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Experimental Investigation on Strength, Durability and Micro Structural Characteristics of Slag-Based Cement Mortar

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ABSTRACT

Cement mortar is used as a bonding agent between building materials in the construction of stone masonry and brick masonry. The focus on reducing the environmental burden caused by the high emission of carbon with the consumption of cement has gained interest. In this study, experimental investigations are conducted using two slag-based materials, i.e., Portland Slag Cement (PSC) and Processed Granulated Blast Furnace Slag Sand (PGBFS, iron slag), as a replacement for Ordinary Portland Cement (OPC) and River Sand (RS). The paper aims to investigate the influence of PSC with slag sand on the strength, durability, and microstructure of cement mortar. The present work specifically investigates the strength improvement of cement mortar with slag cement and slag sand by varying the curing period, comparing the results at 7, 14, and 28 days of curing. OPC is replaced fully with PSC, and River sand is replaced partially or fully with slag sand in different percentages, i.e., 0%, 20%, 40%, 60%, 80% and 100% for different types of mixes. Results showed the highest increase in compressive strength and high resistance to acid attack in cement mortar with 100% PSC and 60% Slag Sand replacement. The consumption of proposed materials will benefit the construction industry to achieve the net zero target.

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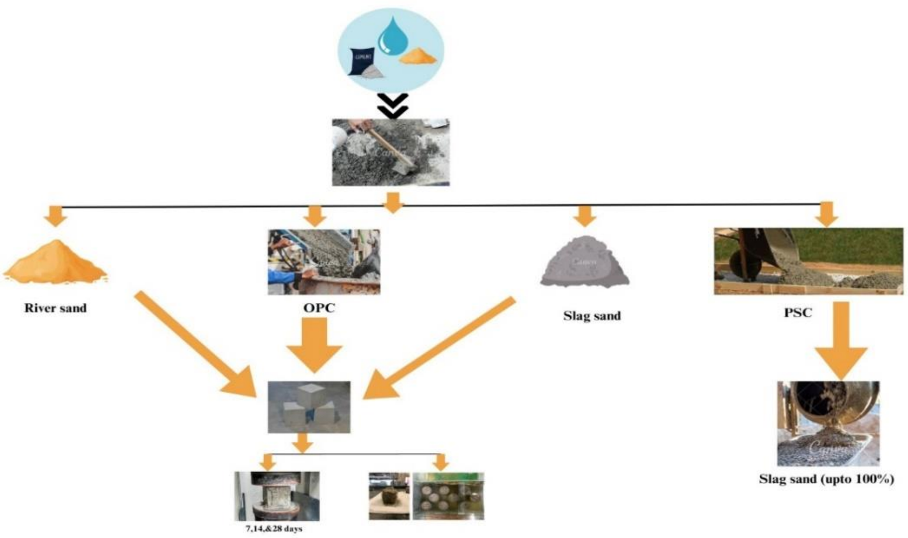
Graphical Abstract



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1. INTRODUCTION

Cement plays a crucial role in the construction industry; however, its widespread use significantly impacts the environment and contributes significantly to energy consumption. This is primarily due to the harmful emissions of carbon dioxide during the cement manufacturing process, making it a major environmental concern in the realm of construction materials (1). Every year, the global construction industry goes through billions of tonnes of cement. This number is only going to continue to rise if there is a need for both newly built and renovated infrastructures. Cement manufacturing is energy-intensive and emits 5% - 7% CO_2, according to various reports (2). Cement production is a highly energy-intensive process that involves the extraction of raw materials, such as limestone and clay, and the high-temperature calcination of these materials in kilns to produce cement clinker. The calcination process releases carbon dioxide (CO_2) as a byproduct, resulting in significant greenhouse gas emissions. In addition, fossil fuels, such as coal, are commonly used as a source of heat in cement kilns, further contributing to CO_2 emissions. It is estimated that the production of one ton of Ordinary Portland cement (OPC) releases about 0.8 tons of carbon dioxide making it a significant contributor to climate change (1-7). The global increase in CO_2 emission and the associated impact on global warming motivated studies seeking to investigate the suitability of certain materials for partial or complete replacements of ordinary Portland cement (OPC) as concrete binders (7, 8). Currently, with the construction projects worldwide developing, plenty of natural materials such as natural sand (RS) are used to produce concrete (9, 10). The over-exploitation of high-quality river sand has not only led to a scarcity of resources, but also to a surge in the price of natural sand materials (11). Cement mortar (CM) is one of the most widely used construction materials; its “green” development is bound to help the construction industry (12, 13). Cement mortars are used in multiple applications in construction, such as plastering/rendering purposes, bonding layers in masonry walls, and fillers in repairing works. Unlike concrete, cement mortars are made with designated cement or supplementary cementitious material (as binder) and fine sand (as filler), where they are mixed in terms of volume/mass ratios to meet the targeted compressive strength and consistency (14). The adoption of sustainable practices during the OPC production phase includes replacement with renewable energy resources and carbon dioxide sequestration techniques is in practice. However, replacing the use of OPC with finding a suitable alternative that can match the performance and cost-effectiveness of conventional cement can be an immediate and effective choice, to achieve the target of net zero. The use of blended cement such as slag-based cement is environmentally friendly due to the reduction in CO_2 emission during the clinkering process (10). This work enhances the mechanical properties and can help prevent the CO_2 from releases to the atmosphere (4). Eco-friendly materials, waste materials might be incorporated as replacements for aggregate and cement. It has been reported that utilizing waste materials in cementitious composites improved their mechanical characteristics (15). The development of sustainable construction materials based on these waste materials is of great value (11). The use of PSC is known to result in CO_2 emission by 70% compared to OPC but still, the consumption of PSC for construction activities seems significantly less (9). Despite the environmental benefit that can be derived by using PSC, the low rate of heat of hydration and lower early compressive strength development is reasoned for the scarce consumption (3).

Sand forms a major composition for the preparation of cement mortar and concrete. However, the demand for sand has led to several issues, including limited sand supplies, illegal and unsustainable sand mining, and environmental degradation caused by sand mining activities. These issues highlight the need for sustainable and responsible management of sand resources. The ecological balance is disturbed by the ongoing usage of natural sand, which depletes river beds. Thus, research focusing on using industrial wastes as a replacement for conventional river sand has been expanding for a decade (2, 16-18). These studies have also identified that using steel slag as a replacement for river sand will increase the compressive strength of concrete mixes. Cement mortar (CM) is one of the most widely used construction materials; its “green” development is bound to help the construction industry (19). The workability and cohesiveness of mortar are enhanced due to the finer and more consistent grain size of slag sand compared to natural sand. The additional cementitious bond formed by the slag sand reacting with water and calcium content in cement is also known to contribute to the durability (13). Thus, using slag sand will reduce the environmental burden by reducing the demand for the extraction of natural sand and effective waste disposal (20, 21). It is understood that there is lack of extensive studies on the cement mortar prepared with PSC and slag sand, and studying the behaviour of mortar with these environmentally friendly materials will add to the wealth of literature related to the analysis of sustainable material-based mortars. Also, considering the shortcomings of using river sand (RS) and OPC, and the advantages of utilizing slag sand (SS) with PSC, the present study is aimed at assessing the role of slag sand as a replacement for river sand in PSC. The mortar prepared with varying slag sand content with PSC is tested for variation in compressive strength and durability against acid, sulfate, and chloride attack along with microstructural analysis.

2. MATERIALS

2. 1. Cement Commercially available Ordinary Portland Cement OPC 53 (confirming IS 12269) (22) and Portland Slag Cement (PSC) confirming to IS: 455 (1989) (23) manufactured by Jindal Steel Works, Bellary, India is used in this work. The chemical composition of OPC and PSC determined using X-ray Fluorescence analysis is listed in Table 1. The fresh properties of OPC and PSC are listed in Table 2.

2. 2. Fine Aggregate

2. 2. 1. River Sand River sand is collected and bought from locally available sand distributors in Kurnool, Andhra Pradesh, India (Figure 1) and slag sand is shown in Figure 2.

2. 2. 2. Slag Sand Processed Granulated Blast Furnace Slag (PGBFS) manufactured by JSW Cement Limited, conforming to IS 16714: 2018 (24), is used for the preparation of mortar mix. The sieve analysis of PGBFS is classified as Grading Zone III as per IS:383(2016) (25). The physical properties of river sand and slag sand are shown in Table 3 and the grain size distribution of river sand and slag sand is shown in Figure 3.

TABLE 1. Chemical composition of OPC and PSC

Constitutes	Chemical composition (%)	
	OPC 53	PSC
CaO	61.85	43
SiO_2	20.07	12
Fe_2O_3	4.62	12
MgO	0.83	6.7
Al_2O_3	5.32	21
SO_3	2.5	2.59
Lime Saturation Factor	0.91	-
Ratio of Alumina/Iron oxide	1.18	-
Insluble reside % by mass	-	0.37
Loss on ignition % by mass	-	1.66
Chloride content	0.0028	0.0017

TABLE 2. Fresh Properties of OPC and PSC

Property		OPC	PSC
Fineness		220 m^2/kg	370 m^2/kg
Initial Setting Time		34 min	30 min
Final Setting Time		550 min	600 min
	3 days	22 MPa	24 MPa
Compressive Strength	7 days	25 MPa	30 MPa
	28 days	52 MPa	58 MPa

Figure 1. River sand

Figure 2. Slag sand

TABLE 3. Physical Properties of RS and SS

Property	River Sand	Slag Sand
Fineness Modulus	2.85 m^2/kg	2.30 m^2/kg
Water Absorption	0.8%	0.92%
Apparent Density (Loose)	1595 kg/m^3	1333 kg/m^3
Apparent Density (Rodded)	1765 kg/m^3	1475 kg/m^3

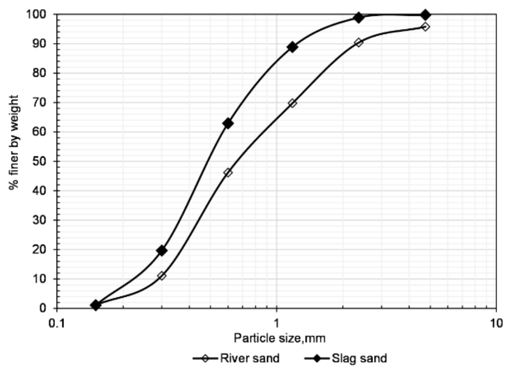


Figure 3. Grain size distribution curve fine aggregates

3. EXPERIMENTAL METHODS

Initially, the mix design for the cement mortars were set as (1: 3, 1:4 and 1:6) for cement: sand which is the common mortar mixtures prepared (2). The tests conducted on cement mortar mix with 1:3, 1:4 and 1:6 ratio is shown in Figure 4, and cement mortar mix prepared using different materials are shown in Figure 5.

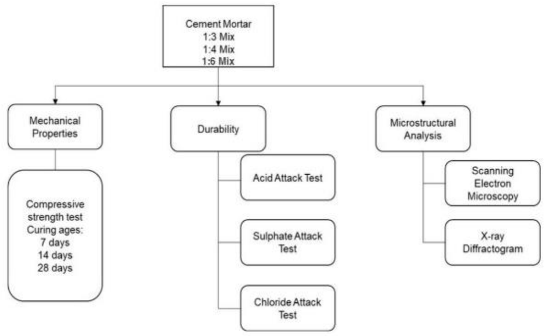


Figure 4. Methodology representing the experimental phases

The methodology for laboratory analysis of hardened cement mortar properties with two different proportions to assess the influence of river sand replacement with slag sand, along with detailed micro-level examination, is mentioned as a flowchart (Figure 5).

The designation of cement mortar mix with different proportions is listed in Table 4.

3. 1. Preparation of Cement Mortar The dry cement and sand were mixed first followed by mixing with water and intermixed adequately to achieve a homogeneous mortar mix. A water binder ratio of 0.45 is used as a water-cement ratio (w/c) as referred to Jin and Guo (18). The mixtures were filled in cube moulds of size 7.06 x 7.06 x 7.06 cm. The samples were cured as shown in Figure 6.

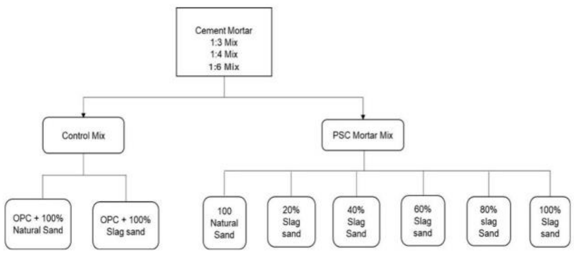


Figure 5. Framework showing the materials used for investigation

TABLE 4. Designation of cement mortar mixes

Mix Proportion	Designation
OPC+100%RS	OPCRS100
OPC+100%SS	OPCSS100
PSC+0%SS+100%RS	PSCSS0
PSC+20%SS+80%RS	PSCSS20
PSC+40%SS+60%RS	PSCSS40
PSC+60%SS+40%RS	PSCSS60
PSC+80%SS+20%RS	PSCSS80
PSC+100%SS+0%RS	PSCSS100

3. 2. Compressive Strength The compressive strength of mortar mix (1:3, 1:4 and 1:6) of OPCRS100, OPCSS100 and PSC with 0%, 20%, 40% 60%, 80% and 100% SS at w/c of 0.45 at different curing ages i.e., 7-, 14- and 28-days were measured by using the automatic compressive strength testing machine, following the procedure of IS 4031(Part 6): 1988 (18, 23, 26).

3. 3. Durability Different methods are used to test the acid, chloride and sulfate attack resistance of concrete, and each method has certain advantages and disadvantages. The durability of the control mortar mix and PSC with SS mortar mix was studied by immersing the cured mortar cubes in the water bath with 5% Sulphuric acid (H_2SO_4) and 5% hydrochloric acid (HCl). The mortar cubes were exposed to acid attack for 28 days. The immersed cubes after the corresponding exposure period were removed from the acid solution bath and surfaces were cleaned with a soft nylon wire brush under the running tap water to eliminate weak products and loose material from the surface. The specimens were tested for mass loss and compressive strength after surface drying the mortar cubes.

3. 4. X-Ray Diffraction Analysis The X-ray diffractograms of the control mortar and PSC with SS mortar were recorded between diffraction angles (2 theta) of 10° to 80° to identify the hydration product formation in the mortar mix after sufficient curing. Like SEM analysis, specimens were extracted from the samples after compressive strength testing. The X-ray diffractograms of cement mortar mixes (i.e., 1:3, 1:4 and 1:6) with PSC and SS as a replacement to RS are obtained between 2θ = 10º to 80º (25).

3. 5. Scanning Electron Microscope A scanning electron microscope (SEM) allows the surface of a sample to be examined in three dimensions by scanning

Figure 6. Cement mortar cubes for compressive strength test

the surface with a thin electron beam and generating secondary electrons. Micrographic images of the control mix and PSC mortar with varying percentages of SS as a replacement to RS were obtained for triplicate specimens extracted carefully from compressive strength tested samples. The samples were gold coated using a sputter coater before conducting SEM analysis (27).

Micrographic images of the control mix and PSC mortar with varying percentages of SS as a replacement to RS were obtained for triplicate specimens extracted carefully from compressive strength tested samples. The samples were gold coated using a sputter coater before conducting SEM analysis. Samples collected after compressive strength testing were powdered and gold sputter coated to study the morphological changes in cement mortar mixes prepared with PSC and SS using scanning electron microscopy (SEM). Energy dispersive X-ray analysis (EDAX) was used to characterize the elemental compositions.

3. 6. Numerical Simulation Numerical simulation of cement mortar cubes of size 70.6 cm X 70.6 cm X 70.6 cm was carried out using ANSYS software. The material properties used for the simulation is listed in Table 5.

4. RESULTS AND DISCUSSION

4. 1. Compressive Strength The compressive strength of mortar mix ratio of 1:3 with OPC and 100% RS, 100% SS and PSC with varying dosages of SS are shown in Figure 7. The compressive strength of all samples showed an increase within curing ages and the rate of increase in compressive strength of OPC with 100% RS is 36% and 100% whereas PSC with 100% RS shows an increase of 22% and 122% when curing period is increased from 7 days to 14 and 28 days respectively. The rate of increase is lesser in OPC as well as PSC with 100% SS compared to that mix containing 100% RS. This can be attributed to the low rate of chemical reactivity of slag and the dilution effect as mentioned in earlier research (9). The low rate of chemical reactivity of PSC can be ascribed to the low rate of compressive strength gain compared to OPC. However, with an increase in SS content from 20% to 60%, the strength gain increased and maximum compressive strength was observed for PSC and 60% SS as a replacement for RS. The compressive strength of PSC with a further higher proportion of SS (i.e., 80% and 100%) reduced and a similar trend of less rate of strength gain is reported elsewhere by Shengtao et al. (16) and Sande et al. (28).

The compressive strength of mortar mix ratio of 1:4 with OPC and 100% RS, 100% SS and PSC with varying dosages of SS are shown in Figure 8. The trend of compressive strength variation is like that observed in 1:3 concrete mix and the strength of PSC with 60% SS is comparable with the strength of OPC with RS without any replacement. The compressive strength of mortar mix ratio of 1:6 with OPC and 100% RS, 100% SS and PSC with varying dosages of SS are shown in Figure 9. The rate of strength reduction in PSC with SS at varying proportions compared to the strength of the control mix is comparatively less compared to that observed in the 1:3 and 1:4 mix which can be attributed to the high bulk density of SS and similar observation is reported.

TABLE 5. Material properties

Material Property	Value
Young's modulus	20000 MPa
Density	1900 kg/m^3
Poisson's ratio	0.18
Mesh size	1 cm
Load	150

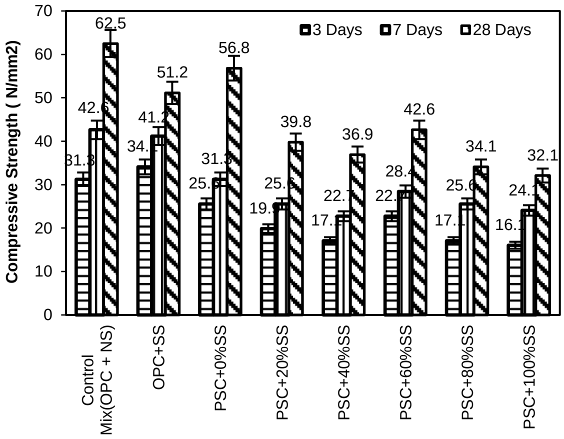


Figure 7. Compressive strength of mortar for 1:3 mix

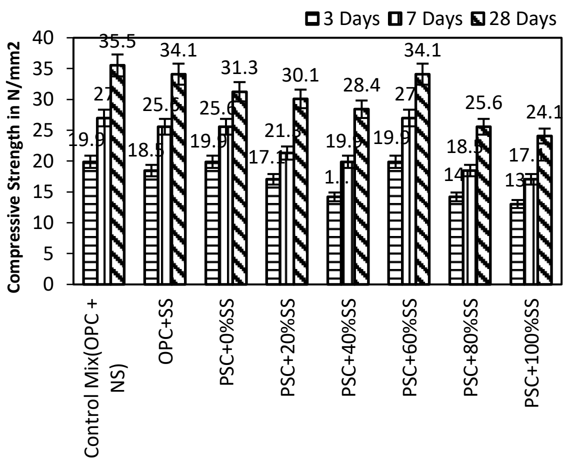


Figure 8. Compressive strength of mortar for 1:4 mix

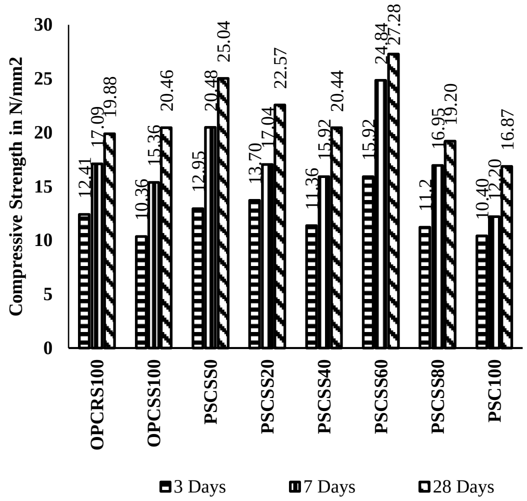


Figure 9. Compressive strength of mortar for 1:6 mix

4. 2. Durability The durability of control cement mortar cubes and cubes prepared with varying PSC and SS content in the mix ratio of 1:3, 1:4 and 1:6 was evaluated for weight loss and compressive strength variation after exposure to acids.

4. 2. 1. Acid Attack Test Physical and mechanical changes observed in the cement mortar cubes before and after immersion in sulphuric acid solution are shown in Figures 10a and 10b and Tables 6, 7 and 8. The exposure to acid reduced the compressive strength of the control mortar mix proportion of 1:3 by 45% and a 32% reduction in compressive strength of PSC with RS mortar mix is observed in Figure 11. The exposure of PSC with SS mortar mix showed an increase in the percentage of strength loss but for PSC with 60% SS, there was a reduction in the rate of strength loss. Thus 60% SS as a replacement to RS in PSC will impart high resistance to acid attack and specimens retain high strength during the acid exposure period of 28 days (29-31).

(a)

(b)

Figure 10. a) before and b) after Acid attack

TABLE 6. Change in weight and compressive strength of Mix 1:3 after acid exposure

Mix Proportions	Weight before exposure (kg)	Weight after exposure (kg)	Compressive strength before exposure (N/mm^2)	Compressive strength after exposure (N/mm^2)
OPCRS100	0.741	0.620	62.51	34.17
OPCSS100	0.810	0.658	51.15	29.47
PSCSS0	0.718	0.621	56.83	38.64
PSCSS20	0.730	0.613	39.79	24.27
PSCSS40	0.720	0.595	36.79	20.97
PSCSS60	0.788	0.671	42.62	28.06
PSCSS80	0.730	0.601	34.10	19.35
PSCSS100	0.718	0.599	32.10	13.80

TABLE 7. Change in weight and compressive strength of Mix 1:4 after acid exposure

Mix Proportions	Weight before exposure (kg)	Weight after exposure (kg)	Compressive strength before exposure (N/mm^2)	Compressive strength after exposure (N/mm^2)
OPCRS100	0.710	0.583	35.52	18.47
OPCSS100	0.730	0.589	34.10	18.84
PSCSS0	0.692	0.593	31.25	20.31
PSCSS20	0.710	0.602	30.09	17.18
PSCSS40	0.705	0.606	28.41	16.47
PSCSS60	0.720	0.629	34.10	22.06
PSCSS80	0.652	0.539	25.57	14.88
PSCSS100	0.688	0.577	24.07	14.48

TABLE 8. Change in weight and compressive strength of Mix 1:6 after acid exposure

Mix Proportions	Weight Before Exposure (kg)	Weight After Exposure (kg)	Compressive Strength before Exposure (N/mm²)	Compressive Strength After Exposure (N/mm²)
OPCRS100	0.67	0.548	19.89	9.98
OPCSS100	0.657	0.531	20.46	11.86
PSCSS0	0.664	0.520	21.82	10.56
PSCSS20	0.670	0.580	22.50	12.02
PSCSS40	0.684	0.582	21.87	12.51
PSCSS60	0.710	0.624	27.28	15.20
PSCSS80	0.620	0.522	20.42	11.60
PSC100	0.580	0.500	18.66	10.24

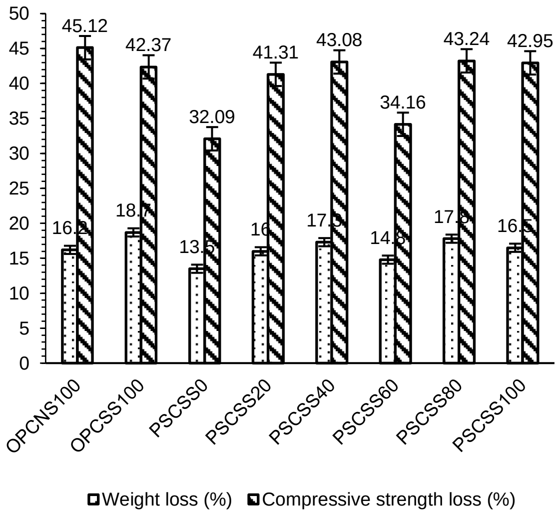


Figure 11. Weight loss and compressive strength loss in 1:3 mix after exposure to hydrochloric acid

The weight loss and compressive strength loss of mortar mix proportion of 1:4 also showed a similar response to acid exposure as that of 1:3 mortar mix. The results are depicted in Figure 12. It is evinced that PSC with no replacement of RS showed the lowest rate of reduction in compressive strength followed by PSC with SS content of 60% and 40% of RS as fine aggregate. This shows that the PSCSS60 sample resists acid attacks like the sample with 100% RS. The results of the weight loss and compressive strength loss of mortar mix proportion of 1:6 are shown in Figure 13.

4. 2. 2. Sulfate Attack Sulfate attack on mortar is to determine the resistance of cement mortar under Magnesium sulfate acid exposure. The samples after curing and after exposure to sulfate attack are shown in Figures 14a and 14b.

The weight loss and compressive strength loss observed after exposure to 5% Magnesium sulfate for 28 days are listed in Tables 9, 10 and 11 for cement mortar of 1:3 mix and 1:4 mix, respectively.

Figures 15, 16 and 17 show the comparison of the rate of strength and weight loss in cement mortar mixes of 1:3, 1:4 and 1:6 proportion with varying cement and fine aggregate content. It is observed that all samples were highly resistant to sulfate attack compared to the hydrochloric acid attack in the case of both 1:3, 1:4 and 1:6 mix proportions. The rate of weight loss is almost in the same range for all samples, but the compressive strength loss is least by 14.2% and 14% for PSC with 100% RS and PSC with 60% SS as a replacement to RS in 1:3 mortar mix samples (Figure 15). The rate of strength loss observed in the 1:4 mix is least by 12% for PSC with 60% SS followed by 15% in PSC with 100% RS and the rate of strength loss observed in the 1:6 mix

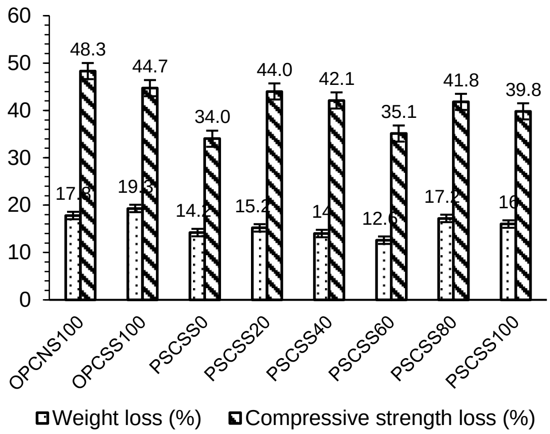


Figure 12. Weight loss and compressive strength loss in 1:4 mortar mix after exposure to hydrochloric acid

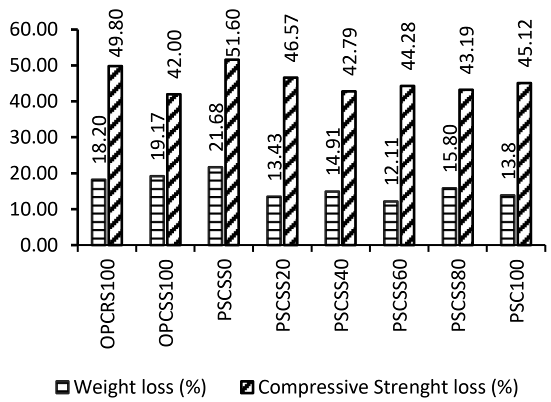


Figure 13. Weight loss and compressive strength loss in 1:6 mortar mix after exposure to hydrochloric acid

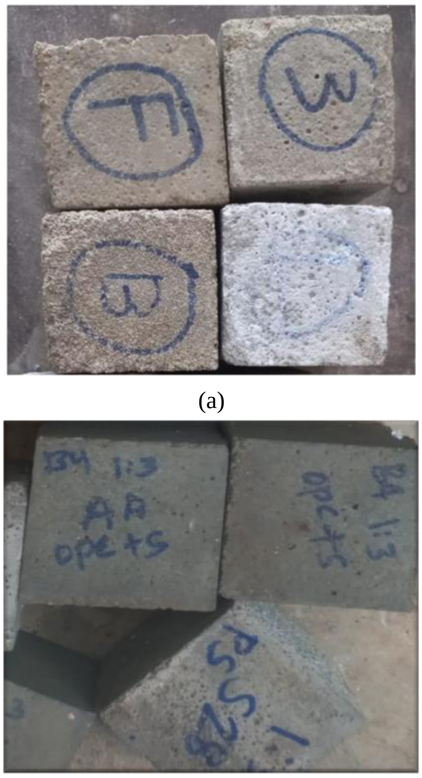


Figure 14. a) before and b) after sulfate attack

TABLE 9. Variation in weight and compressive strength due to sulfate attack 1:3 mortar mix

Mix proportions	Weight before exposure (kg)	Weight after exposure (kg)	Compressive strength before exposure (n/mm^2)	Compressive strength after exposure (n/mm^2)
OPCRS100	0.736	0.704	62.51	50.42
OPCSS100	0.738	0.702	51.15	42.58
PSCSS0	0.730	0.702	56.83	48.87
PSCSS20	0.710	0.687	39.79	32.99
PSCSS40	0.748	0.718	36.79	31.27
PSCSS60	0.766	0.737	42.62	35.80
PSCSS80	0.726	0.698	34.10	28.57
PSCSS100	0.724	0.694	32.10	26.64

TABLE 10. Variation in weight and compressive strength due to Sulfate attack test for 1:4 mix

Mix Proportions	Weight before exposure (kg)	Weight after exposure (kg)	Compressive strength before exposure (N/mm^2)	Compressive strength after exposure (N/mm^2)
OPCRS100	0.723	0.695	35.52	28.40
OPCSS100	0.690	0.667	34.1	27.62
PSCSS0	0.703	0.683	31.25	26.56
PSCSS20	0.681	0.655	30.09	25.93
PSCSS40	0.690	0.661	28.41	24.04
PSCSS60	0.680	0.657	34.1	30.08
PSCSS80	0.644	0.613	25.57	20.71
PSCSS100	0.682	0.650	24.07	20.56

TABLE 11. Variation in weight and compressive strength due to Sulfate attack test for 1:6 mix

Mix Proportions	Weight Before Exposure (kg)	Weight After Exposure (kg)	Compressive Strength before Exposure (N/mm^2)	Compressive Strength after Exposure (N/mm^2)
OPCRS100	0.708	0.682	19.68	16.84
OPCSS100	0.641	0.624	21.82	17.67
PSCSS0	0.638	0.612	18.75	14.34
PSCSS20	0.642	0.624	22.50	20.22
PSCSS40	0.634	0.602	21.62	18.24
PSCSS60	0.612	0.584	23.10	21.02
PSCSS80	0.562	0.532	20.02	17.24
PSC100	0.542	0.522	18.22	15.46

is least by 12% for PSC with 60% SS followed by 15% in PSC with 100% RS. This again confirms the potential of PSC-based mortar with 60% SS to replace RS to resist the acidic environment expected due to contact with industrial effluents etc. and a similar observation is reported (9, 31).

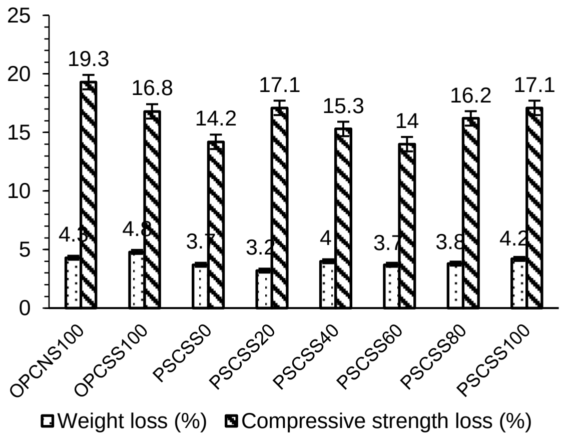


Figure 15. Weight loss and compressive strength loss in 1:3 mortar mix due to sulfate attack

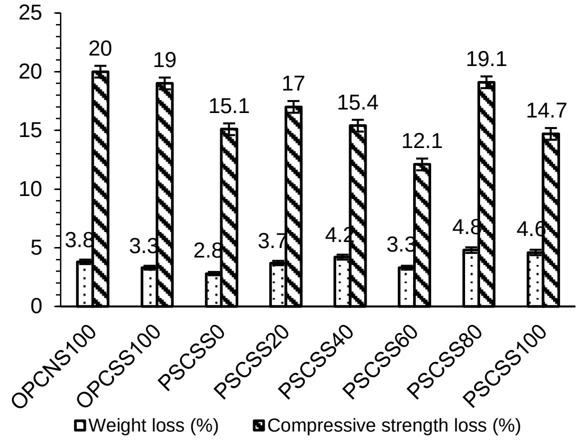


Figure 16. Weight loss and compressive strength loss in 1:4 mortar mix due to sulfate attack

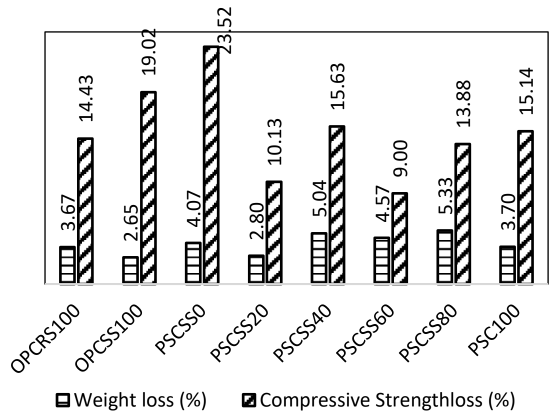


Figure 17. Weight loss and compressive strength loss in 1:6 mortar mix due to sulfate attack

4. 2. 3. Chloride Attack Test The effect of hydrochloric acid exposure to cement mortar was assessed by weight loss and compressive strength reduction. The mortar samples subjected to chloride attack are shown in Figures 18a and 18b. The loss in weight and compressive strength of samples after exposure to chloride solutions is listed in Tables 12, 13 and 14.

The rate of weight loss and compressive strength of 1:3 mortar after the chloride attack is shown in Figure 19. It can be observed that PSC with 60% SS is only 1.7% whereas it is maximum by 3.1% in conventional cement mortar (i.e., OPCRS100). The strength reduction in mortar after chloride attack is least in PSC with 100% RS followed by PSC with 60%SS.

Table 12 shows the change in weight and compressive strength of 1:4 mortar mixes after exposure to a chloride environment using 5% hydrochloric acid. Figure 20 shows the rate of weight loss and compressive

(a)

(b)

Figure 18 a) before and b) after chloride attack

TABLE 12. Variation in weight and compressive strength due to chloride attack test for 1:3 mix

Mix Proportions	Weight before exposure (kg)	Weight after exposure (kg)	Compressive strength before exposure (N/mm^2)	Compressive strength after exposure (N/mm^2)
OPCRS100	0.762	0.738	62.51	57.47
OPCSS100	0.826	0.804	51.15	47.96
PSCSS0	0.720	0.705	56.83	53.98
PSCSS20	0.704	0.688	39.79	37.40
PSCSS40	0.734	0.720	36.79	34.49
PSCSS60	0.740	0.727	42.62	40.07
PSCSS80	0.710	0.692	34.10	31.52
PSCSS100	0.711	0.691	32.10	30.07

TABLE 13. Variation in weight and compressive strength due to chloride attack test for 1:4 mix

Mix Proportion	Weight before exposure (kg)	Weight after exposure (kg)	Compressive strength before exposure (N/mm^2)	Compressive strength after exposure (N/mm^2)
OPCRS100	0.706	0.688	35.52	31.25

OPCSS100	0.712	0.692	34.1	30.79
PSCSS0	0.685	0.659	31.25	28.40
PSCSS20	0.708	0.688	30.09	29.06
PSCSS40	0.687	0.673	28.41	26.42
PSCSS60	0.670	0.653	34.1	32.05
PSCSS80	0.684	0.662	25.57	23.27
PSCSS100	0.652	0.629	24.07	22.26

TABLE 14. Variation in weight and compressive strength due to chloride attack test for 1:6 mix

Mix Proportions	Weight Before Exposure (kg)	Weight After Exposure (kg)	Compressive Strength before Exposure (N/mm^2)	Compressive Strength after Exposure (N/mm^2)
OPCRS100	0.648	0.640	19.89	16.87
OPCSS100	0.665	0.652	22.50	19.70
PSCSS0	0.650	0.622	20.82	16.20
PSCSS20	0.648	0.610	19.86	17.02
PSCSS40	0.666	0.641	21.87	18.50
PSCSS60	0.631	0.610	26.28	23.82
PSCSS80	0.602	0.582	22.42	19.54
PSC100	0.582	0.502	20.02	18.62

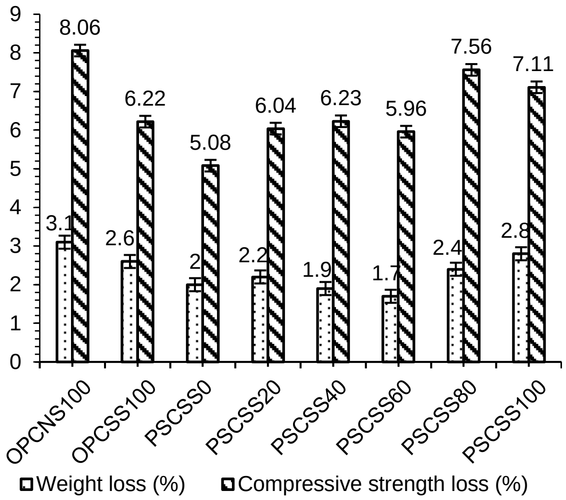


Figure 19. Weight loss and compressive strength loss in 1:3 mortar mix due to chloride attack

strength observed in the mortar samples. Table 13 shows the change in weight and compressive strength of 1:6 mortar mixes after exposure to a chloride environment using 5% hydrochloric acid. Figure 21 shows the rate of weight loss and compressive strength observed in the mortar samples.

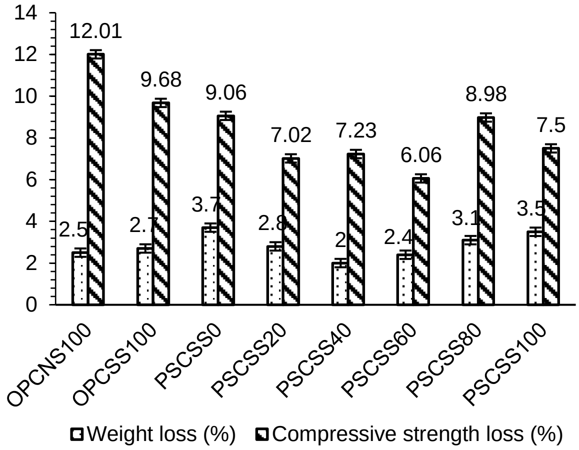


Figure 20. Weight loss and compressive strength loss in 1:4 mortar mix due to chloride attack

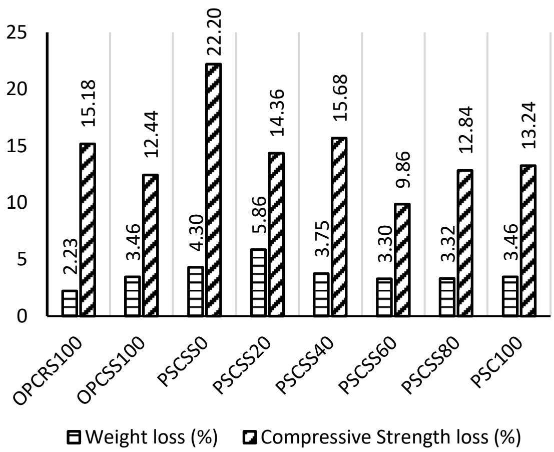


Figure 21. Weight loss and compressive strength loss in 1:6 mortar mix due to chloride attack

The weight loss in PSCSS60 mortar is 2.4% which is higher than that observed in 1:3 samples and a similar comparison in rate of compressive strength loss can also be observed.

4. 2. 4. X-ray Diffractogram Analysis The XRD pattern of 1:3 cement mortar mixes prepared using PSC mixed with 100% RS and PSC mixed with 60% SS are shown in Figures 22 and 23. In Figure 22, the diffractogram peak intensity of quartz, alite (C_3S) and belite (C_2S) are higher than compared to that observed in Figure 23. The reduction in peak intensities can be attributed to the formation of cementing bonds with the fine aggregate and the presence of new peaks is also shown in Figure 23.

The XRD pattern of 1:4 cement mortar mixes prepared using PSC mixed with 100% RS and PSC mixed with 60% SS is shown in Figures 24 and 25. The diffractogram shows a similar observation as that seen in

Figures 22 and 24 indicating the availability of enough silicates as alite, belite and quartz in PSCSS0. The reduction in peak intensities and the presence of newer peaks (Figure 25) confirms the dissolution of silicates and the formation of cementing products with SS in the PSCSS60 mortar mix (32-34).

4. 2. 5. Scanning Electron Microscopic Analysis

The scanning electron microscopic images for 1:3 mortar mix prepared with PSC and 100% RS as well as PSC with 60% SS are shown in Figures 28 (a) and 28 (b). The PSC mortar mix with 100% RS shows the formation of CSH

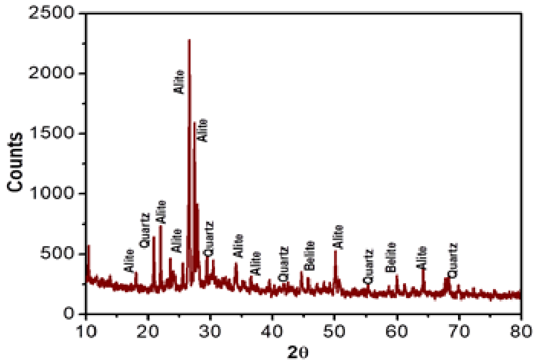


Figure 22. X-ray diffractogram of cement mortar mix used in the study of PSCSS0 (1:3)

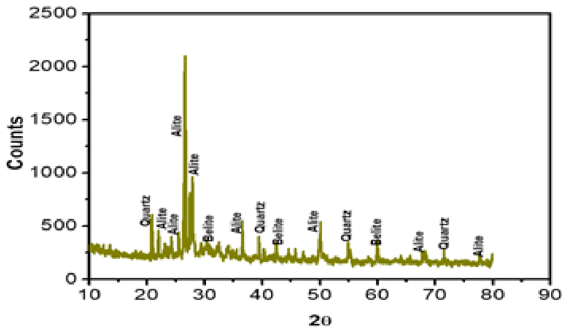


Figure 23. X-ray diffractogram of cement mortar mix used in the study of PSCSS60 (1:3)

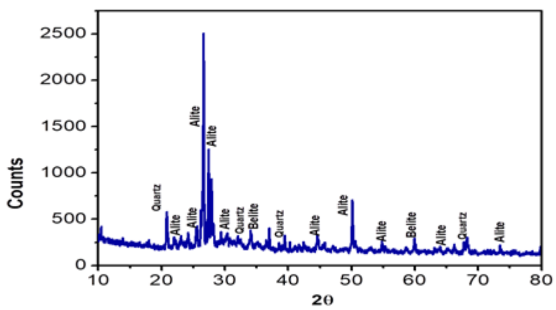


Figure 24. X-ray diffractogram of cement mortar mix used in the study of PSCSS0 (1:4)

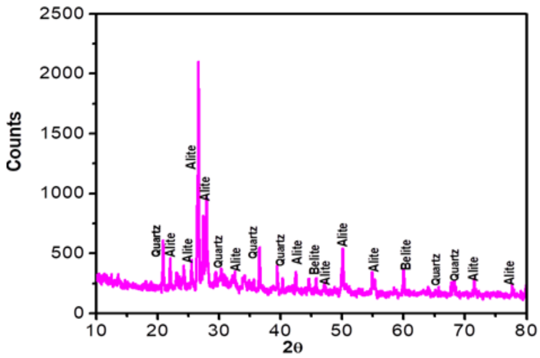


Figure 25. X-ray diffractogram of cement mortar mix used in the study of PSCSS60 (1:4)

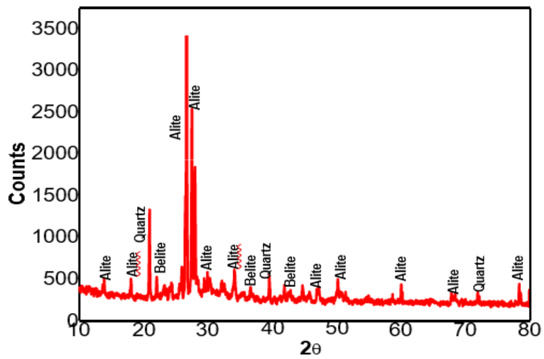


Figure 26. X-ray diffractogram of cement mortar mix used in the study of PSCSS0 (1:6)

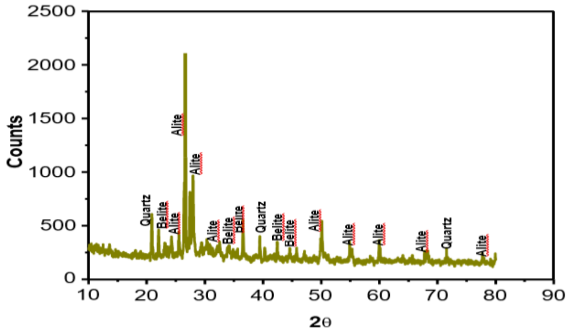


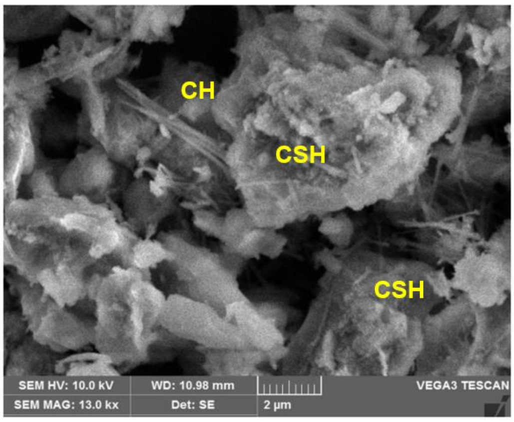
Figure 27. X-ray diffractogram of cement mortar mix used in the study of PSCSS60 (1:6)

and CH (9, 35, 36). The presence of ettringite as Aft along with CSH is observed in PSC with 60% SS. This can be ascribed to the high strength retention in PSC with SS as a replacement for RS by 60% as observed from durability studies (37, 38).

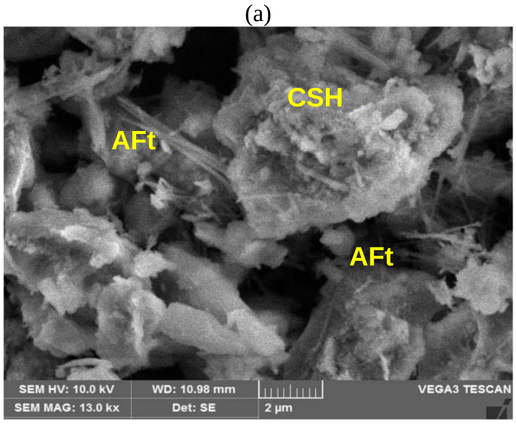
The comparison of the elemental composition of PSCSS0 and PSCSS60 as shown in Figures 23 and 24 illustrates the reduction in silica and increase in calcium content and the formation of newer peaks representing calcium in PSCSS60. This indicates the reactivity of PSC and SS as well along with PSC hydration reaction, that is contributing to enhanced strength and a high rate of strength retention.

The energy dispersive x-ray (EDAX) spectroscopic results of Portland slag cement mortar mix 1:4 prepared with 100% RS and 60% SS as a replacement to RS are shown in Figures 34 and 35.

The elemental compositions obtained from EDAX spectroscopy are used to determine the Calcium (Ca)/Silica (Si) ratio (Table 14). The Ca/Si ratio is approximately 1.00 for all samples indicating the presence of CSH as a tobermorite gel phase and the lower values of Ca/Si ratio are speculated to correspond to a higher content of CSH resulting in densified mortar matrix (10).



(a)



(b)

Figure 28. Micrographs of 1:3 cement mortar mix a) PSCSS0 b) PSCSS60

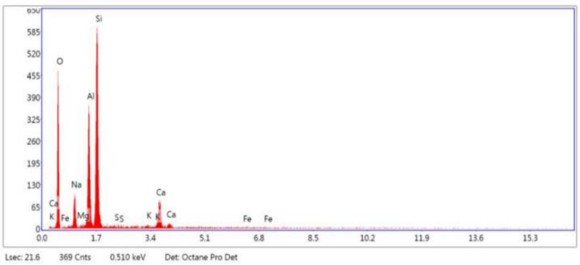


Figure 29. EDAX image of 1:3 PSC mortar with 100% RS (PSCSS0)

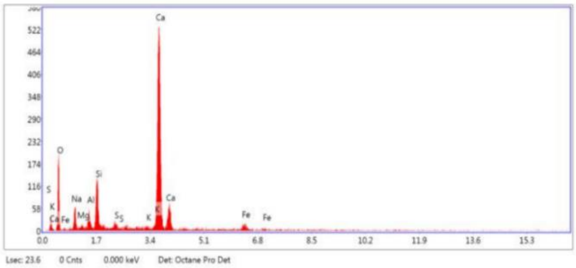


Figure 30. EDAX image of 1:3 PSC mortar with 60% SS (PSCSS60)

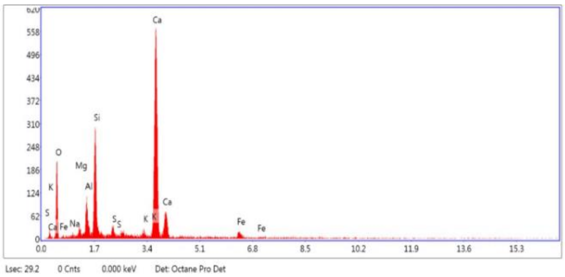


Figure 31. EDAX image of 1:4 PSC mortar with 100% RS (PSCSS0)

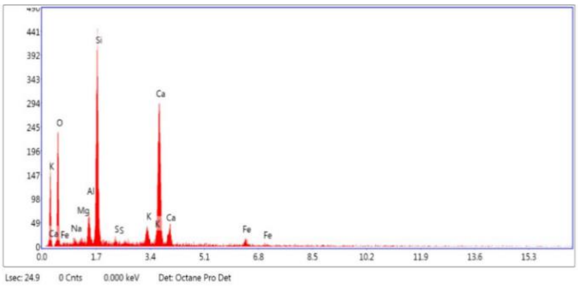
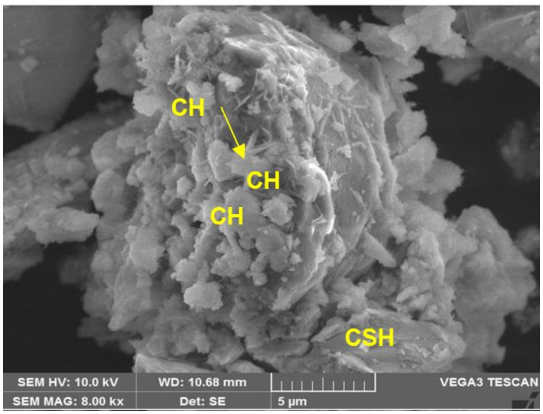
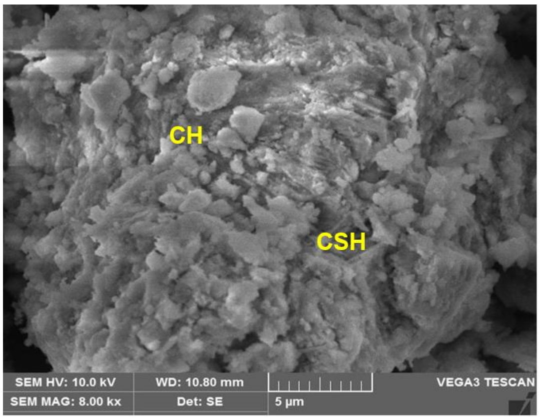


Figure 32. EDAX image of 1:4 PSC mortar with 60% SS (PSCSS60)



(a)



(b)

Figure 33. Micrographs of 1:4 cement mortar mix a) PSCSS0 b) PSCSS60

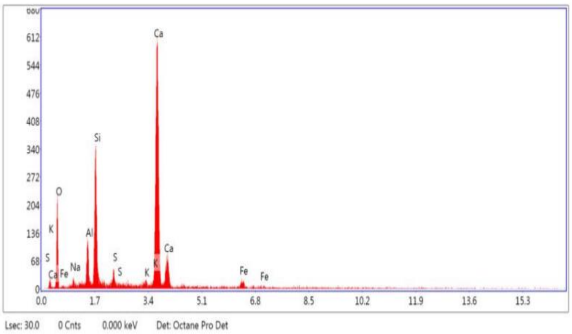


Figure 34. EDAX image of 1:4 PSC mortar with 100% RS (PSCSS0)

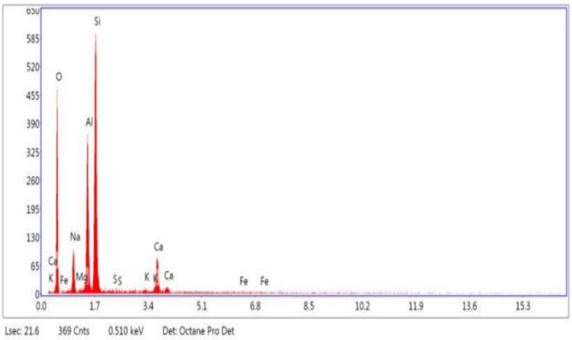


Figure 35. EDAX image of 1:4 PSC mortar with 60% SS (PSCSS60)

TABLE 14. Ca/Si ratio of PSC-based mortar mix

Mix ratio	Sample	Ca/Si
1:3	PSCSS0	1.09
1:3	PSCSS60	1.06
1:4	PSCSS0	1.00
1:4	PSCSS60	0.98

5. NUMERICAL STIMULATION

A finite element model (FEM) of the segmental girder specimen under the same conditions as the test is established, as shown in Figure 36 To verify the reliability of the FEM and parameters, the calculated results of the damage pattern and response of the specimen model are compared with the test data. The results are done numerical stimulation by using the Ansys software. Figure 36 shows the variation of stress in the sample under the simulated compressive load. The maximum stress of 50 MPa is exhibited by the proposed cement mortar model which is similar to the experimental values obtained for OPC with SS.

The deformation under the applied load condition showed the maximum of 0.11 mm in the simulated cement mortar cube (See Figure 37).

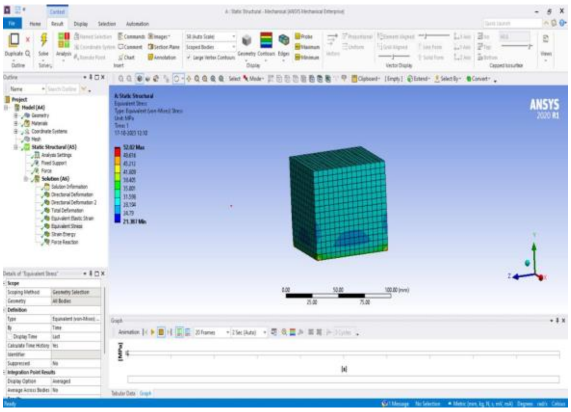


Figure 36. Results of stresses in Ansys model for the cube

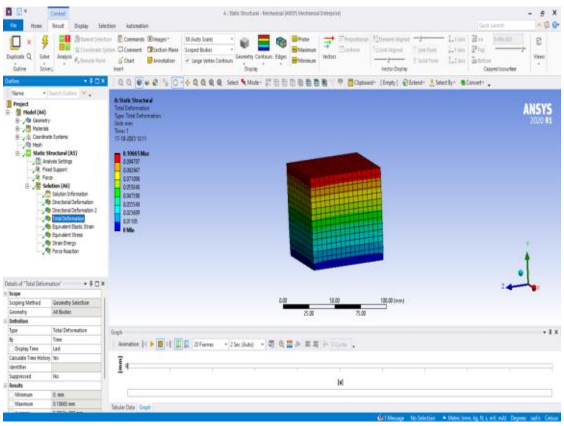


Figure 37. Results of deformations in the cube

6. CONCLUSION

The strength and microstructural change in cement mortars with OPC and PSC on partial to full replacement of natural river sand with slag sand has been assessed based on compressive strength and mass loss after acid attack, sulfate attack and chloride attack along with SEM-EDAX and XRD analysis. Conclusions from the present study can be proposed as follows:

1) The 28-day compressive strength of PSC mortar mix with 60% SS as a replacement to RS shows maximum strength gain compared to other percentages of NS replacement. The strength of PSC-based mortar mix is lesser than the strength gain observed in OPC-based mortar mix which can be ascribed to the lower rate of strength gain in PSC-based mortar. The optimum content of SS as fine aggregate for the maximum increase in compressive strength of PSC mortar is 60% with 40% RS.
2) Durability studies show that PSC with 60% SS as a replacement to RS shows high resistance to s ulfate and chloride exposure compared to the strength loss observed after acid attack testing. This shows that PSCSS60 will be effective in a corrosion-prone environment.
3) The formation of cementitious gel phases was observed in XRD as well as EDAX spectroscopy. The SEM image analysis showed the formation of a densified mortar matrix in PSCSS60 with higher CSH formation which is confirmed by Ca/Si ratio ≈ 1.0. Thus, the improvement in mechanical properties and durability against aggressive environmental influence is correlated well with the microstructural analysis.
4) Numerical simulation of stress deformation analysis by FEM approach using ANSYS software for the optimized cement mortar cube under a compressive load of 150 kN resulted in maximum stress of 50 MPa and deformation of 0.11 mm. The results validate the reliability of experimental results discussed in the present study.

It is understood that the replacement of OPC with PSC and natural river sand with slag sand to prepare cement mortar will satisfy the strength and durability as well as an economically and environmentally sustainable option.

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Persian Abstract

چکیده

ملات سیمان به عنوان عامل اتصال بین مصالح ساختمانی در ساخت سنگ تراشی و سنگ تراشی آجری استفاده می شود. تمرکز بر کاهش بار زیست محیطی ناشی از انتشار بالای کربن با مصرف سیمان مورد توجه قرار گرفته است. در این مطالعه، بررسی‌های تجربی با استفاده از دو ماده مبتنی بر سرباره، یعنی سیمان سرباره پرتلند (PSC) و ماسه سرباره کوره بلند دانه‌بندی شده پردازش شده (PGBFS، سرباره آهن)، به عنوان جایگزینی برای سیمان پرتلند معمولی (OPC) و ماسه رودخانه انجام شد. (RS) هدف این مقاله بررسی تاثیر PSC با ماسه سرباره بر استحکام، دوام و ریزساختار ملات سیمان است. کار حاضر به طور خاص بهبود مقاومت ملات سیمان با سیمان سرباره و ماسه سرباره را با تغییر دوره پخت بررسی می‌کند و نتایج را در روزهای ۷، ١٤ و ۲۸ روزه مقایسه می‌کند. OPC به طور کامل با PSC جایگزین می شود و ماسه رودخانه به طور جزئی یا کامل با ماسه سرباره در درصدهای مختلف جایگزین می شود، یعنی ۰٪، ۲۰٪، ٤۰٪، ٦۰٪، ۸۰٪ و ۱۰۰٪ برای انواع مختلف مخلوط ها. نتایج نشان داد که بیشترین افزایش مقاومت فشاری و مقاومت بالا در برابر حمله اسیدی در ملات سیمان با جایگزینی ۱۰۰٪ PSC و ٦۰٪ Slag Sand وجود دارد. مصرف مصالح پیشنهادی به نفع صنعت ساخت و ساز برای دستیابی به هدف خالص صفر خواهد بود.