Durability Studies on Conventional Concrete and Slag-Based Geopolymer Concrete in Aggressive Sulphate Environment

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Abstract

As a potential substitute to conventional concrete, slag-based geopolymer concrete can be a promising material towards green and low carbon building approach. However, the lack of understanding of its performance subjected to sulphate environment can prohibit its use to some extent. This study examines the properties of conventional concrete exposed to a severe sulphate environment in comparison to slag-based geopolymer (SGPC). Plain cement concrete (PCC) also known as conventional concrete was cast using ordinary Portland Cement (OPC) as a binder. The durability of both types of concrete was examined by immersing test specimens in sulphate solutions (for varied salt concentrations of 2 and 4 g/l) for different curing ages up to a year. The performance of both types of concrete was studied for both mechanical and durability properties. Mechanical properties included compressive, tensile and flexural strengths (FS), while durability consisted of sorptivity, chloride diffusion, corrosion, EDS and SEM studies. The outcomes of this study revealed that the compressive (CS) and split tensile strengths (STS) of both OPC and SGPC decreased with the increase in magnesium sulphate salt concentrations and curing age. After being exposed to a 4% sulphate solution for 365 days, a decrease in the compressive strength was observed by 36.53% in SGPC and 55.97% in OPC, and a similar trend was found for the FS and STS. Rapid chloride permeability (RCPT) and sorptivity test results showed an increased diffusion with age and thus supported the findings of the compressive strength. Micro-structural properties were also studied, and observations showed that the formation of Sodium alumino-silicate hydrate (N-A-S-H) and Calcium alumino-silicate hydrate (C-A-S-H) was more obvious with the curing age in SGPC. At the same time, C-S-H gel formation decreased in conventional concrete with an increase in sulphate salt concentration. The cumulative effect of all these factors led to a much

higher corrosion rate of rebars embedded in conventional concrete than in SGPC. Therefore, slag-based geopolymer concrete performed better than conventional concrete in an aggressive sulphate environment for all curing periods.

Keywords: Slag-based geopolymer concrete (SGPC); Compressive strength; Tensile strength; Flexural strength; Chloride diffusion; Sorptivity; Polarization resistance.

Abbreviations

Calcium silicate hydrates:	C-S-H
Calcium alumino-silicate hydrate:	C-A-S-H
Coarse Aggregate:	CA
Compressive Strength:	CS
Energy Dispersive Spectroscopy:	EDS
Fine Aggregate:	FA
Flexural Strength:	FS
Global warming potential	GWP
Ground granulated blast-furnace slag:	GGBFS
Ordinary Portland Cement:	OPC
Rapid chloride permeability:	RCPT
Scanning electron microscopy:	SEM
Slag-based geopolymer concrete:	SGPC
Sodium alumino-silicate hydrate:	N-A-S-H
Tensile Strength:	TS
Ultrafine Slag:	UFS

1. Introduction

Concrete is the most extensively used construction material in the present scenario for rapid infrastructure development (Mustakim et al. 2021) as its demand approaches to 30 billion metric tons and it remains the main material used worldwide (Vázquez-Rowe et al. 2019). Concrete is often made from locally accessible resources such as cement, water, sand, and aggregates, with matrix cement serving as a binding agent (Edser 2005). Portland cement in conventional concrete used as binding material has several drawbacks. The production of traditional Portland cement (PC)-based concrete is energy-intensive (Malhotra 2010) and adds to greenhouse gas emissions by emitting roughly 5–7% of total CO_2 worldwide, which may climb by 50% in the future from current levels (Joseph et al. 2012). This fact shows that cement is not an environmentally-friendly material for long-term use because of its high energy consumption and CO_2 emission. Meanwhile, GBFS is advantage over conventional concrete as it has 44.70% lower global warming potential (GWP) (Barcelo et al. 2014; Robayo-Salazar et al. 2018). Clinker is created at temperature of approximately 1400^0C, therefore, the energy required to achieve this temperature results for roughly 5% of worldwide CO_2 emissions (Malhotra 2010). Also, according to International Energy Agency, 0.81 kilogram of CO_2 produced for every kilogram of cement produced globally each year (Hendriks et al. 2003) which causes green- house affect. Further, durability of conventional concrete in an aggressive environment has been still questionable, and it has been a major concern of many standard guidelines to ensure concrete's durability.

A new type of concrete coined geopolymer concrete has attracted a lot of interest from researchers as it utilizes waste materials such as fly-ash, ground-granulated blast-furnace slag (GGBFS), etc. and does not require much energy in its production (Pasupathy et al. 2021). Geopolymer materials are well known for having low embodied energy and low carbon emissions, and as a result, they are considered a viable substitute material for ordinary Portland cement (OPC) in conventional concrete. Previous studies also showed that a combination of rise husk and fly ash with OPC in a binder matrix, cured under a hot air curing (HAC) condition, gave the best compressive and flexural strengths with lower water absorption (Aljerf, 2015). The results reported in the recent past about its strength like compressive strength, flexural and split tensile strengths and durability properties under aggressive environments (Albitar et al. 2017; Jindal et al. 2018; Punurai et al. 2018) are also encouraging.

The industrial waste product such as slag used to make geopolymer concrete primarily high in silica and alumina is activated by an alkali solution containing sodium/potassium (Mustakim et al. 2021). In a previous study, it was discovered that the polymerization of geopolymer concrete was significantly influenced by alcofine (Parveen et al. 2018). Polymerisation is basically responsible for enhanced strength and dense microstructure. The study also showed that geopolymer concrete can obtain strength comparable to those of regular Portland and mixed-cement concrete even at room temperature. Muhammed et al. (2022) also studied the ultimate load of different types of reinforced concrete columns attacked by sulphate. Balamuralikrishnan and Saravanan (2021) studied the effect of addition of alcofine on the compressive strength and concluded that the addition of alcofine increases the strength. Thanh et al. (2022) studied the compressive strength of GPC using sea sand and sea water mixture and concluded that GPC concrete has a higher compressive strength than that of conventional concrete. Durability studies on geopolymer concrete exposed to aggressive environment also have been studied. Previously researcher also examined the performance of geopolymer concrete when exposed to acid solution (5% solution of acetic and sulfuric acid both) (Bakharev 2005b). It was observed that when GPC was prepared with sodium hydroxide and cured at elevated temperature, its performance was superior to conventional concrete in term of weight change, compressive strength and microstructural changes. When all the specimens were exposed to different sulphate environments (5% sodium sulphate and magnesium sulphate respectively and 2.5% sodium sulphate and 2.5% magnesium sulphate), the best performance was observed in geopolymer concrete. These specimens had 4-12% increase in strength when immersed into sulphate solution. The investigation period in these studies was, however, limited to short period of 9 months. It is still necessary to verify the material's long-term durability, particularly with regard to the protection of the reinforcing steel. Previous studies also indicated that sulphate environment or aggressive environment is more critical for durability prospective (Souza et al. 2020) and rendering rebars more susceptible to corrosion in case of conventional reinforced concrete. Therefore, this study has been undertaken to fill the gap and study the durability properties up to a period of one year in accelerated marine sulphate environment. Attempts have further been made to discuss the difference in mechanism in SGPC and conventional concrete.

The present study investigates the mechanical and durability properties of slag based geopolymer concrete (SGPC) and OPC concrete under an aggressive sulphate environment for one year. SGPC can be considered a sustainable material due to its low carbon emissions. This material can solve the environmental problems due to dumping of industrial wastes. Considering such issues and global demand of sustainable and durable products, this research intentionally introduces young researchers and industrialists an alternatve product to conventional concrete. It is noted that geopolymer concrete has been developed in the field, there are numerous studies which explain the properties of GPC, but there is far more limited studies available in the literature which explore the performance of GPC in a aggressive environment for a long period. Furthermore, only basic data are available in public domain regarding strength and durability properties of SGPC in aggressive environments. This study, therefore, fills these research gaps.

2. Materials and methods

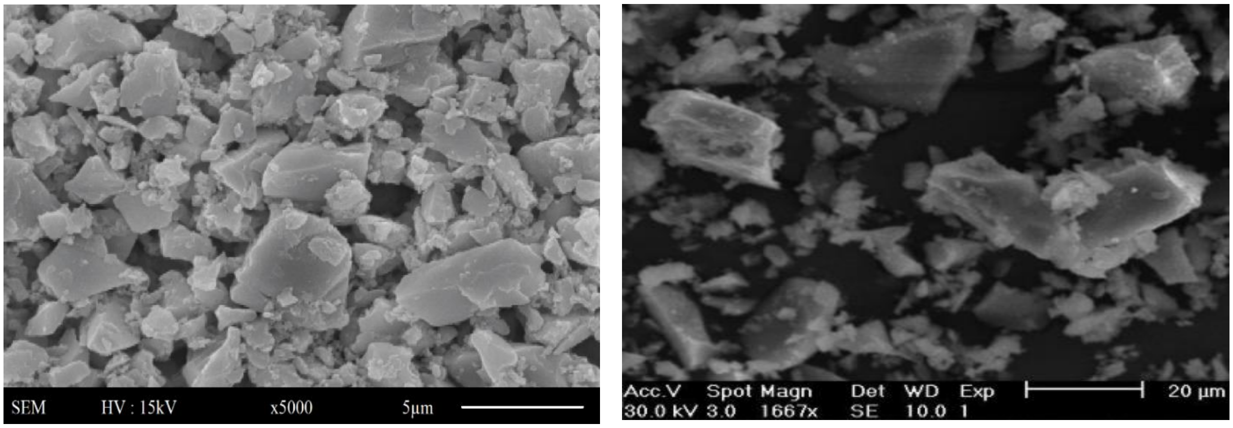
The properties of materials and methodologies used in this study are discussed below.

2.1 Materials

The chemical compositions of OPC and GGBFS (Ground granulated blast-furnace slag) are given in Table 1. Scanning electron microscopy (SEM) was used to determine the particle shapes of OPC and GGBFS, as shown in Fig 1.

Table 1 Chemical composition of OPC and GGBFS (by weight).

Chemical composition	CaO	Al_2O_3	SiO_2	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	LOI
OPC	66.24	4.48	18.02	4.31	1.42	0.42	0.06	3.62	1.43
GGBFS	41.20	13.60	38.70	2.0	3.75	---	0.12	0.20	0.55



(a) OPC (b) GGBFS

Fig. 1 SEM images of OPC and GGBFS.

The coarse and fine aggregates complied with the requirements of IS 383 2016 (Bureau of Indian Standards 2016). The specific gravity of coarse aggregates (CA) and fine aggregates (FA) was tested and found to be 2.64 and 2.61, respectively. The coarse aggregates were of 14 mm mean particle size.

2.2 Sample preparation and testing

In current study, specimens of OPC and SGPC were cast as cubes of 150 mm for the compression tests, prism of 100 x 100 x 500 mm for flexural tests and cylinders of sizes 300 x 150ϕ mm for split tensile tests. For Rapid Chloride Permeability Test (RCPT) and sorptivity testing, cylinder samples of sizes 100 x 50ϕ mm and 70 x 30ϕ mm were prepared, respectively. Also, for the determination of polarization resistance, cube samples of 150 mm were cast with a steel rod at its center and potential (mV) was measured for 200 s. To compare the mechanical and durability properties, OPC and SGPC samples were cast for the target strength of 38.25 MPa, corresponding to M30 grade as per IS:456 2000 (Plain and Reinforced Concrete - Code of Practice 2000). Clause 8.2.8 of IS:456 2000 (Plain and Reinforced Concrete - Code of Practice 2000) further suggests minimum M30 grade concrete in a sea environment. The mix of OPC was designed following IS:10262 2019 (Concrete mix Proportioning – Guidelines 2019), and Parveen and Singhal (2017) proposed the mix design procedure and for GPC concrete. Accordingly, SGPC with the activation's molarity M12 was designed with the help of available literature (Parveen et al. 2017).

For preparation of SGPC, ultrafine slag (UFS) named as alcofines was used as a binder. The mix proportioning is summarized in Table 2 and a systemic testing flow chart is shown in Fig. 2.

Table 2 Mix design proportions used.

Mix	**M1-OPC***	**M2-SGPC***
OPC (kg/m^3)	365	-
GGBFS (kg/m^3)	-	320
Ultrafine slag (kg/m^3)	-	80
Sand (kg/m^3)	700	522
Coarse Aggregate (kg/m^3)	1200	1240
AAL/binder ratio	-	0.45
AAL (kg/m^3)	-	180
NaOH (kg/m^3)	-	51
Na_2SiO_3 (kg/m^3)	-	129
Na_2SiO_3/NaOH	-	2.5
Water (kg/m^3)	160	28
Admixture (%)	1.5	1.5

Notes:

M1-OPC: Mix 1 with ordinary Portland cement

M2-SGPC: Mix 2 slag-based geopolymer concrete

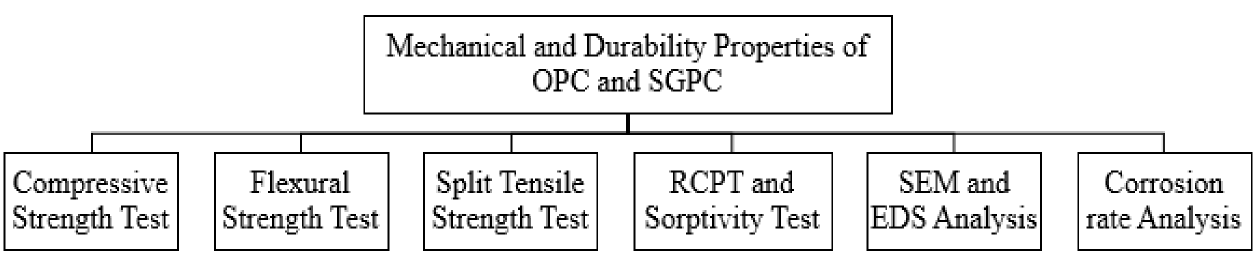


Fig. 2 Systemic testing flow chart.

The specimens were cast and cured at room temperature, i.e. 25±3^{0}C. The specimens were filled in three layers, and compaction was done through a table vibrator. Specimens were taken out of the mold 24 hrs after the casting and then cured in water and in $MgSO_4$ solutions containing 2 and 4g/l salt, respectively.

To examine the performance of OPC and SGPC during the fresh stage, workability tests were performed by using slump and compaction factor tests. The compressive, flexural, and split tensile tests of OPC and SGPC were performed at ages 7, 28, 56, 90, 180, 270, and 365 days as per IS: 516:2018 (Methods of Tests for Strength of Concrete 2018). The strength in all the discussions had been the average of five identical specimens. Rapid chloride permeability (RCPT) and sorptivity tests were also conducted at these curing ages as mentioned for compressive strength test except at 7 days. SEM and EDS studies and measurements of the corrosion rate were conducted at 180 and 365 days. For the durability study, the specimens were submerged in the solutions for half of the depth in order to expedite the corrosion process. A previous study suggested that the concentration of chloride slats in sea water varies from 3.96 to 23 g/l with an average of 19 g/l (Buenfeld et al. 1984). A previous study also showed that the concentration of sulphate salts in sea-water varies from 0.58 to 4 g/l with an average of 2 g/l (Liptak 1974). Accordingly, this study adopted the concentration of sulphate of 2 or 4 g/l. Therefore, submerging the specimens to half of the depth in solutions containing twice the average sulphate salt concretion of sea-water covered would simulate one of the critical condition of durability of climatic variation.

3. Results and discussion

3.1 Workability

Fig. 3 shows the workability of the conventional concrete (M1-OPC), and slag-based geopolymer concrete (M2-SGPC) in terms of slump (mm) and compaction factor values.

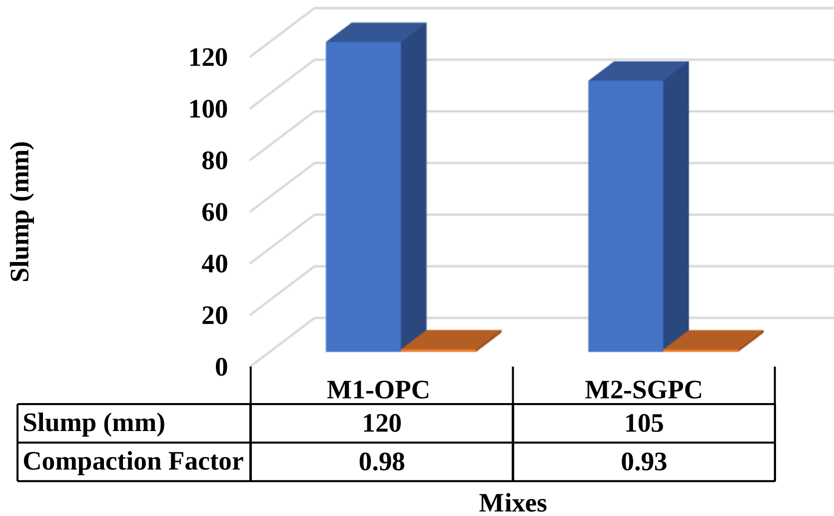


Fig. 3 Slump and Compaction factor of different concrete mixes.

The maximum slump (120 mm) and compaction factor (0.98) were observed in OPC, while SGPC showed a bit lower slump and compaction factor values (105 mm and 0.93, respectively). The viscosity of the alkaline solution used in SGPC may be the reason for the reduction in slump and compaction factors. Slump values more than 100 mm and compaction factor greater than 0.9 in SGPC indicated that GPC mixes are workable despite the fact that water content in GPC mixes was much less than OPC. Higher finer particles in GPC lead to lower workability as reported in a previous study (Patankar et al. 2013). Based on the workability test, it can be stated that both conventional and geopolymer concrete were workable as per Indian Standard guidelines.

3.2 Compressive strength

In order to study mechanical properties, the compressive strength of both conventional and geopolymer concrete was determined at different ages as discussed above in both normal and aggressive environment.

3.2.1 Compressive strength of water cured concrete samples

The compressive strength of both OPC and SGPC cured in water is shown in Fig. 4. It can be seen from the figure that the compressive strength increased with age, and the compressive strength of SGPC was higher than that of OPC. The compressive strength (46.25 MPa at 28 days) was observed in M2-SGPC, while concrete with OPC (M1-OPC) showed a lower compressive strength (41.33 MPa). The percentage increase in the compressive strength after 7 days was considerable for both; however, it was no longer significant after 28 days. For example, M1-OPC and M2-SGPC showed an increase of 49.25% and 38.88%, respectively, in the compressive strength at 28 days when compared with those at 7 days. It can be also concluded from the figure below that SGPC maintained higher strength throughout all the curing periods.

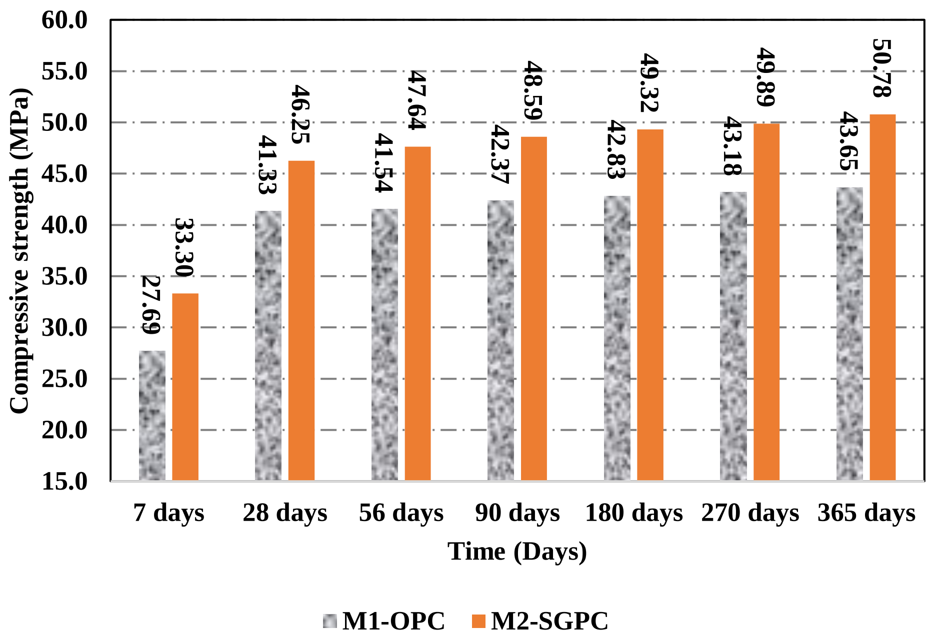


Fig. 4 Compressive strength (CS) of water-cured concrete mixes.

3.2.2 Compressive strength of concrete exposed to $MgSO_4$ concentrations(2 and 4 g/l)

The effects of $MgSO_4$ concentrations (2 and 4 g/l) on the compressive strength of different mixes were studied and have been shown in Fig. 5.

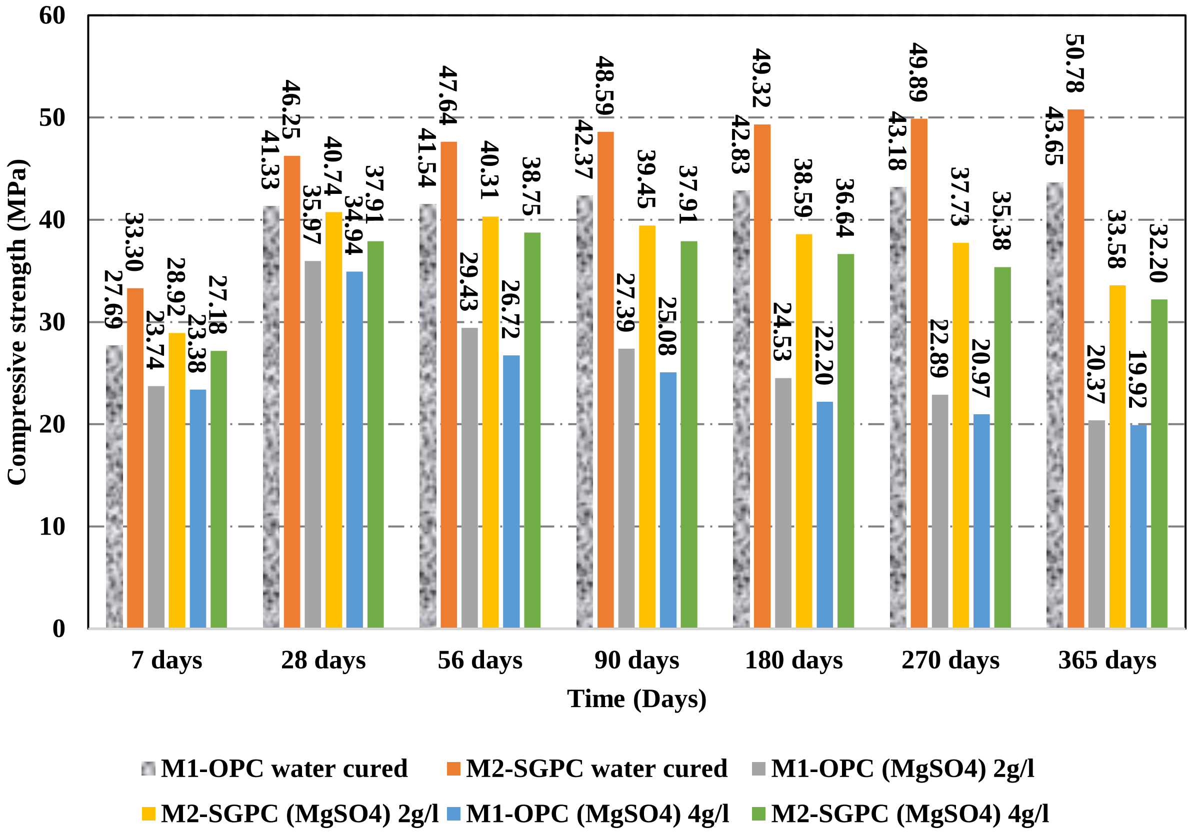


Fig. 5 Compressive strength after exposure to a sulphate environment.

When samples were exposed to $MgSO_4$ solution, a noticeable drop in the compressive strength was observed for both the cases of OPC and SGPC after the curing age of 28 days with respect to water cured specimens. During the curing phase, the compressive strength M1-OPC samples decreased by a higher proportion than slag-based geopolymer concrete. Table 3 shows the percentage decrease in the compressive strength of OPC and SGPC samples.

Table 3 Percentage decrease of the compressive strength in sulphate environment.

Mix	Curing period	Water cured sample compressive strength (MPa)	Compressive strength (MPa) of specimens exposed to $MgSO_4$ (2 g/l)	% decrease in Compressive strength (MPa)	Compressive strength (MPa) of specimens exposed to $MgSO_4$ (4 g/l)	% decrease in Compressive strength

M1-OPC	28 Days	41.33	35.97	12.97	34.94	15.46
	365 Days	43.65	20.37	53.33	19.22	55.97
M2-SGPC	28 Days	46.25	40.74	11.91	37.91	18.03
	365 Days	50.78	33.58	33.81	32.2	36.53

The percentage drop in the compressive strength of M1-OPC was 55.97% after 365 days (in 4g/l solution) when compared with water cured samples, while M2-SGPC showed better performance (36.53% decrease in the compressive strength after 365 days at 4g/l) and this might be due to the formation of a considerably denser microstructure of SGPC in presence of alcofines (UFS), which is confirmed in the following SEM analysis.

3.3 Flexural and split tensile strengths of concrete exposed to MgSO4 concentrations (2 and 4 g/l)

Figs. 6 (a) and 6 (b) show that the flexural and split tensile strengths follow the exact trend of the compressive strength results. A high $MgSO_4$ concentration, i.e. 4 g/l, resulted in a more significant strength drop for both M1-OPCand M2-SGPC when compared with the specimens cured in $MgSO_4$ concentration of 2 g/l. Similar results have also been reported by Bakharev (2005a). This observation suggests that an increase in sulphate salt concentration resulted in a decrease in the concrete strengths at all ages, irrespective of their binding materials.

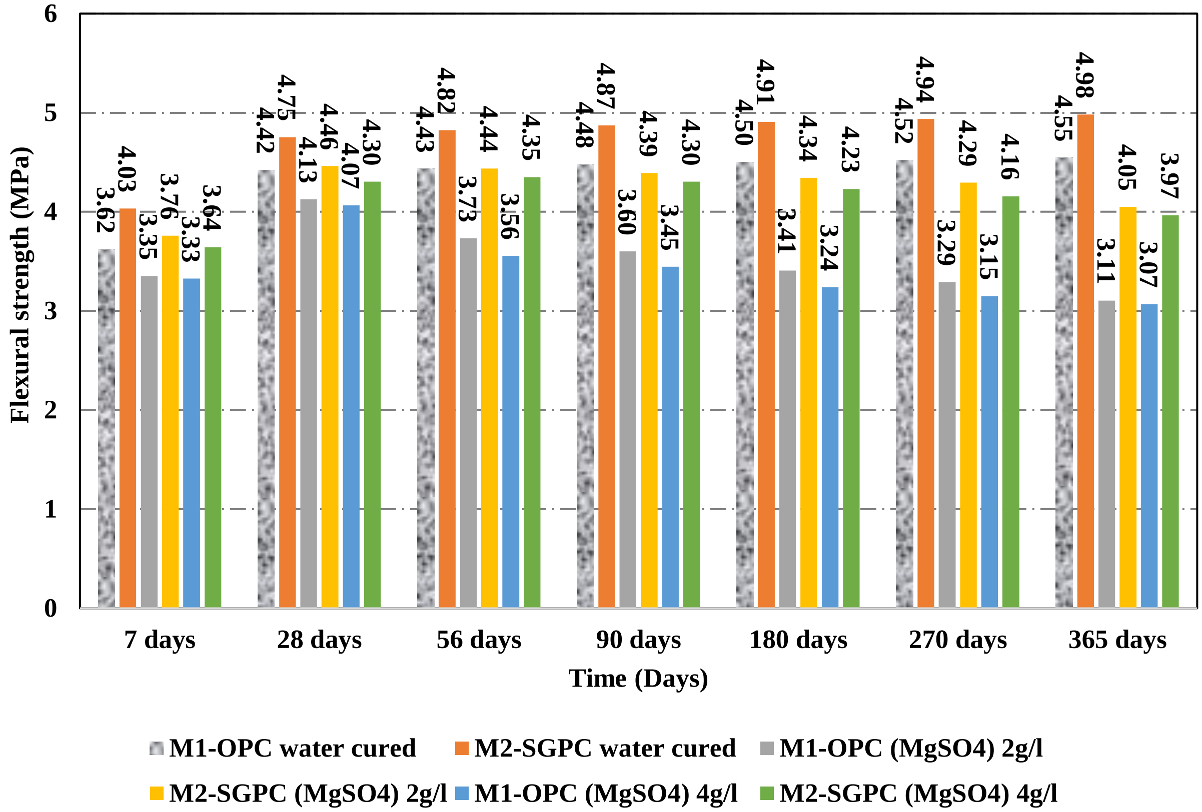


Fig. 6(a) Flexural strength of samples exposed to sulphate environment.

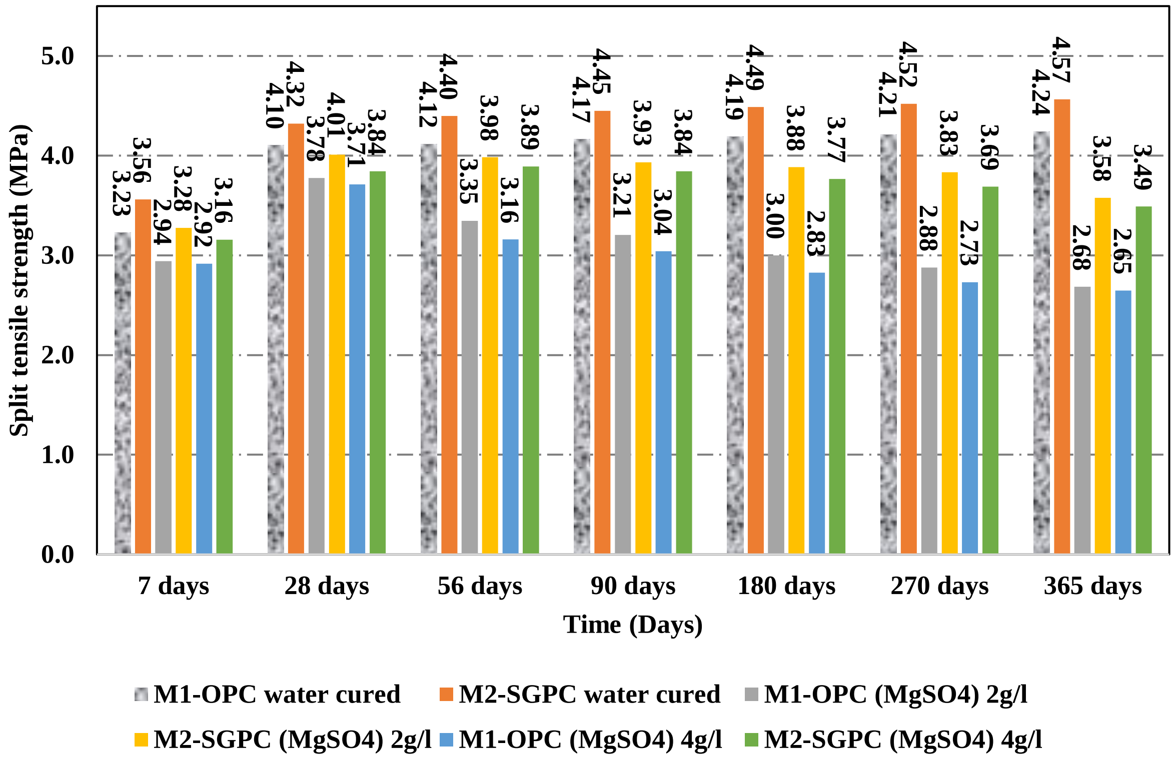


Fig. 6(b) Split tensile strength of samples exposed to sulphate environment.

The percentage drop in the flexural and split tensile strengths of M1-OPC samples when exposed to $MgSO_4$ (4 g/l) was 32.52% and 37.50% as compared with water cured specimens at the same age, respectively. Meanwhile, M2-SGPC submersed in the same sulphate solution showed a 20.28% and 25.26% drop in the flexural and split tensile strengths, respectively. It is obvious from the observation above, M2-SGPC exhibited better structural performance in an aggressive sulphate environment. This was attributed to the formation a much denser microstructure of SGPC in presence of alcofines (UFS), which enhanced geopolymeric gel synthesis as also observed in the previous study (Parveen et al. 2019).

3.4 Durability properties of slag based geopolymer (SGPC) and OPC

Durability investigations included RCPT tests, sorptivity, SEM and EDS studies, and polarization resistance for the specimens cured under sulphate are presented in this section.

3.4.1 Chloride penetration and sorptivity of water cured samples

The samples were exposed to an aggressive sulphate environment for examining their durability characteristics. Furthermore, RCPT test was also conducted on these specimens cured in the sulphate environment to study the permeability because durability of concrete significantly depends on its permeability. The mechanism for chloride transportation are attributed to (a) Diffusion (driven by concentration difference), (b) Permeation (driven by pressure difference) and (c) Migration (driven by voltage difference). The average RCPT values over five specimens are reported in Fig. 7(a). Furthermore, Fig. 7(b) presents the outcomes of sorptivity testing.

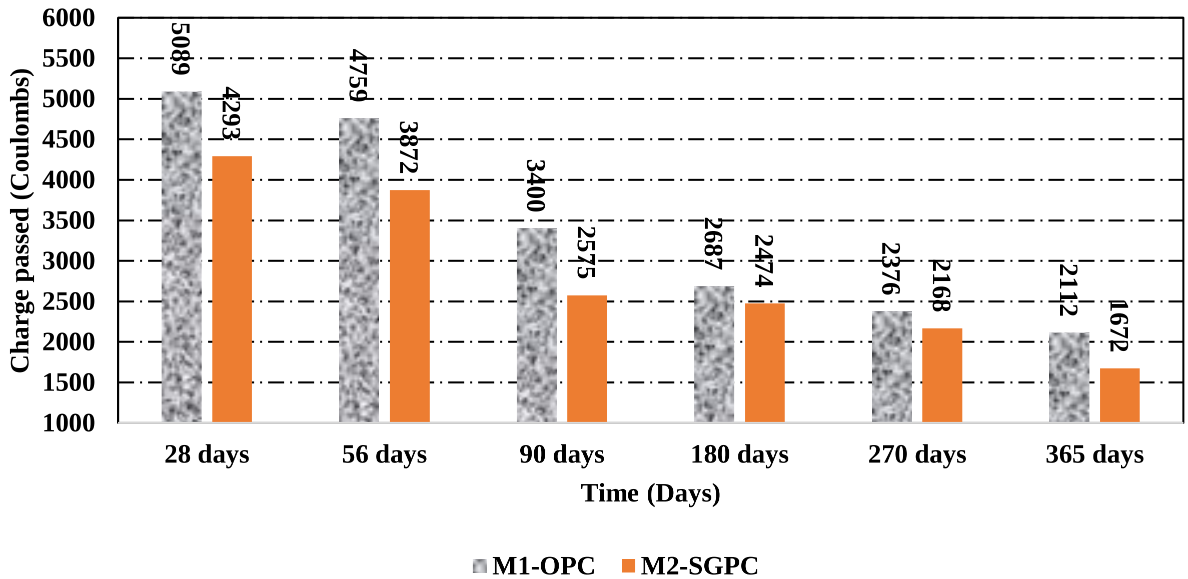


Fig. 7(a) RCPT values for the water cured concrete mixes.

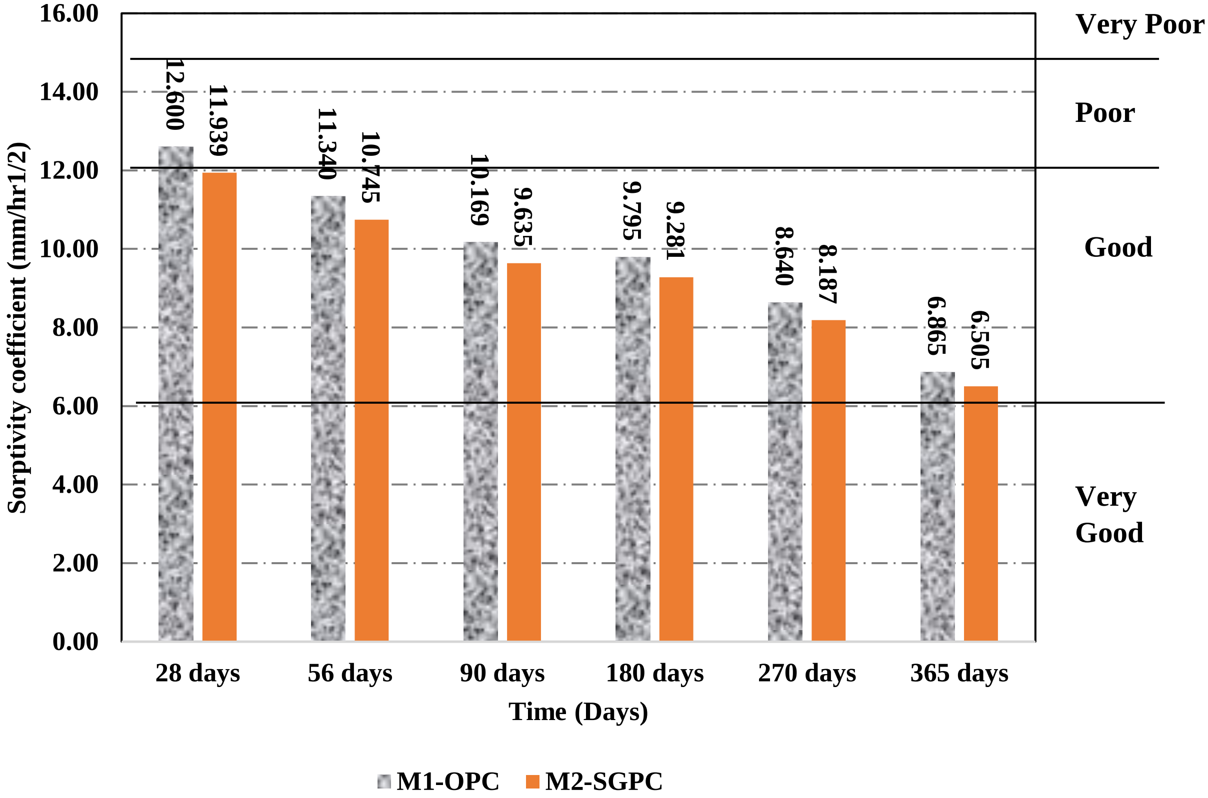


Fig. 7(b) Sorptivity coefficients for the water cured concrete mixes.

It is clear from the above figures that the charge passed in terms of coulombs and sorptivity coefficients decreased with the increase in age in all the specimens. The decrease in charge passed directly indicated that the permeability decreased with the increase in age. It is evident from these figures that the permeability of M2-SGPC concrete was lower than M1-OPC at all ages, which might again be due to better denser microstructure. The effects of adding nitrite- based inhibitor in OPC was also studied by Sangoju et al. (2015) who concluded that with the addition of calcium nitrite inhibitor there is reduction in the compressive strength of specimens. Also, there was an increase in RCPT values when compared with the control samples. This may be due to the high ionic nature of calcium nitrite inhibitor which causes more negative charges to pass through concrete (Sangoju et al. 2015).

3.4.2 Chloride penetration and sorptivity coefficient of concrete samples exposed to $MgSO_4$ (2g/l and 4g/l)

RCPT values were expected to increase when exposed to $MgSO_4$ solution as the exposure of $MgSO_4$ damages the cementitious properties as also observed in the previous study (Wee et al. 2000). The exposure of both M1-OPC and M2-SGPC in the sulphate environment increased the chloride permeability with the curing age. This trend was just opposite when compared with their respective specimens cured in water as shown in Fig. 8.

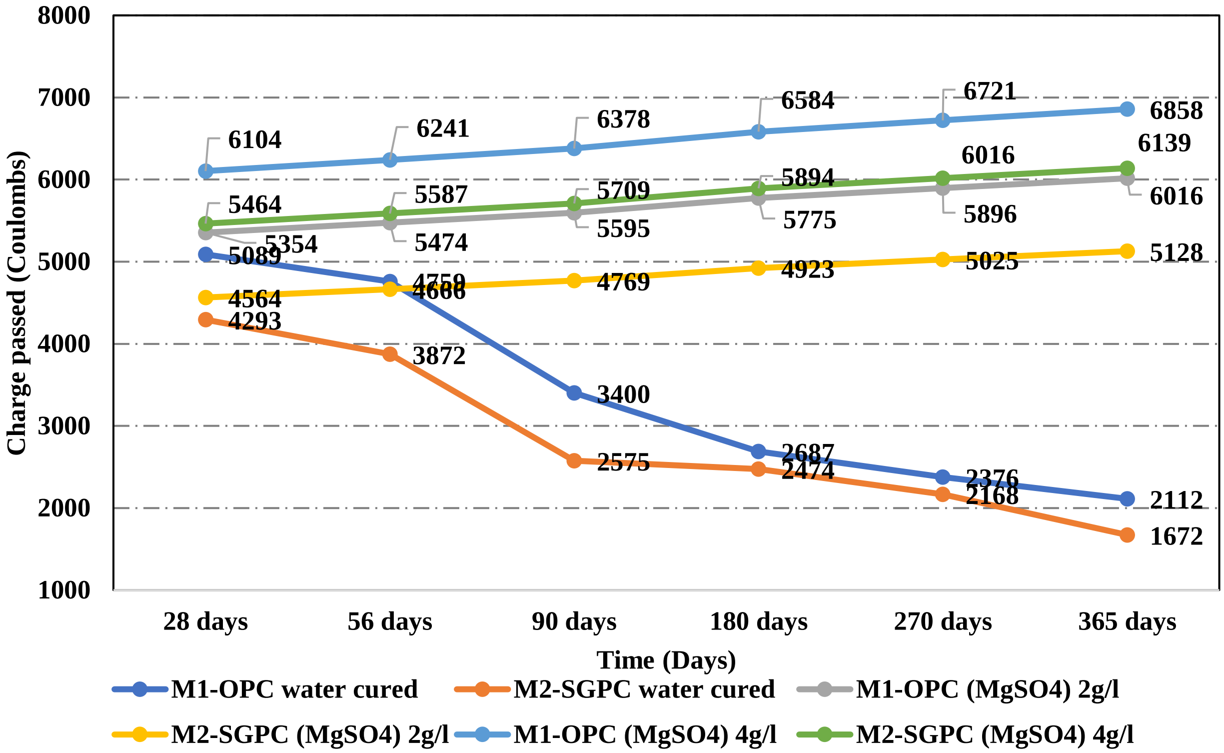


Fig. 8(a) RCPT values of different concrete mixes exposed to $MgSO_4$ (2 g/l and 4 g/l).

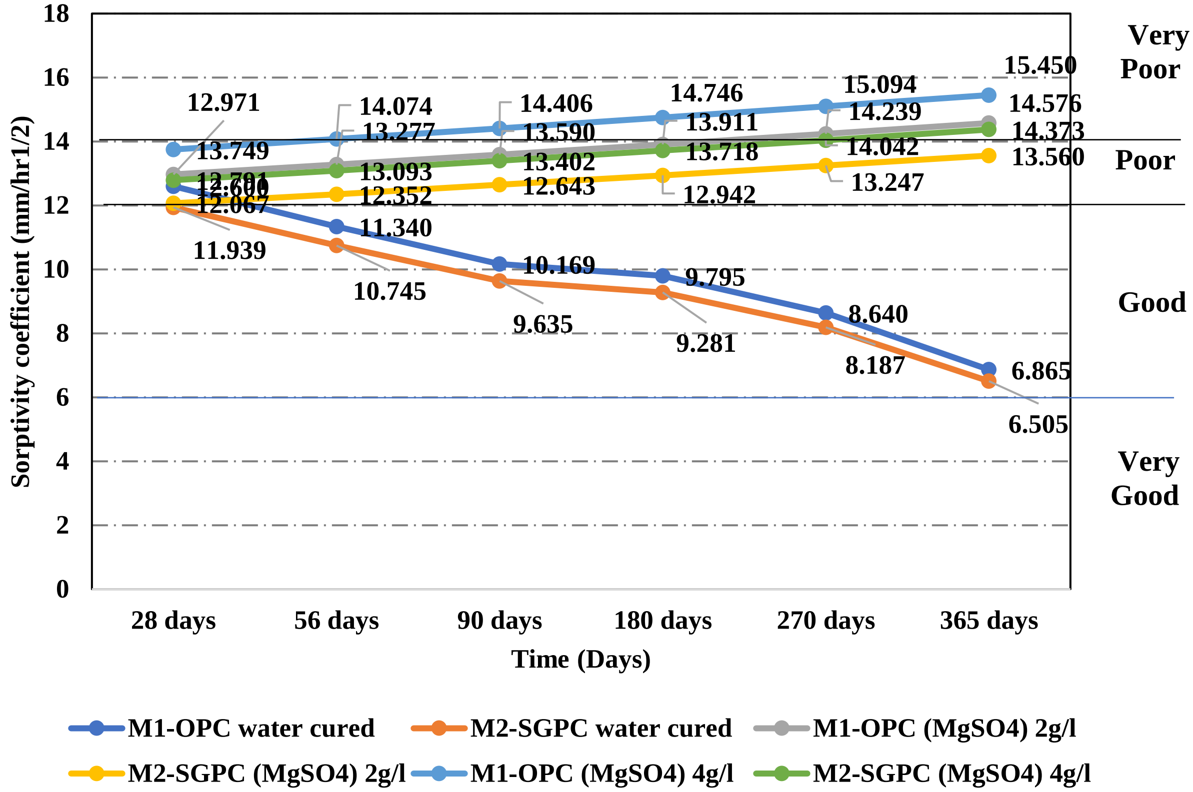


Fig. 8(b) Sorptivity coefficients of different concrete mixes exposed to $MgSO_4$ (2 g/l and 4 g/l)

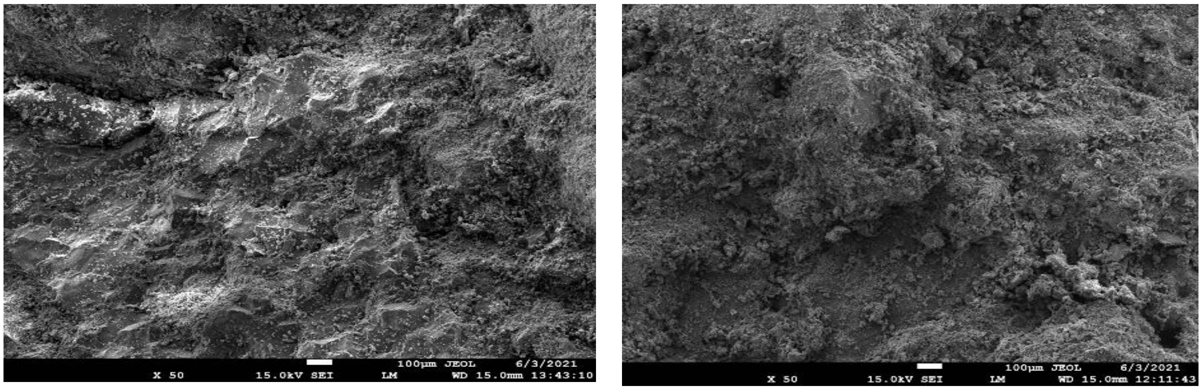
The permeability increased with the concentration of $MgSO_4$ solution. For example, when mixes of M1-OPC and M2-SGPC exposed to $MgSO_4$ (4 g/l) at 365 days are compared with the same mixes exposed to $MgSO_4$ (2 g/l) at 180 days, RCPT results show 6,858 and 6,139 coulombs and 6,584 and 5,894 coulombs, respectively. These results confirmed that permeability was higher when exposed to higher sulphate concentration. Fig. 8(a) further confirms that chloride permeability of M2-SGPC specimens remained lower than M1-OPC specimens throughout the curing period.

The same trend was observed in the sorptivity test. Sorptivity increased with the compressive strength and RCPT test results as predicted. Exposure to higher $MgSO_4$ concentration, i.e., 4 g/l, led to a substantial rise in sorptivity coefficients for both M1-OPC and M2-SGPC mixes, see Fig. 8(b). For example, when sorptivity of mixes M1-OPC and M2SGP exposed to $MgSO_4$ (4 g/l) at 365 days are compared with the same mixes exposed to $MgSO_4$ (2 g/l) at 28 days, it shows sorptivity coefficients of 15.45, 14.37 and 12.97, 12.06, respectively. Fig 8(b) also confirms that sorptivity coefficients were higher for the specimens exposed to higher $MgSO_4$ salt concentration. The rise in sorptivity coefficients of geopolymer concrete specimens with $MgSO_4$ exposure was lesser than that of OPC concrete specimens, making the SGPC more resistant to water permeation. A lower sorptivity of SGPC as compared to OPC has also been reported by Mathew and Usha (2016). The findings of the current study are also in line with the results reported by Gupta and Siddique (2020).

Above observations and discussions confirm that SGPC maintained better strength than OPC when exposed to sulphate environment at all curing periods. One of the reasons can be attributed to the less permeability of SGPC as compared to that of OPC as confirmed above with RCPT and sorpivity tests. Further, addition of alcofines in SGPC provided required strength even at room temperature, which was also reported by Saloni et al. (2020).

3.5 SEM and EDS analysis

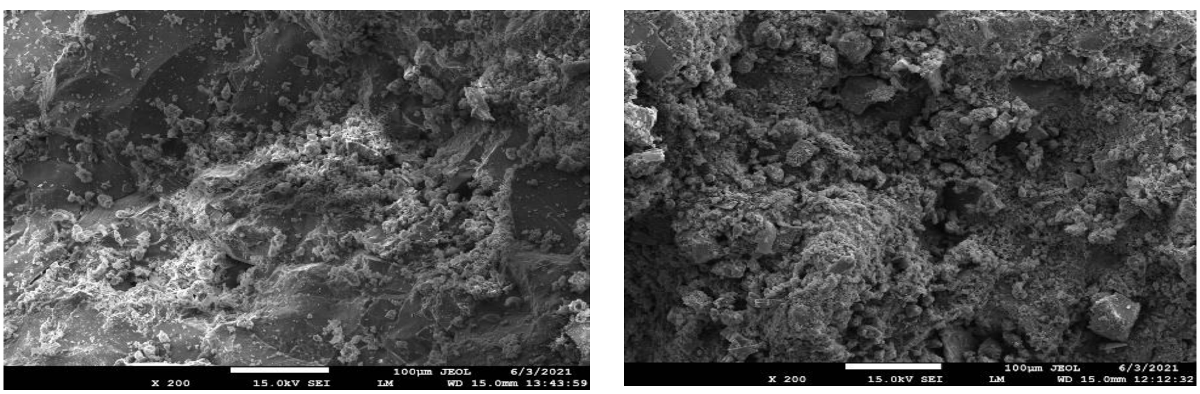
Figs. 9 -14 show SEM images and EDS test results of OPC and SGPC. M1-OPC was cast with OPC containing C_3S and C_2S. These compounds, i.e. C_3S and C_2S, when hydrates form crystalline $Ca(OH)_2$, floc, and hydrated calcium silicate gel before being subjected to a magnesium sulphate solution. During hydration of cement, C_3S and C_2S react with water and calcium silicate hydrate (C-S-H) is formed along with calcium hydroxide CH. This calcium silicate hydrates are the most important product for strength gain. It is the essence that determines the good properties of concrete. A heat increase happens due to the reaction between calcium silicate (C_3S and C_2S) which creates the silicate hydrate C-S-H. EDS study revealed that the main chemical product in the paste is C-S-H (calcium silicate hydrate) gel along with other products like NASH. Calcium silicate hydrate is indeed crucial component for extra strength gain in the geopolymer concrete. The maximum atomic percentage of silicon (Si) and calcium (Ca) were noticed.



Elements	O	Al	Mg	Si	S	Ca	Fe	Na	k	Ca/Si	Si/Al
M1-OPC Atomic %	58.95	1.28	0.84	9.75	1.82	25.79	1.57	----	----	2.65	7.62
M2-SGPC Atomic %	46.84	1.71	0.94	7.46	1.15	19.37	0.93	11.23	0.62	2.60	4.36

Fig. 9(a) Water cured OPC **Fig. 9(b)** Water cured SGPC

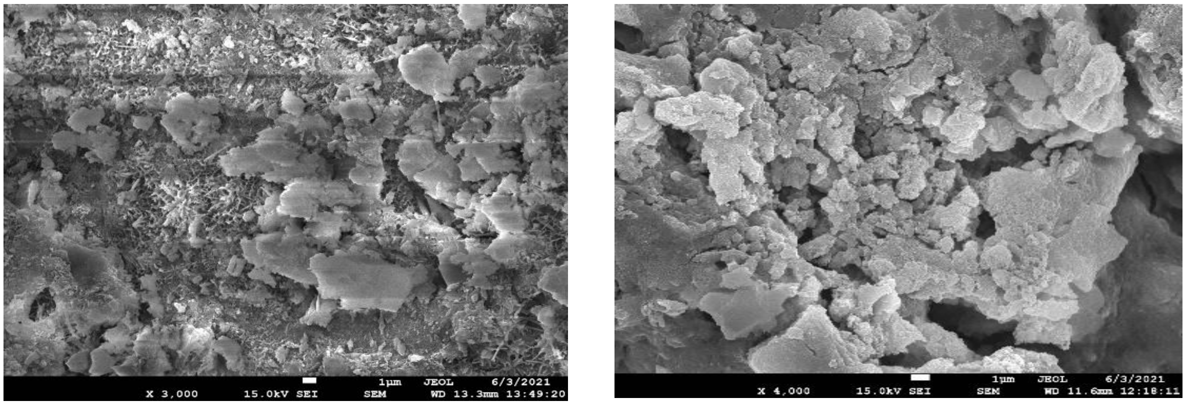
Fig. 9 SEM and EDS images of water cured concrete samples at 180 days



Elements	O	Al	Mg	Si	S	Ca	Fe	Na	k	Ca/Si	Si/Al
M1-OPC Atomic %	57.04	1.15	0.89	9.81	1.83	28.01	1.27	–	–	2.86	8.53
M2-SGPC Atomic %	47.15	1.38	0.94	6.63	1.07	20.05	0.92	11.98	0.51	3.02	4.80

Fig. 10(a) Water-cured OPC **Fig. 10(b)** Water-cured SGPC

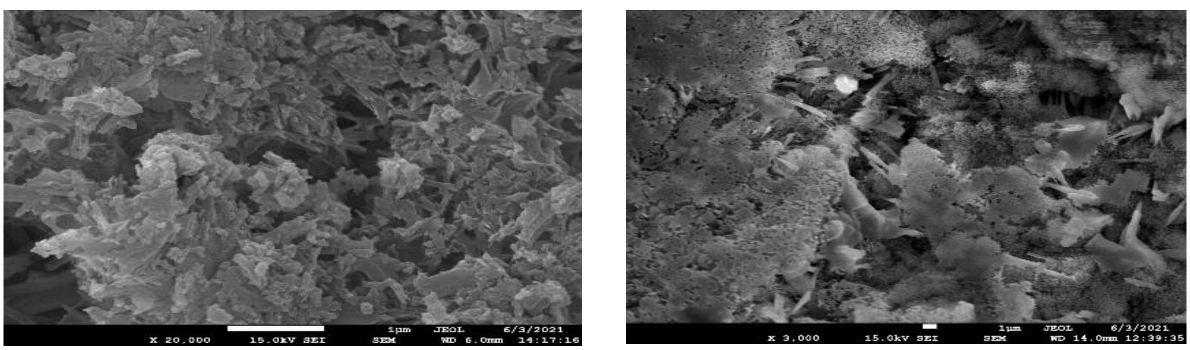
Fig. 10 EDS and SEM image of water cured concrete samples at 365 days



Elements	O	Al	Mg	Si	S	Ca	Fe	Na	k	Ca/Si	Si/Al
M1-OPC Atomic %	60.70	1.59	0.96	9.77	1.68	23.61	1.69	---	---	2.42	6.14
M2-SGPC Atomic %	51.34	1.76	1.1	7.32	1.25	14.76	0.95	10.03	0.62	2.02	4.16

Fig. 11(a) M1-OPC samples **Fig. 11(b)** M2-SGPC samples

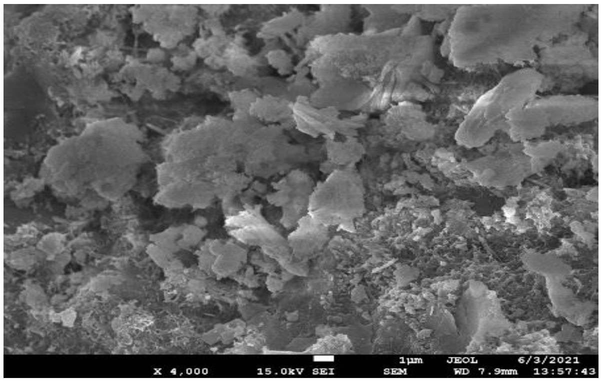
Fig. 11 EDS /SEM images of samples immersed in $MgSO_4$ (2g/l) solution for 180 days

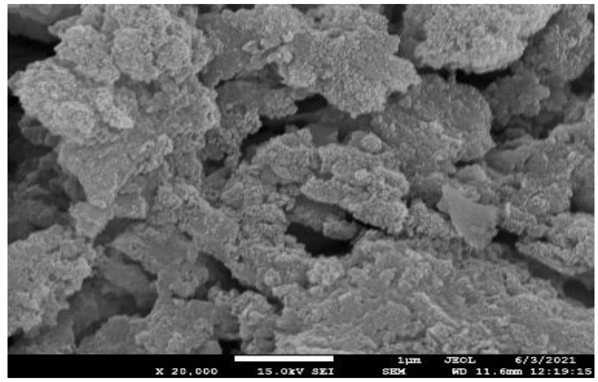


Elements	O	Al	Mg	Si	S	Ca	Fe	Na	k	Ca/Si	Si/Al
M1-OPC Atomic %	61.20	1.61	0.89	9.59	1.94	23.01	1.76	---	---	2.40	5.96
M2-SGPC Atomic %	54.27	1.79	0.91	7.36	1.19	13.58	0.93	9.51	0.63	1.85	4.11

Fig.12(a) M1-OPC samples **Fig.12(b)** M2-SGPC samples

Fig. 12 EDS /SEM images of samples exposed to $MgSO_4$ (4g/l) solution for 180 days

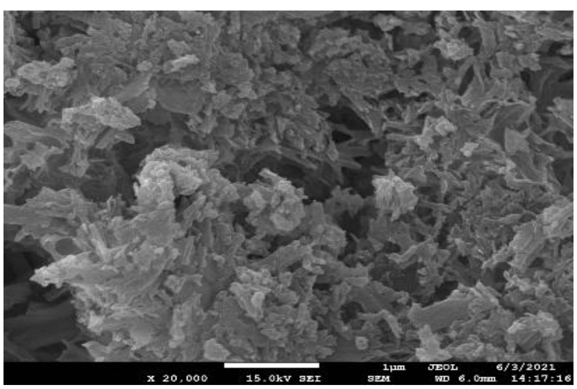


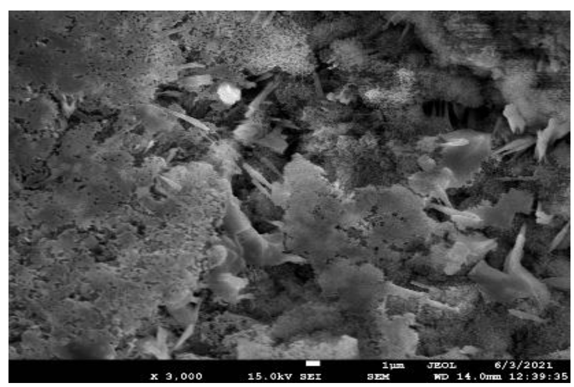


Elements	O	Al	Mg	Si	S	Ca	Fe	Na	k	Ca/Si	Si/Al
M1-OPC Atomic %	61.22	1.20	1.23	9.63	1.93	22.93	1.86	--	--	2.38	8.03
M2-SGPC Atomic %	54.79	1.53	0.94	6.89	1.07	14.01	0.92	9.56	0.92	2.03	4.50

Fig.13(a) M1-OPC samples **Fig. 13(b)** M2-SGPC samples

Fig. 13 EDS /SEM images of samples exposed to $MgSO_4$ (2g/l) solution for 365 days





Elements	O	Al	Mg	Si	S	Ca	Fe	Na	k	Ca/Si	Si/Al
M1-OPC Atomic %	63.06	1.23	0.96	9.8	1.68	21.3	1.97	--	--	2.17	7.97
M2-SGPC Atomic %	56.89	1.49	0.97	6.61	1.02	12.98	0.92	9.26	0.49	1.96	4.44

Fig.14(a) M1-OPC samples **Fig.14(b)** M2-SGPC samples

Fig. 14 EDS /SEM images of samples exposed to $MgSO_4$ (4g/l) solution for 365 days

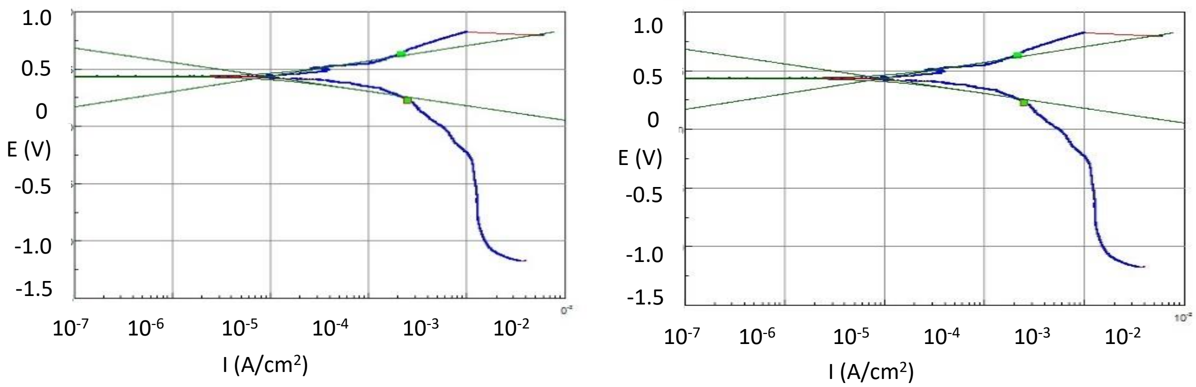
Figs. 9 and 10 show the SEM and EDS results of M1-OPC and M2-SGPC at 180 and 365 days when cured with water. A comparison of EDS results for OPC and SGPC specimens makes it clear that the total atomic percentage of Ca and Si in OPC were higher than that in SGPC. However, Na is the additional element found in SGPC; this confirms the formation of C-S-H gel in OPC and alkali-activated N-A-S-H in SGPC. Fig. 10 confirms that with an increase in age, Ca and Si contents increased in OPC, while in addition to Ca and Si contents alkali-activated N-A-S-H increased in SGPC. Although, it was quiet difficult to figure out the difference between the denseness of both the mixes but when we correlate SEM images (Fiq. 10) with compressive strength results then it can be confirmed that SGPC was denser than OPC. This fact has further been supported by the RCPT and sorptivity results.

When comparing with water cured samples (Figs. 11 to 14), EDS results showed that with an increase in salt concentration $MgSO_4$ (2g/l to 4g/l), the Ca/Si, and Si/Al ratio decreased at all ages. Also, the formation of C-A-S-H and N-A-S-H decreased in SGPC when specimens were exposed to sulphate salts, which explain the lower performance of SGPC when exposed to higher concentration of $MgSO_4$ for a longer period.

Furthermore, Si/Al and Ca/Si atomic ratios were calculated to better understand the different binders and matrices. The above observations suggest that the compressive strength increased with Ca/Si and Si/Al ratios, particularly for water cured specimens. However, the compressive strength decreased when samples were exposed to the $MgSO_4$ (2 g/l and 4 g/l) and SEM and EDS results confirmed this statement when showing decreased Ca/Si and Si/Al ratios. The above findings are in line of the tests results reported by other studies (Sasui et al. 2020). The results of the compressive strength are in well agreement with the EDS studies. High Ca/Si and Si/Al ratios boosted the development of calcium silicate-based compounds in the hybrid paste matrix, which mostly contributed to the increased strength (Saloni et al. 2021).

3.6 Corrosion rate analysis of OPC and SGPC

In order to study the corrosion rate of OPC and SGPC specimens exposed to sulphate environment, corrosion analysis was also conducted. The corrosion rate on steel bars embedded in concrete was measured using Potentiostat. The corrosion results of the samples were measured after 180 and 365 days and are shown in Figs. 15 to 20.



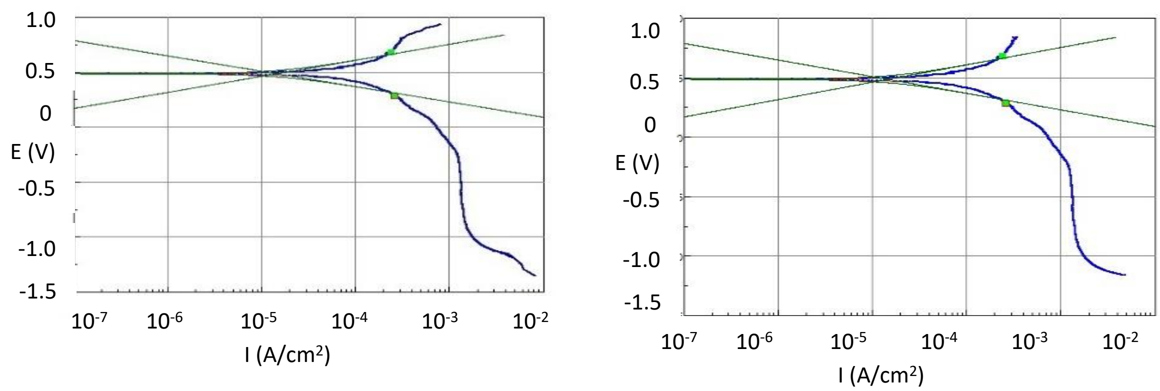
Corrosion rate (mm/a) = 0.095

(a) Tafel plot of water cured conventional concrete at 180 days

Corrosion rate (mm/a) = 0.082

(b) Tafel plot of water cured SGPC at 180 days

Fig. 15 Tafel plot of OPC and SGPC under water curing at 180 days



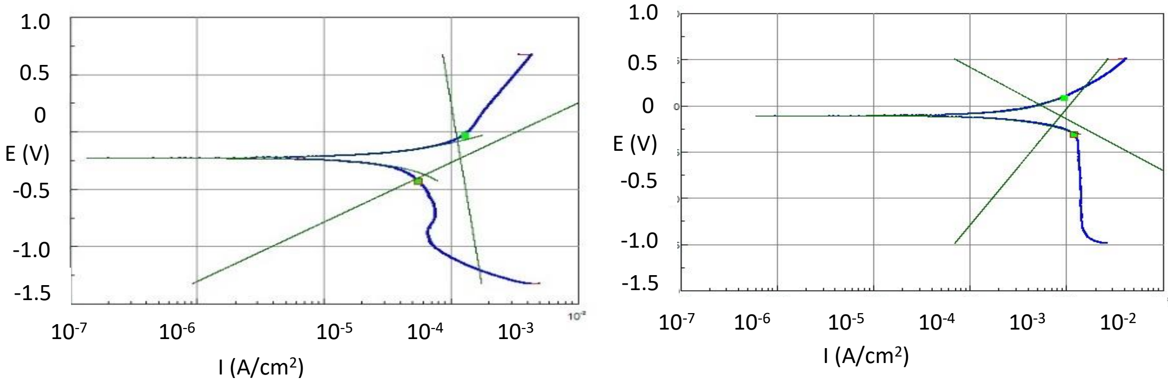
Corrosion rate (mm/a) = 0.098

(a) Tafel plot of water cured conventional concrete at 365 days

Corrosion rate (mm/a) = 0.087

(b) Tafel plot of water cured SGPC at 365 days

Fig. 16 Tafel plot of OPC and SGPC under water curing at 365 days



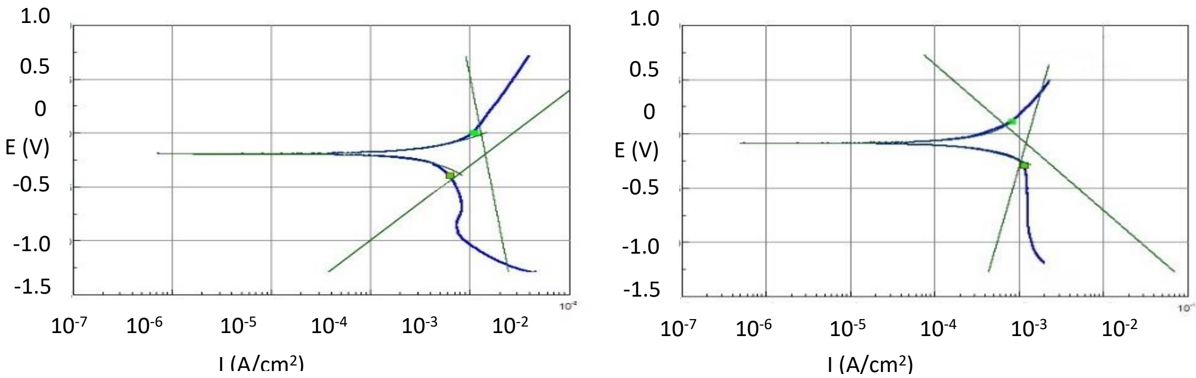
Corrosion rate (mm/a) = 0.615

(a) Tafel plot of M1-OPC concrete sample exposed to $MgSO_4$ (2 g/l) at 180 days

Corrosion rate (mm/a) = 0.569

(b) Tafel plot of M2-SGPC concrete sample exposed to $MgSO_4$ (2 g/l) at 180 days

Fig. 17 Tafel plot of OPC and SGPC under sulphate environment (2 g/l) at 180 days



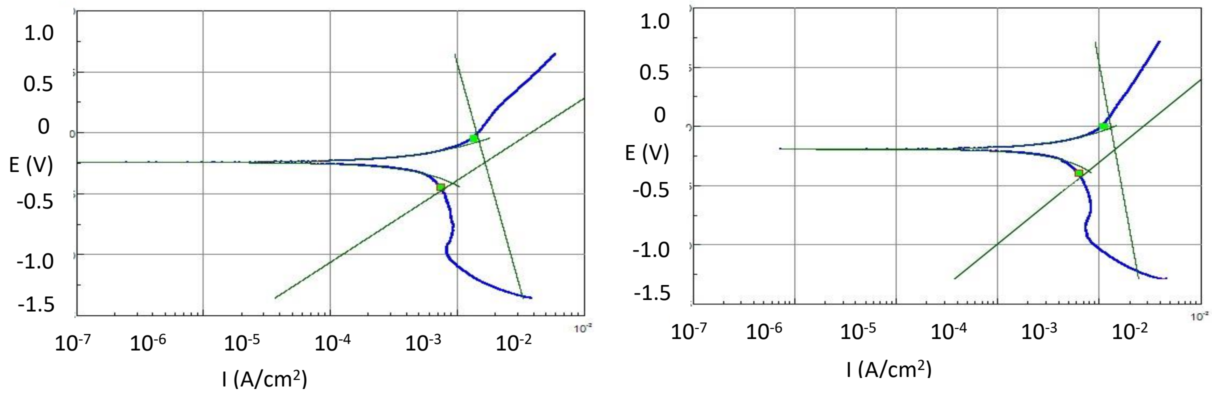
Corrosion rate (mm/a) = 0.675

(a) Tafel plot of M1-OPC concrete sample exposed to $MgSO_4$ (2 g/l) at 365 days

Corrosion rate (mm/a) = 0.598

(b) Tafel plot of M2-SGPC concrete sample exposed to $MgSO_4$ (2 g/l) at 365 days

Fig. 18 Tafel plot of OPC and SGPC under sulphate environment (2 g/l) at 365 days



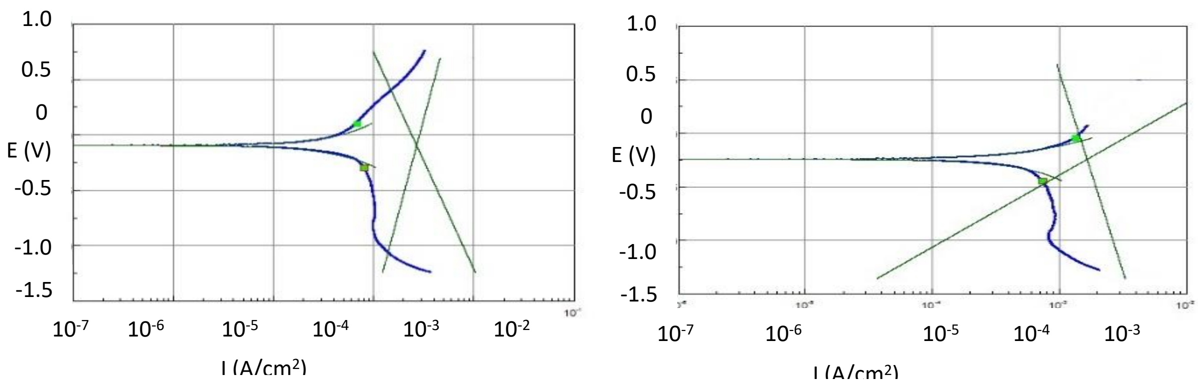
Corrosion rate (mm/a) = 0.628

(a) Tafel plot of M1-OPC concrete sample exposed to $MgSO_4$ (4 g/l) at 180 days

Corrosion rate (mm/a) = 0.608

(b) Tafel plot of M2-SGPC concrete sample exposed to $MgSO_4$ (4 g/l) at 180 days

Fig. 19 Tafel plot of OPC and SGPC under sulphate environment (4 g/l) at 180 days



Corrosion rate (mm/a) = 0.709

(a) Tafel plot of M1-OPC concrete sample exposed to $MgSO_4$ (4 g/l) at 365 days

Corrosion rate (mm/a) = 0.664

(b) Tafel plot of M2-SGPC concrete sample exposed to $MgSO_4$ (4 g/l) at 365 days

Fig. 20 Tafel plot of OPC and SGPC at 365 days

Typical Tafel polarization curve fitting results for a passive and an active specimen are presented in the above graphs for water cured and exposed samples ($MgSO_4$, 2 g/l or 4 g/l). The horizontal axis is the logarithm of current density, and the vertical axis indicates electrical potential. Straight lines are used to show the theoretical current for the anodic and cathodic reactions. The combined anodic and cathodic current is shown by the curved lines. The extent of corrosion can be measure from the distance between the intersection point and the curve line i.e. as we move away from the curves corrosion rate increases and vice-versa. In the above graphs, it is evident that corrosion has occurred in both cases. The corrosion rate can be compared for the specimens cured in water or the sulphate solution. The corrosion rate of the specimens cured in sulphate was higher than the specimens cured in water. For example, when mixes of M1-OPC and M2-SGPC exposed to $MgSO_4$ (4 g/l) at 365 days are compared with water cured specimens at 365 days, it shows a corrosion rate of 0.709, 0.664 and 0.098, 0.087 respectively. This higher corrosion rate might be because of higher permeability as confirmed by RCPT and sorptivity test results above. Also, the N-A-S-H and C-A-S-H formation were less in SGPC when exposed to $MgSO_4$ (4 g/l), as confirmed by EDS results above. The above observations confirm that corrosion rate is in line with the compressive strength, RCPT and sorptivity test results. Further higher corrosion in the $MgSO_4$ solution cured specimens when compared with water might be because of reduced alkanity and transformation of γ-Fe_2O_3 layer converts into iron sulphate. When Sulphate salts come into contact with steel, they lead to the formation of iron sulphate, placing oxy-hydroxide film on the surface of rebar. This film of iron sulphate is less protective than original passive iron oxide film. Sulphate salt is also responsible for leaching and formation of complex and expansive salt reducing the alkalinity and because of this rate of corrosion increases (Somuah et al. 1991; Berrocal et al. 2016).

In addition, this result shows that SGPC performed better than OPC in terms of corrosion. From Tafel plots (Figs. 15 to 20), it is obvious that he rate of corrosion increased with the exposure time in $MgSO_4$ solution. (Morla et al. 2021) also studied the corrosion evaluation GPC concrete and concluded that the GPC has a higher resistance to chloride-induced corrosion, with a low corrosion rate and lower mass loss percentage, compared to conventional concrete. The results concluded that GPC reduced the corrosion rate compared to OPC, and provided satisfactory results from a durability perspective.

4. Conclusions

Based on the observations and the results presented above the following conclusions can be derived upon

- The slump and compaction factor of all the mixes were above 100 mm and 0.90, respectively, which shows good workability per Indian standards.

- The compressive strength of water cured samples increased with age and this observation was obtained for both the mixes. The highest compressive strength for M1-OPC and M2-SGPC was 43.65 and 50.78 MPa at the age of 365 days. The higher compressive strength of M2-SGPC was due to denser microstructure and formation of addition (C-A-S-H and N-A-S-H) gels. The presence of finer alcofines (UFS) also contributed to this strength enhancement.
- The strength of samples exposed to $MgSO_4$ salts decreased. The maximum percentage loss of the compressive strength for M1-OPC and M2-SGPC mixes was 55.97% and 36.53%, respectively, when the specimens were exposed to $MgSO_4$ (4 g/l).
- Microstructural studies show that the degradation in the compressive strength of M1-OPC and M2-SGPC under $MgSO_4$ was caused by C-S-H and N-A-S-H gels interacting with salts, resulting in low strength with the decrease in formation of C-A-S-H and N-A-S-H.
- This study shows that reinforced SGPC had a lower corrosion rate than OPC even in aggressive suplahte environment.

All above observations and finding suggest that SGPC performed better than OPC in both normal and aggressive sulpahte environments.

5. Recommendation

From the above findings and observation, the following recommendations can be made for future studies as follows:

- By inclusion of alcofine (UFS) along with the main binder (GGBFS) in geopolymer concrete, a high strength can be achieved at ambient temperature.
- Conventional concrete is more prone to higher concentrations of $MgSO_4$ salts than slag-based geopolymer concrete. Therefore, SGPC can be used to replace OPC concrete at harsh conditions.

6. Future scope

- Durability of GPC shall be checked for freezing and thawing, alkali-silica reaction and other acidic environments.
- This study reports the durability of conventional and geopolymer concrete produced using NaOH and Na_2SiO_3 as an alkaline-activators. However, the durability properties of the geopolymer concrete can be examined by using different alkaline activators such as potassium hydroxide and sodium carbonate.
- Durability of geopolymer concrete which has been cured at a high temperature.

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Statements and declarations

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Authors Contributions:

Atul Garg: Conceptualization, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation.

Parveen: Conceptualization, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation, Reviewing and Editing.

Dhirendra Singhal: Reviewing and Editing.

Thong M Pham: Reviewing and Editing.

Deepankar Kumar Ashish: Reviewing and Editing.

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Data availability and materials

Not applicable

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