical attacks. The continuous hydration process of cement and pozzolanic activity of GGBFS that may be in long term diffused the chemical ions and form ettringite, which may contribute in the strength achievements in longer term (Ozbay *et al*., 2013; Liu *et al*., 2017^{b}; Sahmaran *et al.*, 2008).

Numerous researchers claimed that chloride attack is not serious compared to sulphate attack. This indicate that gain in strength in (Na_2SO_4 + NaCl) solution cured specimens, due to the presence of chloride ions slowed down the sulphate ions reaction (Liu *et al.*, 2017^b). Increase in strength in SSP containing mixes due to fine pore structure of SSP that attributed a micro filling effect. In Figure 1(b), SEM photographs of various materials used in this study depicts that the particles size of SSP is very very less as compared to both type of sand's particles size. On the other hand, the slight decrease in strength of fully MSS and FS blended mix proportions was observed due the high size of particles of sands than SSP that may develop some micro voids with hydrophilic nature of PVA fiber.

Electrical resistivity

The electrical resistance (ER) of various mix proportions under laboratory environment and different aggressive substances have been shown in figure 5. The ER of fully MSS blended mix proportion was observed higher than fully FS blended mix proportion, which may be due to fine particles of MSS than FS. Increase in the amount of SSP as substitution of both type of sand (MSS & FS) in cement matrix increased the ER of ECC mixes. The substitution of MSS with SSP at level 25% and 50% increased the ER by 9.24%, 7.21%, 11.60% and 19.04%, 12.37%, 20.19% of water cured specimens after 56d, 90d and 180d respectively. Partial subrogation of FS with SSP at level 25% and 50% increased the ER by 13.72%, 9.71%, 15.17% and 16.86%, 17.62%, 21.87% of water cured specimens after 56d, 90d and 180d respectively. The increase in ER may be attributed to finer pore structure of SSP resulting densification of the whole structure of cement matrix. The optimum ER in both cases i.e. MSS and FS blended mix proportions was found when 50% SSP was charged along with.

Under chloride attack, ER of fully MSS and FS blended mix proportions reduced by 8.95%; 5.35% and 11.46%; 7.44% after 28d; 62days exposure period. And after 152d chloride exposure the ER of fully MSS and FS blended mix proportions was almost same to that of water cured specimens at same age. No slight change was observed after 28d and 62d exposure with the utilization of SSP as replacement of both types of sand's at 25%. At 50% SSP substitution for each type of sand slightly enhanced the ER of various mixes after 28d and 62d exposure. The maximum percentage of ER enhancement was found in FS_SSP50 i.e. 6.26% after 62d exposure. After 152d exposure the ER of SS_SSP25, SS_SSP50, FS_SSP25 and FS_SSP50 mix proportions were increased by 4.30%, 4.86%, 6.75% and 7.52% respectively. Results of ER under chloride exposure showed that increase in utilization percentage of SSP as both types of sand enhanced the resistance against chloride attack.

In case of sulphate attack, ER of fully MSS and FS blended mix proportions were reduced by 3.35%; 3.30% and 6.62; 4.07% after 28d; 62d exposure period. And after 152d immersion ER of fully MSS and FS blended mix proportions was increased by 1.58% and 4.17% respectively. Utilization of SSP as sand replacement (MSS &FS) enhanced the ER and provide resistance against sulphate exposure. Replacement of MSS at 25% and 50% with SSP enhanced the ER by 3.83%; 8.16%; 9.84% and 5.29%; 7.89%; 8.23% after 28d; 62d; 152d immersion. Substitution of FS with SSP at 25% and 50% enhanced the ER by 1.97%; 4.80%; 11.34% and 9.82%; 13.23%; 10.70% after 28d; 62d; 152d sulphate immersion. The optimum percentage of SSP utilization was found 50% in both type of sand replacements.

During combined chemical (chloride and sulphate) immersion, ER of fully MSS and FS blended mix proportions was decreased by 6.15%; 4.64% and 9.56%; 6.38% after 28d; 62d exposure; whereas, after 152d the ER of both the mixes were almost same to the water cured specimens at 180d. Replacement of MSS at 25% and 50% with SSP enhanced the ER by 2.30%; 5.96%; 7.82% and 4.11%; 5.31%; 6.74% after 28d; 62d; 152d combined chemical (chloride and sulphate) attack. Substitution of FS with SSP at 25% and 50% enhanced the ER by 0.91%; 3.17%; 8.98% and 5.77%; 8.68%; 9.17% after 28d; 62d; 152d combined chemical (chloride and sulphate) attack. The optimum ER was found in FS_SSP50 mix proportion at all exposure duration.

The ER results from the various exposure conditions analysed in this work revealed that chloride attack is more serious than sulphate attack for ER performance. The micro pore structure of SSP fill the voids present on the surface of the randomly distributed PVA fibers, protects the surface of fiber from chemical substances up to some limit i.e. due to which increment in the ER of SSP blended mixes was observed. Due to the presence of GGBFS, hydration process of matrix continued for longer period which is responsible for the densify state and ER enhancement up to 180d water curing. The values of ER were observed minimum (42.50 kΩ-cm) in fully FS blended mix proportion at 56d chloride exposure and maximum (133.71 kΩ-cm) in MSS_SSP50 mix proportion at 152d sulphate exposure. All the values of ER were very high which correspond to very very low corrosion rate (Broomfield, 2007). From the experimental results it has been observed that utilization of SSP waste in ECC enhanced the electrical resistivity of various mixes under different environmental conditions.

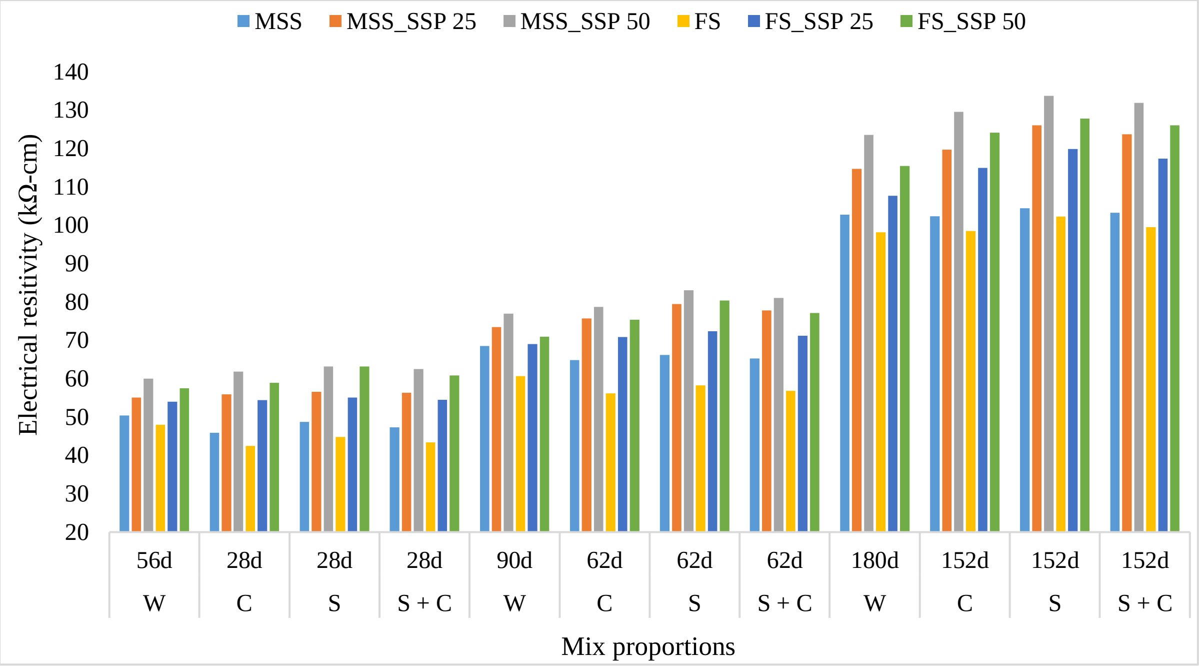


Figure 5. ER behaviour under different environmental conditions at various ages

Tensile behaviour

Tensile strength

Figure 6 presents the tensile strength (TS) of various ECC mix specimens under 56d, 90d and 180d water curing and chemical exposure. TS of fully MSS blended mix was slightly higher than fully FS blended mix under laboratory environment. Substitution of MSS with SSP at level 25% and 50% enhanced the TS by 11.62%; 9.53%; 10.42% and 3.08%; 6.2%; 2.89% after 56d; 90d 180d water curing respectively. Partial subrogation of FS with SSP at level 25% and 50% increased the TS by 18.93%; 13.94%; 17.2% and 12.45%; 7.12%; 10.74% after 56d and 90d water curing respectively. TS increment in SSP containing mixes was may be due to fine pore structure of SSP, acting as a gel when mixed with ECC mixture i.e. filled the micro voids present on the surface of hydrophilic nature of PVA fiber. The optimum TS in both cases i.e. MSS and FS blended mix proportions were found when 50% SSP was charged along this.

In case of chloride attack, the TS of fully MSS and FS blended mix proportion was reduced by 6.36%; 1.61% and 5.34%; 6.82% after 28d; 62d exposure; whereas, at 152d exposure TS increased by 4.52% and 5.15%. Utilization of SSP in MSS blended mix proportion at 25% and 50% enhanced the TS by 1.63%; 5.27%; 7.82% and 1.86%; 8.98%; 11.71% after 28d; 62d; 152d chloride exposure respectively. Substitution of FS with SSP at 25% and 50% enhanced the TS by 2.51%; 7.81%; 10.26% and 3.20%; 9.41%; 13.58% after 28d; 62d; 152d exposure period respectively. The optimum TS was found in 25% SSP blended mix along with FS. The long term pozzolanic reaction of GGBFS and continuous cement hydration process, diffused the chloride ions in the micro pores and reaction of these ions with hydration products form ettringite, which may be responsible for strength achievements.

During sulphate immersion the TS of fully MSS and FS blended mix proportion reduced by 7.59%; 4.33% and 8.09%; 9.79% after 28d; 62d exposure; whereas, at 152d exposure increased by 2.33% and 4.68% respectively. At 25% substitution of MSS and FS with SSP reduced the TS by 2.5% and 0.95% after 28d exposure; whereas at 62d; 152d exposure increased the TS by 1.84%; 2.36% and 3.90%; 3.42% respectively. The 50% utilization of SSP in MSS blended mix proportion did not show slight change in TS after 28d exposure; whereas at 62d and 152d exposure increased the TS by 4.81% and 4.68% respectively. Subrogation of FS with SSP at 50% enhanced the TS by 3.88%, 5.26% and 5.43% after 28d, 62d and 152d chloride exposure. The optimum mix proportion was found FS_SSP 25 at all ages; whereas, the enhancement in TS was observed up to 50% SSP utilization along with each type of sand.

During the combined attack (chloride + sulphate) of chemicals, the TS of fully MSS blended mix proportion was enhanced by 1.08%, 1.87% and 7.27% after 28d, 62d and 152d exposure respectively. The TS of fully FS blended mix proportion was reduced by 3.23%, 1.48% at 28d, 62d exposure and afterwards at 152d exposure period increased by 3.29%. Utilization of SSP in MSS blended mix proportion at 25% and 50% enhanced the TS by 4.44%; 5.80%; 5.34% and 5.25%; 11.23%; 10.67% after 28d; 62d; 152d sulphate exposure respectively. Substitution of FS with SSP at 25% and 50% enhanced the TS by 5.03%; 8.59%; 6.84% and 7.05%; 12.04%; 9.44% after 28d; 62d; 152d exposure period respectively. The optimum TS in both cases i.e. MSS and FS blended mix proportions was found when 25% SSP was charged along with both, under combined chemical exposure. The presence of chloride mitigates the sulphate exposure i.e. may be responsible for strength achievement under combined attack. Micro filling effect of SSP declines the chemical exposure and improve the fiber- matrix interface, which provides higher fiber bridging strength.

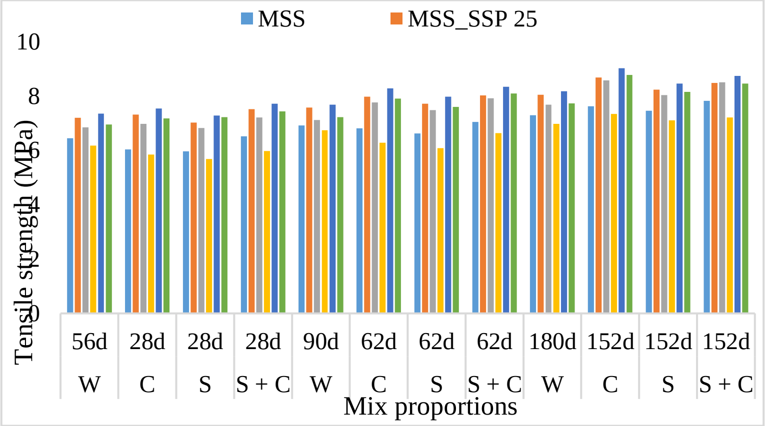


Figure 6. TS behaviour under different environmental conditions at various ages

Tensile strain

Fig. 7 shows the tensile strain of various mixes of ECC specimens under different exposure conditions after 56d, 90d and 180d curing respectively. Tensile strain of fully MSS blended mix was slightly higher than fully FS blended mix under laboratory environment. Substitution of MSS with SSP at level 25% and 50% improved the tensile strain by 7.59%, 13.36%, 8.05% and 13.8%, 24.2%, 18.01% after 56d, 90d and 180d water curing respectively. Results of partial substitution of FS with SSP at level 25% and 50% revealed the increase in tensile strain by 10.11%, 11.73%, 13.09% and 16.47%, 20.4%, 24.4% after 56d, 90d and 180d water curing. The optimum mix proportion was found MSS_SSP50 at 56d and 90d water curing; whereas, at 180d curing FS_SSP50 was showed maximum tensile strain.

Chloride exposures after 28d and 62d reduced the tensile strain of fully MSS blended mix proportion by 5.35% and 3.96%; whereas, after 152d exposure increased by 3.08%. Chloride exposure also affects the tensile strain of fully FS blended mix proportion i.e. tensile strain reduced by 4% and 4.34% after 28d and 62d; whereas, after 152d exposure improved by 5.68%. combined exposure of both chemicals enhanced the tensile strain. Utilization of SSP in MSS blended mix proportion at 25% and 50% improved the tensile strain by 2.90%; 6.11%; 6.35% and 1.96%; 3.18%; 8.04% after 28d; 62d; 152d respectively. Partial substitution of FS with SSP at 25% and 50% enhanced the tensile strain by 2.99%; 5.48%; 8.30% and 3.43%; 4.24%; 10.71% after 28d; 62d; 152d respectively. The finer particles of SSP in ECC mix behave as a gel, which protects the fiber surface from chloride attack that may be responsible for tensile strain enhancement.

During sulphate immersion, the tensile strain of fully MSS and FS blended mix proportions were reduced by 8.03%; 7.92%; 3.80% and 6.82%; 8.16%; 1.72% after 28d; 62d; 152d respectively. Substitution of MSS and FS with SSP at 25% showed slight decrease in tensile strain at initial stage (28d exposure) i.e. 2.07% and 5.56% respectively. The tensile strain of MSS and FS blended mixes along with 25% SSP improved by 3.71%; 4.82% and 3.20%; 4.80% after 62d; 152d exposure respectively. Substitution of MSS with 50% SSP improved the tensile strain by 1.18%, 1.40% and 6.22% after 28d, 62d and 152d sulphate exposure respectively. Subrogation of FS with 50% SSP improved the tensile strain by 1.82%, 1.70% and 8.33% after 28d, 62d and 152d exposure period respectively. The optimum tensile strain in both cases i.e. MSS and FS blended mix proportions was found when 50% SSP was charged along with. Reduction in tensile strain of fully MSS and FS blended mix proportions may be attributed to the change in the fiber-matrix interfacial properties. The presence of finer particles of SSP cover the fiber surface by filling voids present on this; may promote the ductile nature of ECC under humid environment.

Under combined exposure of both chemicals (chloride + sulphate), the tensile strain showed improvement at all curing ages. The tensile strain of fully MSS and FS blended mix proportions increased by 7.14%; 7.92%; 6.16% and 5.64%; 3.31%; 9.13% after 28d; 62d; 152d combined exposure respectively. Substitution of MSS and FS with 25% SSP improved the tensile strain by 6.85%; 12.50%; 9.00% and 7.69%; 8.40%; 11.80% after 28d; 62d; 152d respectively. Substitution of SSP at 50% with MSS and FS improved the tensile strain by 7.06%; 4.38%; 10.84% and 7.88%; 6.78%; 15.47% after 28d; 62d; 152d respectively.

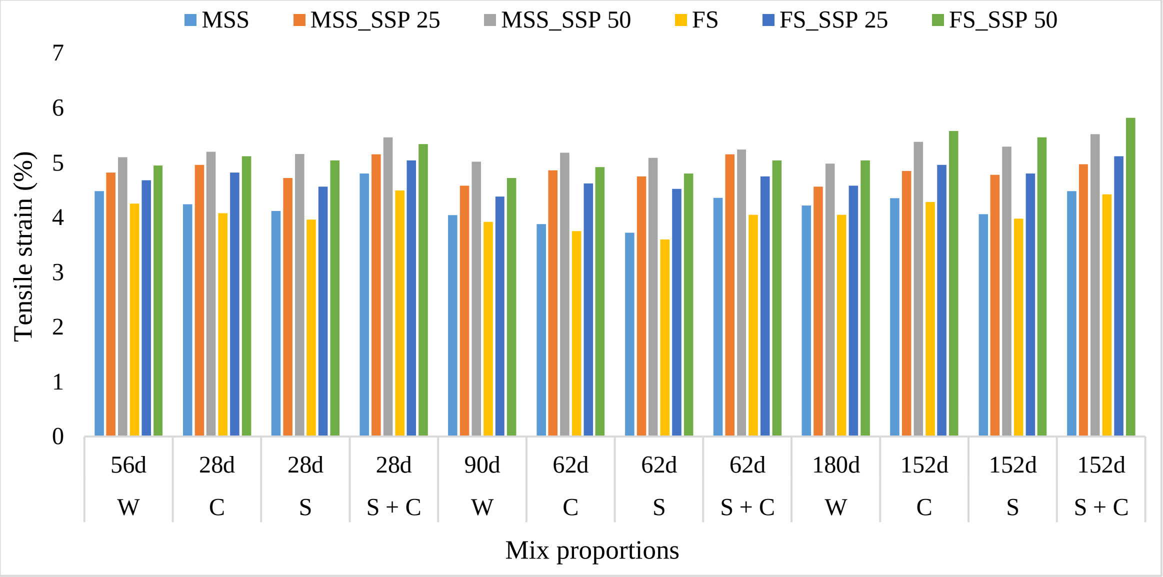


Figure 7. Tensile strain under different environmental conditions at various ages

CONCLUSIONS

This paper experimentally describes the durability performance of various ECC mixes containing SSP. The influence of 25% and 50% SSP as subrogation of micro silica sand and fine sand were investigated through CS, TS, ER and tensile strain characteristics under chloride, sulphate and combined chloride-sulphate environment. The specific conclusions of this comprehensive appraisal are summarized below:

- CS, TS, ER and tensile strain of fully MSS and FS blended mixes decreased after 28 days and 62 days exposure under various aggressive environments. Pozzolanic reactions of GGBFS in long term diffused the chemical ions after 152d exposure and enhanced the performance of fully MSS and FS blended mixes under various aggressive environments.

- The ER of fully MSS blended mix was higher than fully FS blended mix under laboratory and aggressive environment conditions. ER of MSS blended mix was higher due to less voids present with micro size of silica sand than fine sand.
- Utilization of SSP along with both types (MSS & FS) of sand filled the micro voids of cement matrix and improved the compressive, tensile and electrical performance of the mixes under water curing as well as under chemical exposure.
- The ER of fully sand (MSS & FS) containing mixes decreased under aggressive environments. ER of SSP containing mixes was not affected under chloride, sulphate and combined chloride-sulphate solutions. The ER of various mixes revealed that corrosion chances are negligible in ECC.
- Performance of various mixes revealed that the aggressive environments affect the fully FS containing mix more than others due to higher particles size of FS, which makes the porous structure than MSS and SSP.
- Results from various chemical immersion revealed that sulphate attack is more serious than chloride attack; in combined attack the presence of chloride mitigates the sulphate ions, which is responsible for enhancement under combined chemicals exposure.
- Micro size particles of SSP when mixed with water in cement matrix, act as a gel and filled the micro voids present on the surface of hydrophobic nature of PVA fiber, which makes the cement matrix structure denser and protects the fiber surface from various aggressive substances thus responsible for the enhancement in various mechanical properties (CS, TS, ER and tensile strain) under different chemical exposures. The performance of SSP blended mixes as partial subrogation of each type sand remains durable after 28d, 62d and 152d exposure.

Finally, the experimental results from this research demonstrated that SSP containing ECC remains durable under different aggressive environments. The use of SSP as sand in various ECC mixes enhanced the mechanical and durability performance of ECC under aggressive ions. The performance of various mixes revealed that SSP containing ECC can be applied in hydraulic structures under different environment loadings. The present investigation recommends that the SSP can be used up to 50% subrogation along with MSS and FS. Use of SSP in ECC mix solve the problem of utilization of stone waste and saves the natural resources up to some limit, which gives promising effect on eco-friendly nature of environment.

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