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Enhancing Strength and Durability: A Study of Mortar Blocks with Steel Slag Incorporation and the Development of Steel Slag Lime and Cement Blocks

Sravan Chilukuri[1,*], Sanjeet Kumar[2], Ashwin Raut[3]

Abstract

This study is focused on investigating the strength and durability properties of mortar cubes made with slag cement and incorporating Ultra Fine Steel Slag (SS) as a potential replacement for natural fine aggregates (FNA). In some instances, the cement was entirely replaced with hydrated lime to develop the blocks. A battery of tests, including assessments of compressive strength, acid resistance, sulfate resistance, water absorption, and void analysis, were carried out to evaluate the performance of these mortar blocks. For comparison purposes, a control mix comprising 100% natural fine aggregates was also prepared. Notably, mortar cubes incorporating Ultra Fine Steel Slag-Cement (SS-C-1) exhibited a significant increase in compressive strength compared to the control mix. However, it is important to highlight that the compressive strength exhibited a decline in the block's where hydrated lime was used as the primary binder. Exposure to acidic and sulfate-rich environments resulted in a shift in mass and a subsequent reduction in compressive strength for all concrete mixes. Moreover, the results indicated a decrease in water absorption when Steel Slag was used in combination with both cement and lime, in comparison to the natural fine aggregates. Nevertheless, further increases in the Steel Slag content led to a rapid increase in water absorption due to the rise in void content within the mortar. This trend in water absorption was in accordance with the percentage of voids present. Considering these findings, it is recommended to consider Steel Slag as a viable replacement for natural fine aggregates, either in combination with cement or lime, to produce mortar blocks with enhanced strength and durability characteristics.

Keywords: Durability, Steel Slag, sulfate resistance, acid resistance, Sulfuric acid

INTRODUCTION

Cement industry is one of the major contributors of Greenhouse gas (GHG) emissions in the world. This is due to the calcination of raw materials and burning of fuels for temperature maintained in the kilns. In recent years one of the major objectives of countries worldwide is to reduce the amounts of emissions by reducing their emissions and protecting the earth. Emission reduction and climate change has been the important agenda for many counties. This phenomenon increased researchers to study on various waste products to use in construction sector to reduce the usage of cement utilization.

Cement production has undergone a huge development from recent years. The annual global cement production has reached over 4.4 billion metric tonnes in the year 2020 [1]. Easy availability, reasonable cost are the major reasons for cement dominance in the construction industry [2]. The use of cement has wide utilization in structural application like Roads, dams, bridges

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and few non-structural applications like drains, pipe lines etc. [3]. Aggregates in concrete occupy more than 50 % of the concrete volume[4]. In today's construction sector, builders are hugely dependent on natural aggerates like stones and sand which requires huge natural habitat loss and burden on environment as well which results in reducing water holding capacity and erosion. The reduced use of Portland cement and replacing with supplementary cementitious materials that too industrial bi products is bigger step for achieving concrete sustainability [5]. Huge utilization of natural resources leads to resource deficit and increases the material cost. Industrialization led to rapid development of various industries. This resulted in increase of reduction to crater the need of large populations which resulted in increase of waste materials. This created a serious problem for handling and disposal as well [6]. Wood waste ash [7], Rubber in concrete [8], Plastic waste [9], Ceramic and marble waste [10, 11], Paper waste [12], E-waste [13], Argo waste [14] these are some of the industrial and Agri bi-products that are used in construction. Many researches are conducted to state that these materials can be used in construction by considering them as potential sustainable materials [15].

Steel slag is waste product that is obtained after the manufacture of steel. This is highly angular in shape and is rough textured material. Some research studies considered steel slag as Supplementary cementitious material. According to some studies recycling rates of steel slags in developed countries like USA, Germany and Japan are 50%, 30%, and 25%. When it comes to countries like India the utilization rate is very nominal. The simple example of steel slag utilization is China. When we consider China it produces 100 m of steel every year and only utilizes 22 % of it [16]. According to India mineral year book 2018 (part II metal and alloys) an integrated steel plant about 204 tonnes of waste is generated for every tonne of steel produced (including Liquid, solid & gaseous). The utilization can reduce the negative impacts on the environment [17].

Many researches have been done on steel slag being used as a construction material with cement. Concrete prepared with Steel slag aggregate (SSA) helps in reducing the weight when compared with normal traditional concrete[18]. As the content of steel slag increased the concrete had high late compressive strength (After 28 days Compressive strength). Steel slag enhances the permeability of concrete when the water-to-binder ratio is high, but its impact is minimal at low ratios [19]. A study conducted by Onoue K et al.,2014 [20] explored the fatigue properties of steel slag concrete under compression in submerged conditions, suitable for submersible, underwater, and marine applications. Interestingly, utilizing hot metal pre-treated slag as both coarse and fine aggregates led to an increase in fatigue strength. The complete flow of steel slag generation and utilization was shown in the Figure 1.

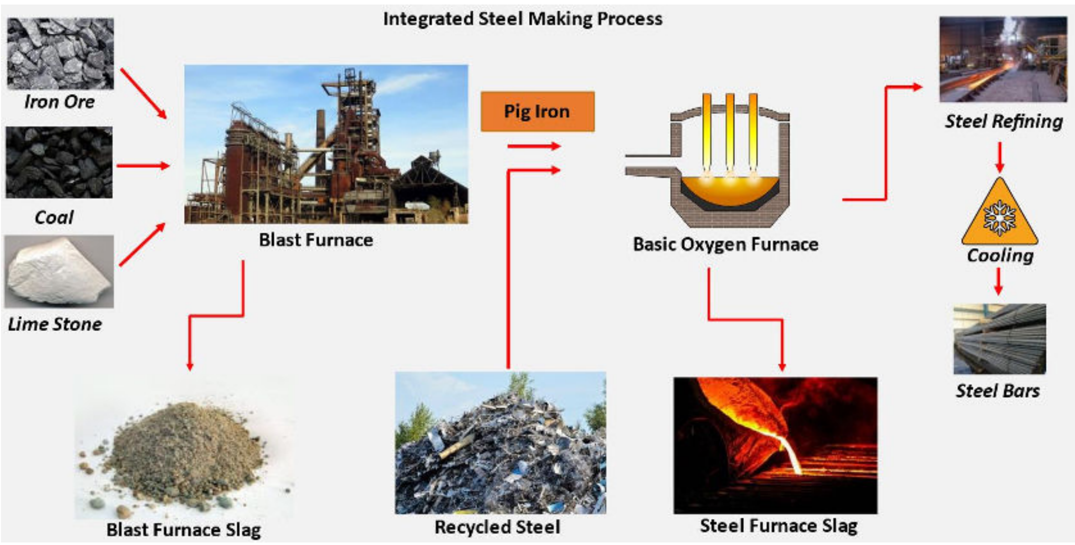

Figure 1. Steel Slag generation and Utilization Flow diagram.

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EXPERIMENTAL PROGRAM

Raw Materials

Ordinary Portland cement (OPC) of grade 43, Steel Slag, Fly Ash and Hydrated lime are used in the experimental investigation and Lime is used as binder throughout the casting process. The analysis was carried out and conforming to IS:8112 specs [21]. The steel slag in Figure 2 (c) was obtained through Rastriya Ispat Nigam Limited (RINL), Vishakhapatnam, Andhra Pradesh.. Physical form of fly ash was shown in the Figure 2(d). Rest of the aggregates are locally sourced. Locally obtained aggregates like crusher dust (6 mm) physical form were shown in Figure 2(b), hydrated lime the physical form was shown in Figure 2(a). Aggregates are conforming to IS 383 [22]. Table 1 shows the chemical compositions of steel slag. The particle Size distribution was shown in the Figure 3. Table 2 shows the physical properties of the raw materials

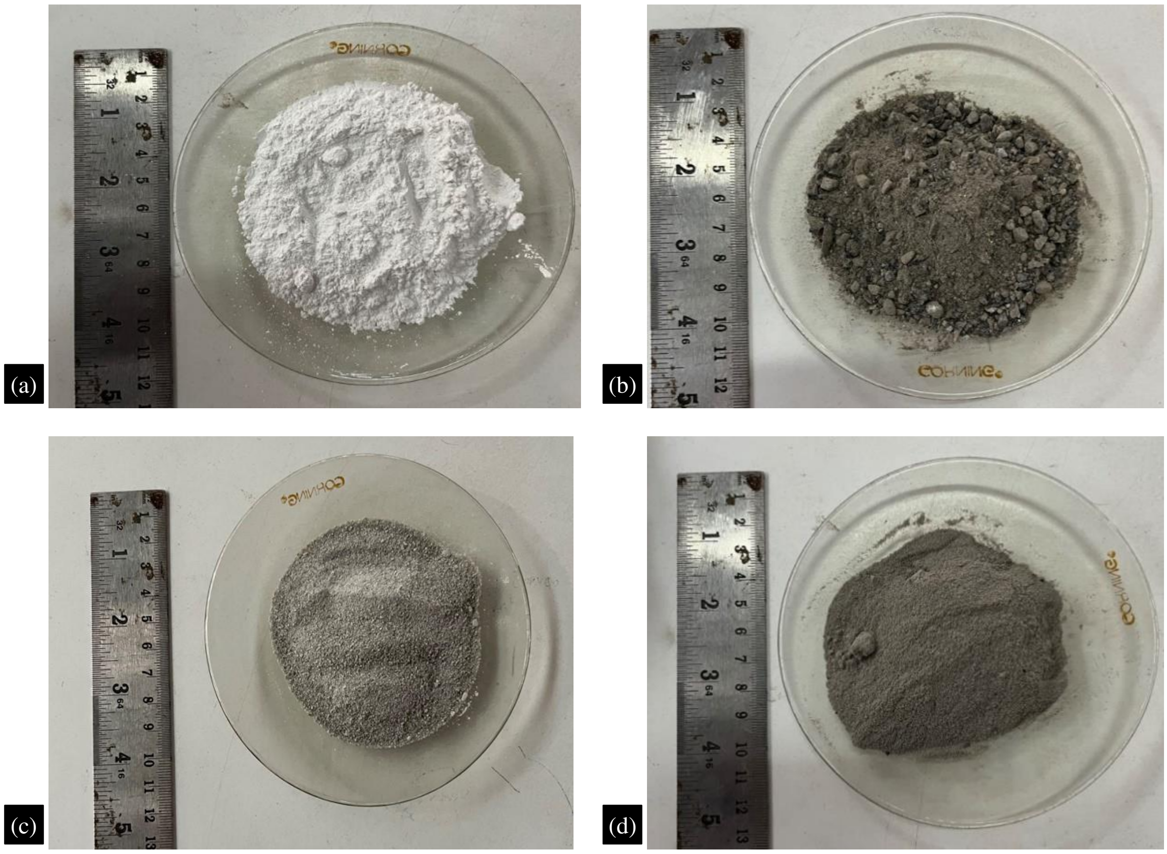

Figure 2. Raw Materials. (a) Hydrated lime Powder, (b) Crusher dust, (c) Steel Slag, (d) Fly ash

Table 1. Chemical properties of materials

Sample	Steel slag	Fly Ash	Lime
SiO_2	69.00%	60.20 %	2.49
Tio_2	702 PPM	1.99 %	0.045
Al_2O_3	1.88 %	27.90 %	1.5
MnO	66.1 PPM	370 PPM	-
Fe_2O_3	0.36 %	4.66 %	2.1
CaO	8.18 %	1.25 %	82
MgO	3.91 %	0.53 %	0.49
Na_2O	14.80 %	593 PPM	7.99
K_2O	8.32 %	1.47 %	-
P_2O_5	308 PPM	0.48 %	0.175

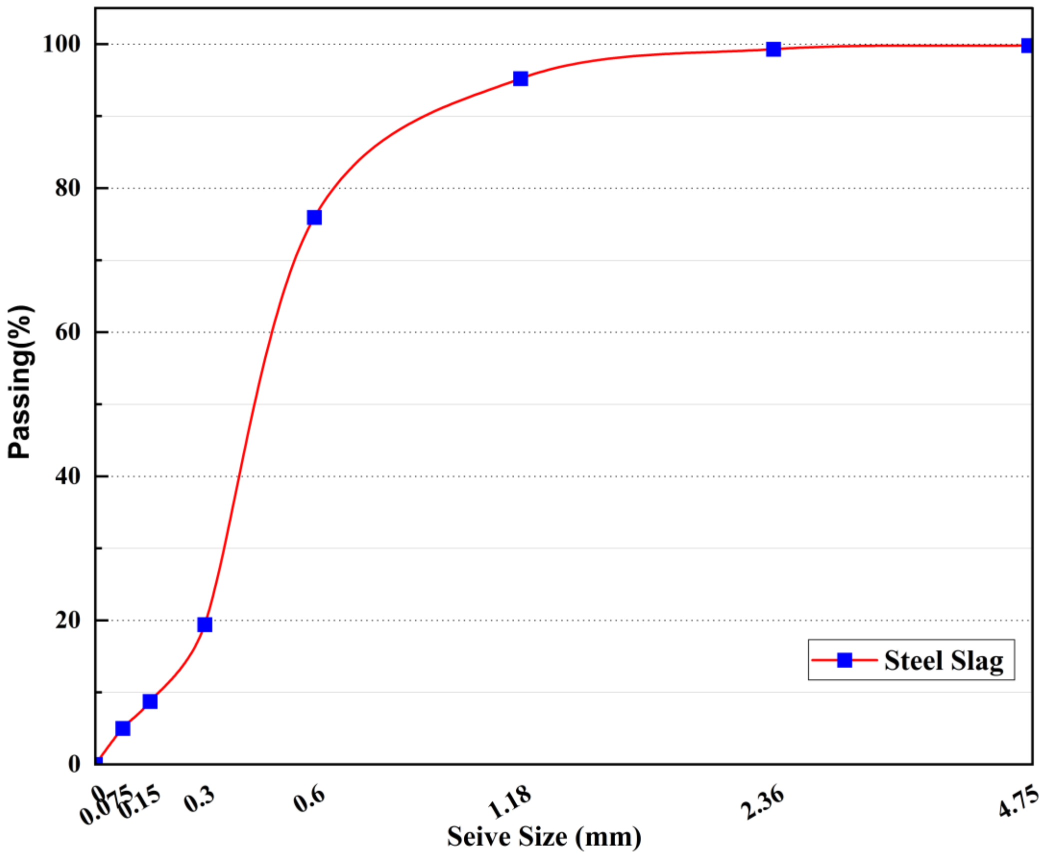

Figure 3. Grain Size Distribution of Steel slag and Crusher Dust.

Mix Proportioning and Casting

The mix proportioning is done according to procedures laid down in IS 10262. Water to binder was fixed at 0.35 % for all the mixes based upon the different steel slag powder replacement. In total % different mortar mixes were prepared with only cement i.e., control, mortar mix with steel slag and cement, mortar mix with steel slag and lime. Control C (100% cement). Steel Slag Lime (25% SS & 25 % lime) (20% SS & 20 % Lime) Steel Slag cement (25% Steel slag & 25% cement) (20% steel slag &20 % cement). The Table 3 shows the mortar mix design. The replacement of raw materials like steels slag, lime, fly ash was done based on volume. Crusher dust was used with fixed percentage (%). In total (mixes were prepared and one control was prepared. Table 3 shows mix proportions with w/b ratio in detail. Initially pre mixing was done thoroughly by adding all the raw materials for achieving the uniform mix all the materials were placed in the mixer and mixing is done by required amount of water to achieve the uniform mix mortar. Then grease is applied to inner surface of the moulds initially for easy removal after the block is developed. Then mortar pouring is done in three layers. Table vibrator is used for compaction. After 24 hours the moulds were de-moulded, marked and all the specimens were kept in curing tank up to 28 days.

Test Procedure

Strength and durability properties were assessed by performing various tests on hardened steel slag lime blocks. All the blocks are of sizes 50 × 50 × 50 mm. Compressive strength was performed in accordance with guidelines listed in IS 516. Curing was done at room temperature for 7 days and 28 days. Before testing the cubes were left for 1 days in dry surface for attaining surface saturation before testing. The compressive strength machine which can apply a peak load of 2000 KN was available in the lab premises was used for testing the cubes. The load was done at the rate of 2.33 kN/s. Three specimens were taken for the testing and average of the three were mentioned to denote the compressive strength of specific mix.

The effect of the sulfuric acid on the mortar mixes were analyzed by using the modified test method B of ASTM C267. Total 3% sulfuric acid was used in our experimental study. The specimens were totally immersed for a period of 56 days after the normal water curing. Here change in the weight and the compressive strength were noted after the experiment. All the cubes were marked and weights were noted initially. In this experimental procedure on weekly basis the acid solution is replaced. After the exposure period of the acid the cubes were removed from the acid solution and dried at open air for a period of 24 hours and to remove ethe loose particles they were brushed thoroughly.

To assess the sulfate attack on the mortar mixes the specimens were immersed in sulfuric acid for a period of 56 days. Initial weights were noted. 5 % Na_2SO_4 Solution was used to prepare the solution. Test method specified in ASTM C1012/ 1012 [24] was used. Changes in the mass as well as compressive strength is noted. For maintain the Ph few drops of (0.1 H_2SO_4) was added.

Test for water absorption and voids was as specified in ASTM C642. after initial curing of 28 days the specimen was left for 56 days in room temperature. Then afterwards four quantities such as Oven dry mass (A), Saturated mass after immersion (B), Saturated mass after boiling (C), and immersed apparent mass (D) were also determined. These were used to determine water absorption and voids. The equations for calculations were presented in (1) & (2)

$$\text{Absorption after immersion in } (\%) = ((B-A)/A) \times 100 \quad (1)$$

$$\text{Permeable pore space volume (voids) } (\%) = ((C-A)/ (C-D)) \times 100 \quad (2)$$

Table 2. Physical properties

Physical properties	OPC	Steel slag	Lime	Fly Ash
Normal Consistency (%)	33			
Initial setting time (min)	68	800 min		
Final setting time (min)	410	1210 min	120	540
Fineness (m^2/Kg)	234	2.560	400 mesh	523.5
Specific Gravity	3.15		2.48	
Bulk density (Kg/m^3)	1440	1600	1587	1250
Fineness modulus	*225 sqm per kg*	3 mm	-	9300 cm^2/g

The permeability to concrete to chloride ion was tested according to ASTM C1202 [25] for period of 28- and 56-days mortar cubes "The standard test for electrical indication of concrete ability to resist chloride ion penetration".

For carbonation test a plastic chamber was prepared and is kept under room temperature. And is used for accelerated carbonation test. After initial cooling in room temperature, they were placed in carbonation chamber for accelerated carbonation test. The depth of carbon is measured after carbonating the sample for 28 days. To know or see the visible interface 1 % phenolphthalein indicator is used.

RESULTS AND DISCUSSIONS

Compressive Strength

The Figure 4 show influence of steel slag on the steel slag lime motor with W/B ratio of 0.35 percentage respectively. It is observed from the results that the increase in the amount of steel slag resulted in decrease in compressive strength of steel slag lime blocks. It is known from the study that higher the days of curing resulted in higher the strength. Here in this study 7 days strengths of developed blocks were minimal, whereas 28 days strength was promising (Refer Figure 5). Some reasons for the early loss of strength are due to when compared with cement early activity of steel slag very low. Here with 30 % replacement and 3 days compressive strength of steel slag lime blocks is very low because reasons like steel slag sometimes decreases the hydration of cement and activity of steel slag is lesser than that of cement.

Table 3. Mix Design

Mix Design (kg)	Binder			Fly Ash	CD	Water
	OPC	*Lime*	*Steel Slag*	-	-	
Control	800	-	-	600	600	0.35 %
SS+C1	200	-	600	600	600	0.35 %
SS+C2	240	-	600	600	560	0.35 %
SS+L1	-	200	600	600	600	0.35 %
SS+L2	-	240	600	600	560	0.35 %

At W/b ratio 0.35 and steel slag at 20 percent replacement it is better when compared with higher replacements like 30% & 40% cement replacement these might be low when compared with pure cement. At 20% replacement the early strength is lower and when it comes to late strengths the gap is not that low when compared with pure cement.

Figure 3 shows about relative compressive strength of various blocks with different fractions of Steel slag, lime and OPC. Strength increment was observed with substitution of steel slag and lime. Mix SS-L1 showed maximum compressive strength of 27, 23, 18 for 3,7 and 28 days. Here the relative compressive strength is defined by percentage of compressive strength accounting for that of cement blocks. It is obvious that relative compressive strength of different concretes increases with age. It is observed that relative compressive strength of concrete with 15 and 20 % steel slag replacement is higher when compared with normal pure cement blocks at lower W/B ratios. The increase of steel slags degree reaction i believed to make direct contribution to the late strength of steel slag lime-based blocks. We should note that steels lag indirectly helps in maintaining late strength of cement by encouraging the late hydration of cement by increasing the water to binder ratio. This might be the reason that Relative compressive strength of steel slag lime blocks is greater than that of normal pure cement blocks. Physical Developed blocks were shown in Figure 6.

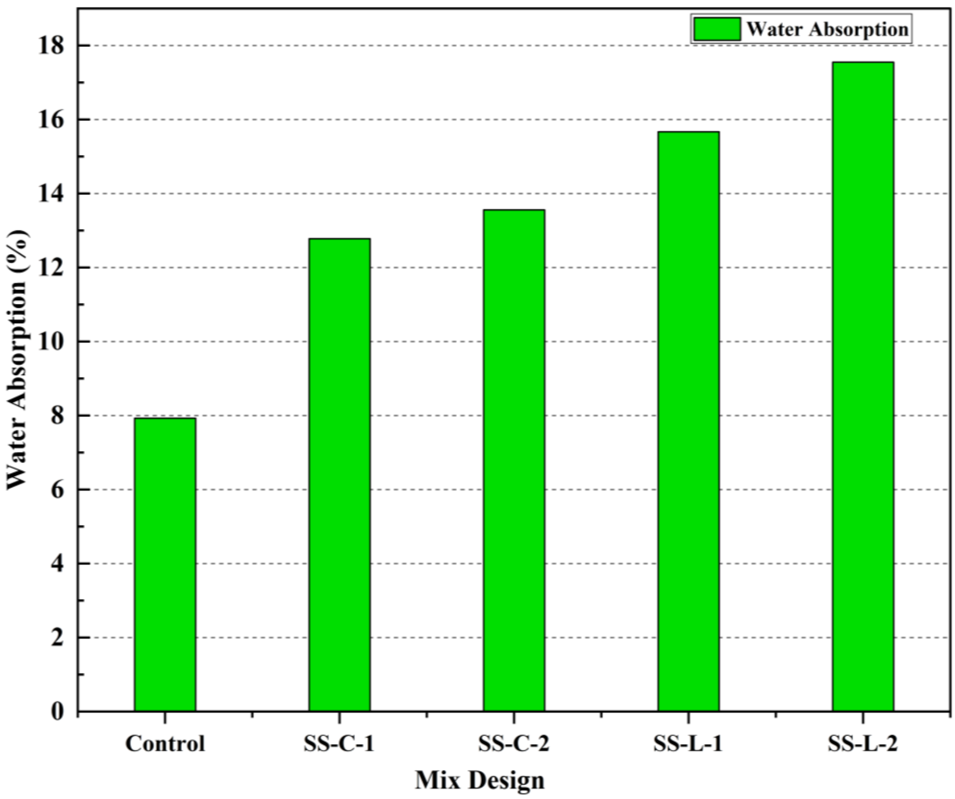

Figure 4. Water Absorption of Developed Blocks.

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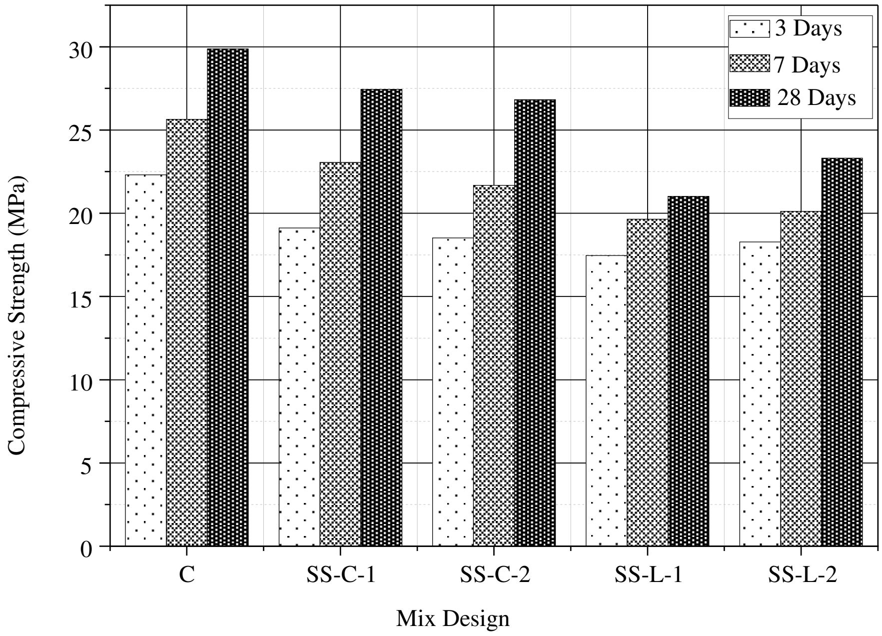

Figure 5. Compressive strength of Developed Blocks

Figure 6. (a) Cement Block (Control) (b) Steel slag-Cement block (c) Steel slag Lime blocks.

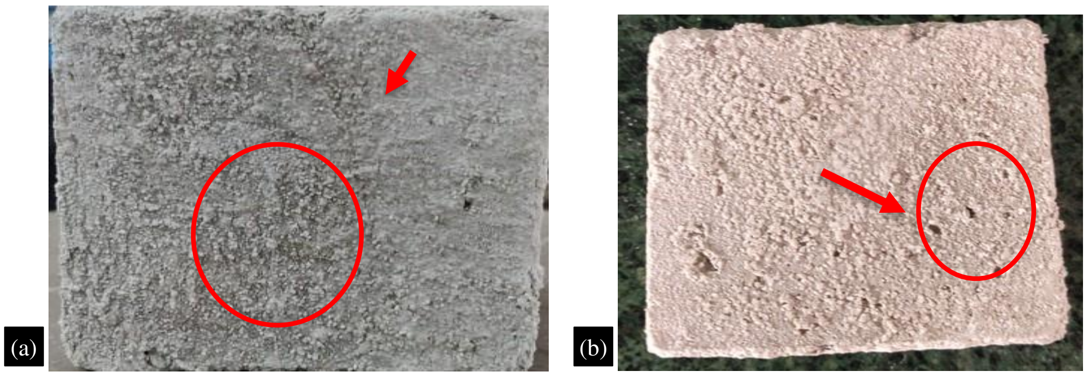

Figure 7. (a) Acid attacked Block (b) Sufate attacked Block.

Acid Attack

The specimens containing different percentages of Steel slag and for comparison samples with lime, fly ash and GGBS were also analyzed. All the samples were curbed for a period of 28 days and were exposed in acid solution for 56 days. Assessment of acid attack was done by evaluation of compressive strength and change in the weight Before and after the exposure. Specimens casted with cement and with lime were compared and analyzed. Blocks after the acid exposure were presented in the Figure 7.

Change in Mass

Figure 8 represents the change in the mass of mortar cubes after being exposed to 56 days Sulfuric acid solution. Test results stated that after 56 days exposure all the specimens lost their weight. Here in this procedure the weight loss decreased with increase in steel slag content up to 30 %. And when it comes to lime the weight reduction increased with increase in lime content. So, weight reduction decreased with increase in addition of steel slag than in lime. SS-C1 reduced the less mass among all the mixes. So here the acid attack resistance is done by addition of steel slag mixed with OPC. The highest mass loss was for one that is mixed with hydrated lime powder. SS-L1 & SS-L2 possessed highest mass loss when compared with control and both SS-C1 & SS-C2.

Change in Compressive Strength

Figure 9 represents the variation sin the compressive strength after 56 days exposure to sulfuric acid. All the samples have shown decrease in compressive strength after being exposed to sulfuric acid for a period of 56 days. All the mixes showed less compressive strength after being exposed sulfuric acid solution. The compressive strength of specimens has reduced in samples with steel slag and OPC than with steel slag and lime. After the control mix SS-C2 performed well and showed decrement in compressive Strength with 22 MPa which was least among all the mixes. In the entire reaction gypsum is formed at the end due to decomposition of $Ca\ (OH)_2$ by sulfuric acid. This reaction results in disintegration of the mortar at the surface and it decomposes the matrix by scaling and softening

Sulfate Attack

The specimens contain steels slag-cement, Steel slag-lime and control were cured in water for 28 days and later exposure to sulfate acid for period of 56 days. Sulfate attack assessment was done by determine compressive strength and change in weight of the mortar cubes.

Change in Mass

The change in the mass of mortar cubes after exposed to 56 days sulfate solution are represented in the Figure 10. After the test is completed, it showed all the cubes gained weight after the exposure. In all the samples we have noticed there is decrement in weight gain with increase in steel slag and lime materials. The reduction in weight gain of samples is observed at SS-C2 with only 0.5% weight gain. This is the least among all the mixes. This mix gained very least weight when compared with control and SS-Lime blocks. The increment in weight is affected by addition of steel slag beyond 30%. The mortar contains Hydrates and $Ca\ (OH)_2$ the sodium sulfate reacts with these chemicals present nd forms needle like structures called ettringite which results in increased weight. The sulfate solution fills the pores in the mortar along with this the precipitation of sulfate in the microstructure increases the weight.

Change in Compressive Strength

The different variations in compressive strength of specimens those are being exposed to sulfate solution for 56 days were shown in the Figure 11. All the specimens showed decrease in compressive straight after exposure to sulfate solution for 56 days. Test results disclose that all the specimens showed decrement in compressive strength after being exposed to sulfate solution for 56 days. It is observed the mixes I.e., SS-C1 & SS-C2 has showed less decreased compressive strength. Amongst all the mixes SS-C1 &SS-C2 showed less decreased compressive strength. The mortar structure and sulfate react and forms ettringite and gypsum due to this internal stress occurs and volume changes. This results in dis integration and deterioration of mortar.

Accelerated Corrosion Testing (Impressed Voltage Test ASTM C-876)

Impressed voltage technique is used to fasten the corrosion process of steel in the laboratory premises. This technique called impressed voltage technique is used in laboratory for monitoring the rate of corrosion on the deterioration of concrete. The schematic diagram of the test apparatus was shown in the Figure 12.

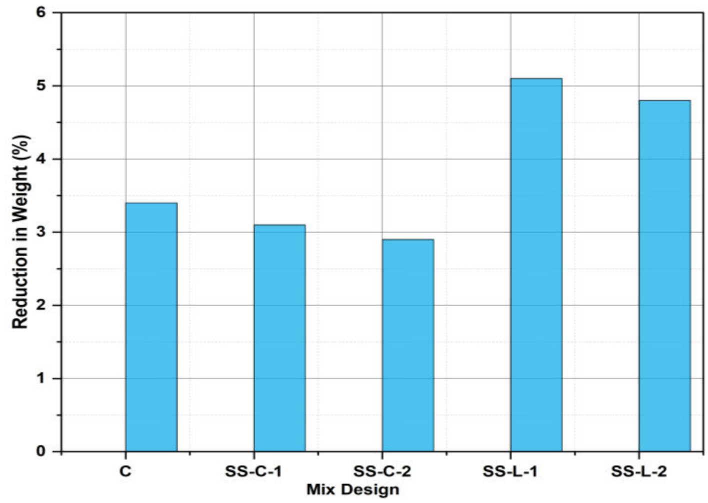

Figure 8. Reduction in weight for Developed Blocks.

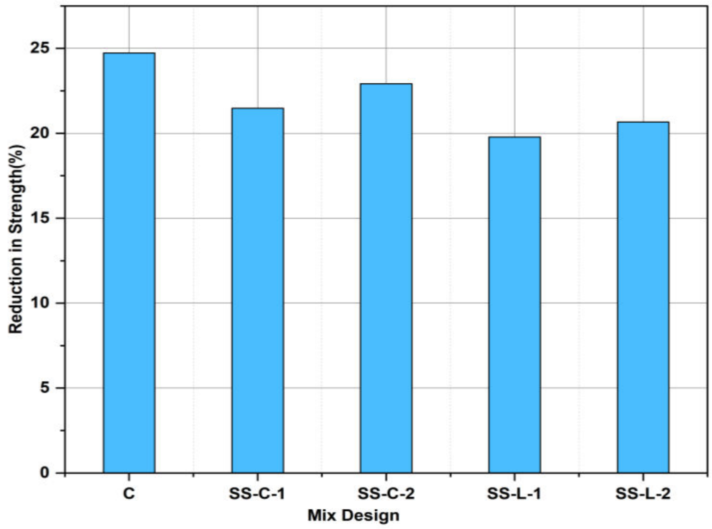

Figure 9. Compressive strength for Developed Blocks.

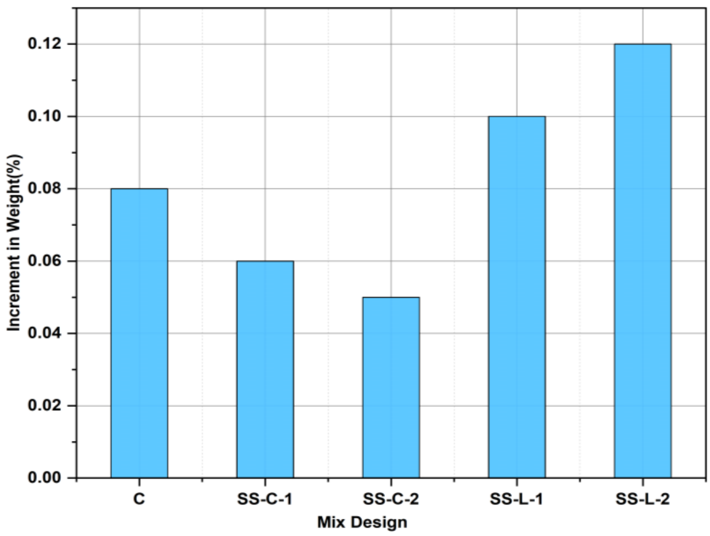

Figure 10. Increment in weight Developed Blocks.

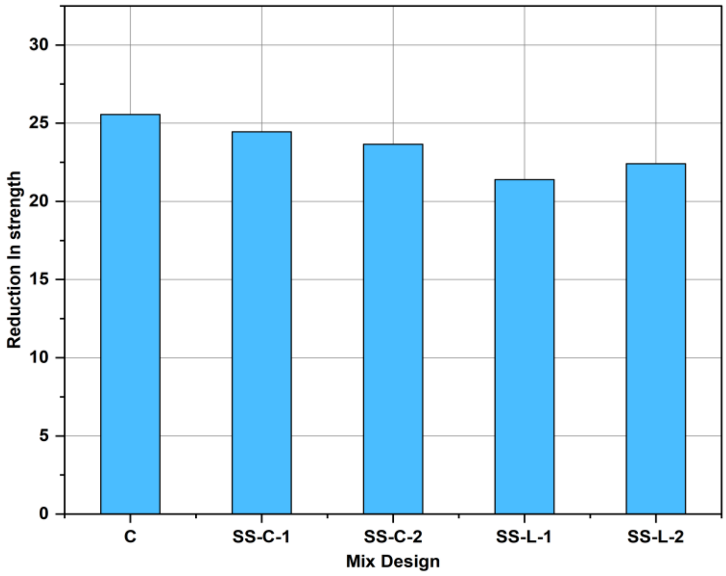

Figure 11. Compressive Strength Developed Blocks.

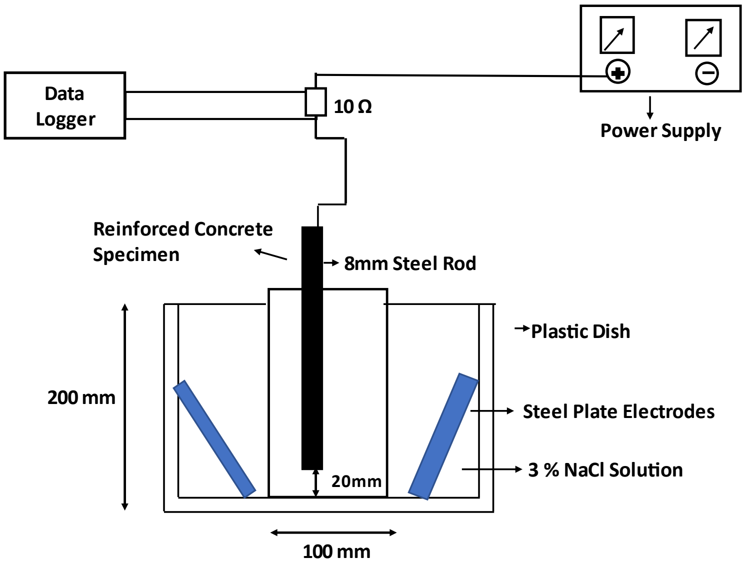

Figure 12. Schematic drawing of Impressed voltage test setup

Apparatus and Procedure for Impressed Voltage Test (ASTM C-876)

The entire test is based on electro chemical polarization. Under accelerated test condition to access the corrosion resistance, mortar cubes of size 50 × 50 × 50 were casted and reinforcement bar of 8mm is embedded in the center of it. Figure 13 shows the lab-based test set up. An immersion sample is prepared with 3% Nacl solution. All the cubes which are casted with rod inserted are immersed into the Nacl solution. The projection rod from the cube sis connected to the Positive terminal (Anode). A stainless-steel plate is placed in the contained of Nacl solution and connected to negative terminal (Cathode). A constant voltage is supplied to the circuit. The variation of the current is maintained to monitor the supply.

Following the test procedure, the mortar specimens were fractured, and the steel rebars were subsequently extracted for mass loss assessments. Before conducting the mass loss measurements, a visual examination of the distinct steel rebars retrieved from the control, SS-C1, SS-C2, SS-L1, and SS-L2 was carried out. And shown in the Figure 14. Based on the information presented in the Figure

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15, it is evident that the steel within the SS-L1 exhibits severe corrosion. In contrast, the corrosion level in mention the other condition is intermediate, and the steel extracted from Control displays the least corrosion, underscoring its higher corrosion resistance within this concrete variant. After the visual observations, mass loss measurements were conducted and corrosion rates were determined by applying the equation specified in ASTM G1-03 [26].

Figure 13. Corrosion resistance Apparatus (Samples with applied voltage).

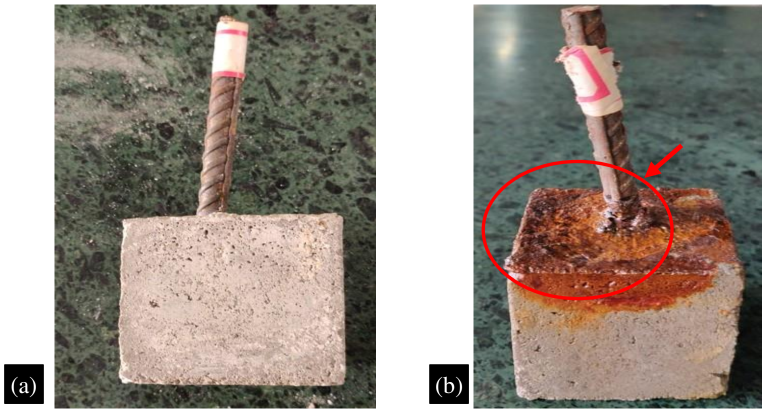

Figure 14. Developed blocks before and after the Test.

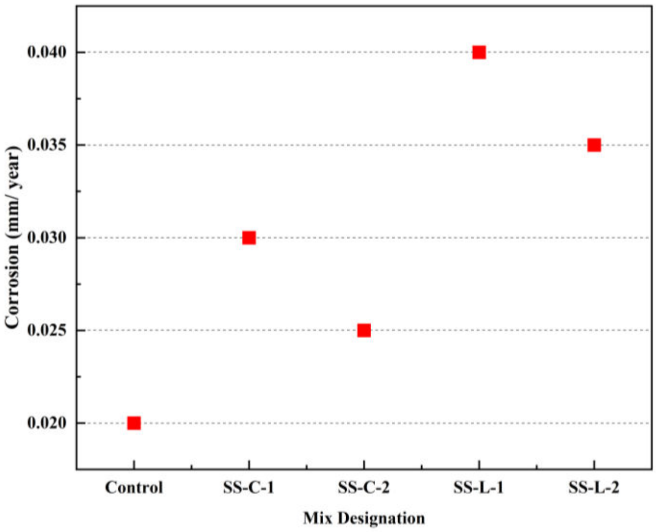

Figure 15. Corrosivity Rate in All Mix Samples.

CONCLUSION

The results obtained after the study indicates improvement in strength and durability properties of the developed blocks. By the obtained results we can consider steel slag cement & steel slag lime as one of the alternatives for mortar applications in construction industry. Following observations are taken while considering steel slag cement and steel slag lime mortar.

- The steel slag when added up to 30 % in the whole mix improved its compressive strength, The CS of SS-C2 was highest when compared to SS-lime and control. Angular shape of steel slag particles enhanced the stress distribution the cement mortar matrix.
- However, there is a decrement in compressive strength of SS-L1 &SS-L2 (steel slag with lime) here compressive strength is marked lowest and below SS-C1 &SS-C2
- All mortar cubes gained weight after 56 days sulfate solution exposure. SS-C2 containing 30 % steel sag showed least change when compared with all the mixes. With only 0.05% change. Filling of pores in the mortar cubes, surface precipitation and formation of ettringite resulted in the increase if weight of specimens. Sulfate solution resulted in decrease of compressive strength of all the mixes. Strength reduction was least for SS-C2 and highest for ones with Steel slag and lime powder. The expansions in the mortar cubes results in development of internal stress and causes the formation of gypsum which leads to cracks and ettringite.
- All the mortar cubes including the control block lost weight after 56 days acid exposure. SS-C2 with 30% steel slag replacement showed less change of mass. The loss of weight is higher for SS-L1 & SS-L2 lime blocks.
- All the mortar cubes including control showed less compressive strength after exposure to 56 days in acid solution. Strength reduction was low for SS-C2 the one with 30% steel slag replacement and highest for steel slag lime. Gypsum is formed by decomposition of $Ca\ (OH)_2$ by sulfuric acid. Results in surface disintegration of the mortar block.
- The binding matrix is typically disturbed when mortar blocks come into contact with sulfate solutions, perhaps resulting in a reduction in the concrete's compressive strength. The reduction in compressive strength was the least pronounced in the SS-C1 & SS-L1 mix and the most significant in the SS-C2, SS-L2 and Control mix. This reduction in strength is attributed to the development of internal stresses within the mortar molecules, caused by the expansion resulting from the formation of gypsum and ettringite. These factors contribute to the development of cracks and the overall deterioration of the concrete.
- Following 56 days of exposure to an acid solution, a reduction in weight was observed in all concrete mixtures. Notably, the CS-40 mix, containing 40% CS, experienced the least mass loss, amounting to 5.63%. However, as the substitution of CS exceeded 40%, the weight loss escalated, reaching its highest level in the CS-100 mix
- All test specimens exhibited a decrease in compressive strength following exposure to the acid solution. The reduction in strength was minimal for SS-L1 & SS-L2 and most pronounced for Control, SS-C1 and SS-C2. This decline in strength can be attributed to the action of sulfuric acid, which decomposes calcium hydroxide ($Ca\ (OH)_2$) and leads to the formation of gypsum. The Mortar Blocks inner structure and exterior surface will gradually deteriorate as a result of this process.
- The incorporation of SS in the concrete mixes demonstrated an enhancement in resistance to water absorption, in Steel Slag cement samples. In the case of the SS-C1 &SS-C2 mortar mix, there was a notable decrease of approximately 17% in water absorption after 28 days compared to the control mix. This highlights the beneficial impact of including SS in improving water resistance properties there by reducing the water absorption
- Water absorption exhibited a notable increase when the substitution of SS exceeded 20%. Among all the mix variations, SS-L1 and SS-L2 showed the highest level of water absorption. This phenomenon can be attributed to the higher proportions of SS, which contribute to an increased free water content within the concrete, subsequently leading to greater void formation.

The study's findings demonstrate that incorporating SS as a replacement for FNA enhances the strength and durability properties of concrete by up to 30%. Consequently, it is recommended to utilize CS as a substitute for up to 40% of the FNA to achieve concrete with commendable strength and durability attributes. Furthermore, the use of slag cement concrete incorporating CS should be seriously considered as a viable option for structural applications.

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