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Evaluation of Steel Industrial Slag as Partial Replacement of Cement in Concrete

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Abstract

Cement is the most important ingredient in concrete, which acts as a binding material. It is evaluated that cement is the second largest industrial source of CO2 on earth. This demands a partial or full replacement of cement by an environment-friendly material. In this research industrial waste slag from a local Steel Mill, namely Mangla Metals was selected as possible replacement of cement. Some preliminary standard tests conducted on the slag showed its strong chances to be used as pozzolana. Slag used for this study was reduced to the particle size passing through ASTM standard sieve #100. Concrete specimens containing 10% and 20% replacement of cement by slag were prepared. The mechanical properties like compressive, split cylinder tensile and flexure strength were determined as per standard ASTM methods. Tests were conducted at 3, 7 and 28 days of concrete age. Results show a decrease of 14% in compressive strength, 7.5% in tensile strength and 10.5% in flexure strength for 10% replacement vis-à-vis control specimens at 28 days. For 20% replacement, the decrease in compressive, tensile and flexure strength are 25.5%, 29%, 31% respectively. Additionally, ASTM standard strength activity index test with finer slag particles passing through ASTM sieve #200 provided compressive strength more than that of control specimen. Based on the results, it is concluded that the industrial slag has the potential to partially replace the cement if slag is ground to the particles, passing through ASTM sieve #200. This could lead to a huge reduction of cement quantity in concrete and the environmental burden due to deposition of waste slag in landfills.

Keywords: Concrete; Cement; Industrial Steel Slag; Mechanical Strength; Strength Activity Index.

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1. Introduction

Concrete is the most important construction material serving mankind since centuries. Concrete is highly versatile and the most widely used material after water. The current usage of concrete is estimated to be about 12 million tons per annum and is still increasing by each passing day. Concrete finds its applications from the houses we live in to the roads & bridges we travel. Concrete is a combination of cement, sand, course aggregates and water. To coupe up with the increasing demands of concrete, efforts are made to increase the production of cement and the natural aggregates. The manufacturing of cement requires a huge amount of energy and releases hazardous gases to our environment. Similarly, the query sites, from where the natural aggregates and the raw material for cement are acquired, are not only polluting our environment but also causing depletion of our natural resources.

In our modern society, everyone is looking for an economical solution that can utilize our industrial waste so that our environmental burden are reduced and our natural resources are protected from depletion. Serious efforts are being made in all over the world to find out the suitable substitution of constitutions of concrete [1-3]. The emphasis on the utilization

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of industrial waste in concrete provides a very environmental-friendly solution [4]. Their safe deposition requires a lot of efforts and still they remain a burden to our environment. Their usage in concrete will be very advantageous. It will not only be financially viable, but it will also reduce the demand of cement thus protecting our environment. The utilization of industrial waste will also help us in their safe disposal.

In this research, we thoroughly checked out the waste material of all the local industries working near Mirpur AJ&K. While going through Mangla Metals (Pvt) Ltd, a local steel industry situated in Khaliqabad (a small town near Mirpur AJK), we found out that they are facing real landfill shortage issues. Currently, the industrial slag is being deposited in large open fields causing not only landfill shortages but also severe environmental threats. So we chose this local industrial waste slag as our case study for use in concrete. Different preliminary tests including XRD, SEM and EDX were conducted; the cement mass in concrete specimen was partially replaced by the powder slag in two proportions i.e 10% and 20%. Different strength tests were conducted and compared with the control specimens; the results proved that the slag can be beneficially recycled in cementitious composites like concrete.

2. Materials and Methods

2.1. Materials

The raw material for casting of specimens include cement, sand, aggregate, industrial waste slag and a superplasticizer. Their properties and source are described below.

2.2. Cement

The cement used for this study is OPC, purchased from Fauji Cement, a renowned local cement brand; the salient features of the cement are described in Table 1.

Table 1. Properties of OPC

Sr No.	Tests		Result
1	Compressive Strength	(28 Days)	9260 psi
2	Setting Time	Initial	180 min
		Final	240 min
3	Soundness	Le-Chatlier Expansion	1.50 mm
4	Fineness		307 m^2/kg
5	Consistency		27%
6	Specific Gravity		3.15

The chemical composition of the cement is given in Table 2.

Table 2. Chemical properties of OPC

Sr. No.	Oxide	Percentage
1.	SiO_2	21.45%
2.	Al_2O_3	5.20%
3.	Fe_2O_3	3.25%
4.	CaO	62.6%
5.	MgO	1.90%
6.	SO_3	2.70%
7.	I.R	0.55%
8.	Total Alkalies	0.70%
9.	C_3A	8.29%
10.	AR	1.60%
11.	SR	2.54%
12.	LSF	0.89%
13.	L.O.I	1.88%

2.3. Aggregates

The aggregates were acquired from a local source. The sand used for this research was obtained from Mangla Query, a local source, and is shown in Figure 1.

Figure 1. Sand from Mangla query

The sieve analysis of the used sand is shown in Table 3.

Table Error! No text of specified style in document.**. Sieve Analysis of Fine Aggregates**

Sr. No.	Sieve No.	Sieve Size (mm)	Mass Retained (gm)	Cumulative Mass Retained (gm)	Percentage Retained (%)	Percent Passing (%)
1	4	4.75	43	43	4.26	95.74
2	8	2.36	116	159	15.74	84.26
3	16	1.18	171	330	32.67	67.33
4	30	0.60	128	458	45.35	54.65
5	50	0.30	268	726	71.88	28.12
6	100	0.15	206	932	92.28	7.72
7	200	0.08	54	986	97.62	2.38

The coarse aggregates were chosen from a local limestone Query namely, Mangla. Figures 2 and 3 show the size of the aggregates used in this study.

Figure 3. Coarse aggregates (10 mm-20 mm)

Figure 2. Coarse aggregates (5 mm-10 mm)

Sieve analysis of both size of aggregates is given in Table 4 and Table 5.

Table 3. Sieve analysis of coarse aggregates (10 mm-20 mm)

Sr. No.	Sieve No.	Sieve Size (mm)	Mass Retained (gm)	Cumulative Mass Retained (gm)	Percentage Retained (%)	Percent Passing (%)
1	¾	19.00	0	0	0.00	100.00
2	½	12.50	857	857	13.19	86.81
3	3/8	9.50	3858	4715	72.59	27.41
4	#4	4.75	1481	6196	95.40	4.60
5	#8	2.36	169	6365	98.00	2.00

Table 4. Sieve analysis of coarse aggregates (5mm-10mm)

Sr. No.	Sieve No.	Sieve Size (mm)	Mass Retained (gm)	Cumulative Mass Retained (gm)	Percentage Retained (%)	Percent Passing (%)
1	3/8”	9.5	209	209	3.60	96.40
2	#4	4.75	4148	4357	74.99	25.01
3	#8	2.36	1290	5647	97.19	2.81
4	#16	1.180	71	5718	98.42	1.58

The important physical properties of aggregates are shown in Table 6**.**

Table 5. Physical properties of aggregates

Sr. no.	Property	Aggregates	Result
1	Specific Gravity (SSD)	Sand	2.71
		Coarse Aggregates (5-10mm)	2.73
		Coarse Aggregates (10-20mm)	2.70
2	Absorption	Sand	1.36
		Coarse Aggregates (5-10mm)	0.56
		Coarse Aggregates (10-20mm)	0.53
3	Moisture %	Sand	1.44
		Coarse Aggregates (5-10mm)	0.1
		Coarse Aggregates (10-20mm)	0.1
4	Finess Modulus	Sand	2.62
5	Sand Equivalent	Sand	89%

2.4. Industrial Waste Slag

Industrial waste slag from a local steel mill named Mangla Metals was obtained. It was ground to fine powder using a ball milling machine. It was then passed through sieve # 100 to get the final fine slag. The images of waste slag in raw form is given in Figure 4 and that after ball milling and sieving is given in Figure 5.

Figure 4. Industrial waste slag in raw form

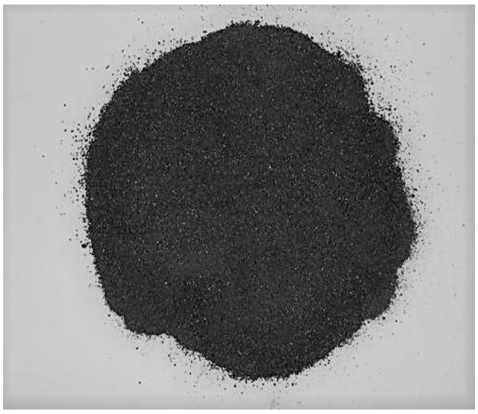

Figure 5. Industrial waste slag after ball milling and sieving

The ball milling machine with balls and industrial waste slag is shown in Figure 6 and Figure 7 respectively**.**

Figure 6. Industrial waste slag and balls placed in ball milling machine

Figure 7. Ball milling machine

2.5. Properties of Industrial Waste Slag

Figure 8 shows the X-ray diffractogram (XRD) pattern of industrial slag. The broad hump between the angles (θ) 50 to 200 clearly indicates that the slag contains amorphous mineral phases, most likely to be silica and magnesia, as has already been shown previously by Kumar et al. [5]. The XRD shows about 80 % amorphous phases [6]. The pattern also elucidates that the slag is, in fact, blast furnace slag [7] characterized by the "glassy state" [8].

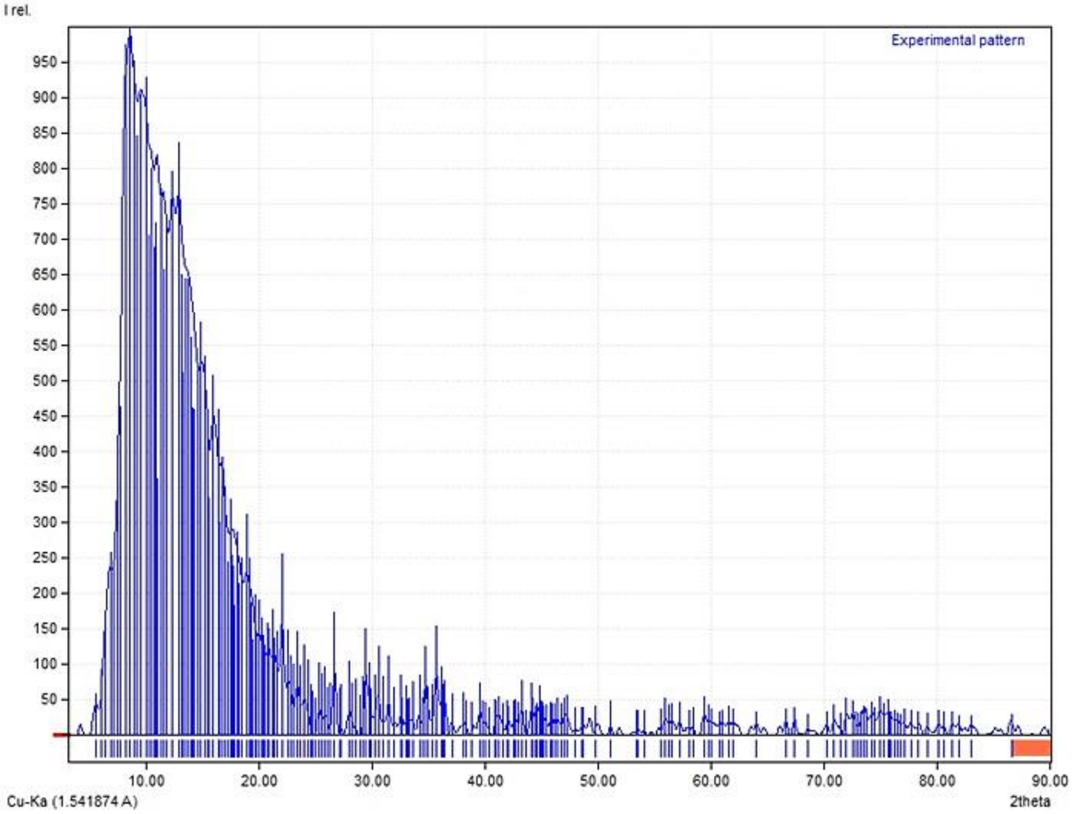

Figure 6. XRD of industrial waste slag

The Scanning electron microscopic images of the slag particles are shown in Figure 9. The slag particles possess sharp edges and irregular shape. The sharp angles and rough texture are responsible for the reduction in the workability and might enhance the water requirements of the concrete mix. The chemical composition of the used slag powder is shown in Table 6. The composition shows that the slag powder is of siliceous nature. The slag particles are rich in SiO_2 along with oxides of Iron, Aluminum, Manganese, Calcium, Zinc and Titanium in smaller quantities. The total oxide composition of SiO_2, Fe_2O_3 and Al_2O_3 is 70.63%, which shows that it might possess pozzolanic character.

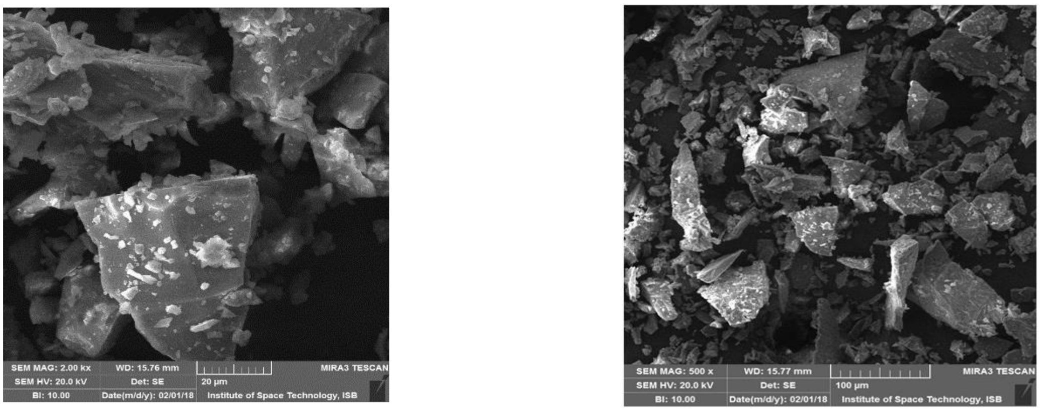

Figure 7. SEM analysis of slag powder particles

Table 6. Chemical composition of slag

Compound	Percentage
Cr_2O_3	2.64
Na_2O_3	0.85
Al_2O_3	8.71
SiO_2	40.02
MgO	1.01
TiO_2	2.42
CaO	7.5
MnO	8.1
Fe_2O_3	21.9
ZnO	2.3

The mix design used for this study is shown in Table 7; it is that as used for the control specimens. For slag concrete, two sets of specimens were prepared by replacing 10% and 20% mass of the cement by the industrial slag a plasticizer (poly-carboxylate ether) with a specific gravity of 1.170 and zero chloride content was also added to the mix. This particular mix design is being used for the construction of a very important local bridge namely, Rathowa-Haryam Bridge, which connects two towns of the state of Jammu and Kashmir across River Jhelum.

Table 7. Mix design used for this study

Sr. No.	Constituent	Quantity per 1 of Concrete
1	Cement	350 kg
2	Fine Aggregates	794.40 kg
3	Coarse Aggregates (10 mm-20 mm)	646.60 kg
4	Coarse Aggregates (5 mm-10 mm)	432.62 kg
5	Water	170.15 kg
6	Admixture	4.91 kg
7	W/C Ratio	0.46

Two types of specimen were prepared for this study. Cylindrical specimen for compression and split tensile test (150 mm diameter and 300 mm length), while beams (515 mmx 136 mmx 87 mm) for flexure strength test as per ASTM standards [9-11]. Three sets of specimens were casted: Each set consisted of 15 Beams and 30 cylindrical specimens. First set consisted of control specimen, while cement is replaced 10% and 20% by waste slag in the other two sets respectively. Total of 90 cylindrical specimen and 45 beams were casted for this study. The casting and curing were done as per ASTM C31[12]. The strengths were determined at 3, 7 and 28 days of concrete age.

Compressive strength test was conducted according to ASTM C39/C39M [13]. Split tensile strength test was performed according to ASTM C496/C496M [10]: This test is significant in evaluating the shear resistance offered by concrete and in determining the development length of reinforcement. In general, its value is greater than direct tensile strength and lower than flexural strength (modulus of rupture). Flexure strength test was carried out according to ASTM C78/C78M [14]: This test is used to determine the flexural strength of concrete. The results of this test method may be used as a basis for mixture proportioning, evaluating uniformity of mixing, and checking placement operations by using sawed beams. It is used primarily in testing concrete for the construction of slabs and pavements.

3. Results and Discussion

The strength activity index test was carried out in accordance with the ASTM C311/C311M [15]. The calculation of flow is shown in Figure 10. The Flow of control specimen, slag mortar and corrected flow of slag mortar are given in Table 9.

Figure 8. Measurement of flow for strength activity test

Table 8. Flow for strength activity index test

Sr. No.	Specimen	Graded Sand (gm)	Cement (gm)	Industrial slag powder (gm)	Water (ml)	Flow (mm)
1	Control Sample	1375	500	0	242 ml	148.67
2	Test Specimen # 1	1375	400	100	242 ml	143.73
3	Test Specimen # 2	1375	400	100	251 ml	148.11

The test results given in Table 8, clearly indicate that the slag particles require more water than the cement to attain the same flow or workability. As discussed earlier, the sharp edges and rough texture of the slag particle are responsible for more water requirement to attain an equivalent workability. A hit and trial method was adapted to equate the workability of slag concrete with that of the control specimens.

The Results of the compressive, split cylinder tensile and flexure strengths are shown in Figures 11, 12 and 13 respectively. The results show that by the age of maturity, the compressive strength reduces to 86% and 74% respectively for 10% and 20% cement replacement by the industrial slag passing through sieve #100. The split tensile strength reduces to 93% and 71% respectively. The flexure strength reduces by 90% and 69% respectively. Above results show that 10% partial replacement of cement gives high initial compressive strength than that of the control specimen. However, 20% replacement provides lesser compressive strength. Compressive strength reduces from 103% of the control specimen to 85% of the control specimen gradually from 3 days to 28 days for 10% replacement. Compressive strength for 20% replacement remains 70% of that of control specimen at all ages of the specimens.

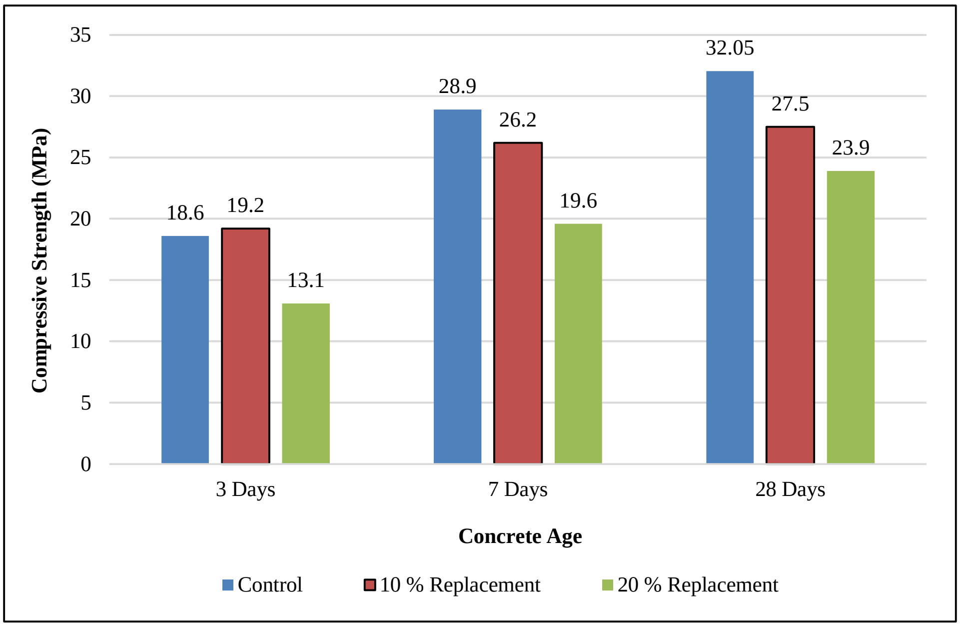

Figure 9. Compressive strength

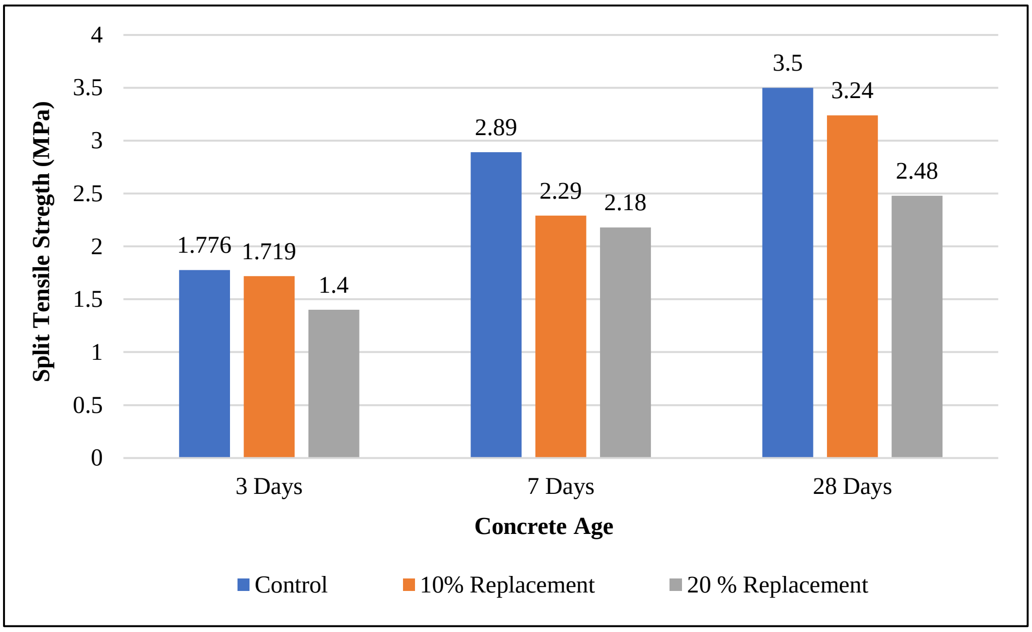

Figure 10. Split cylinder tensile strength

From above results it is evident that split cylinder tensile strength test is 10% of the compressive strength for all control, 10% and 20% partial replacement samples at all 3,7 and 28 days of age. Split cylinder tensile strength decreases from 97% of that of control specimen at 3 days to 93% at 28 days for 10% replacement. Split cylinder tensile strength gradually decreases from 79% of that of control specimen at 3 days to 75% at 7days and 71% at 28 days for 20% replacement.

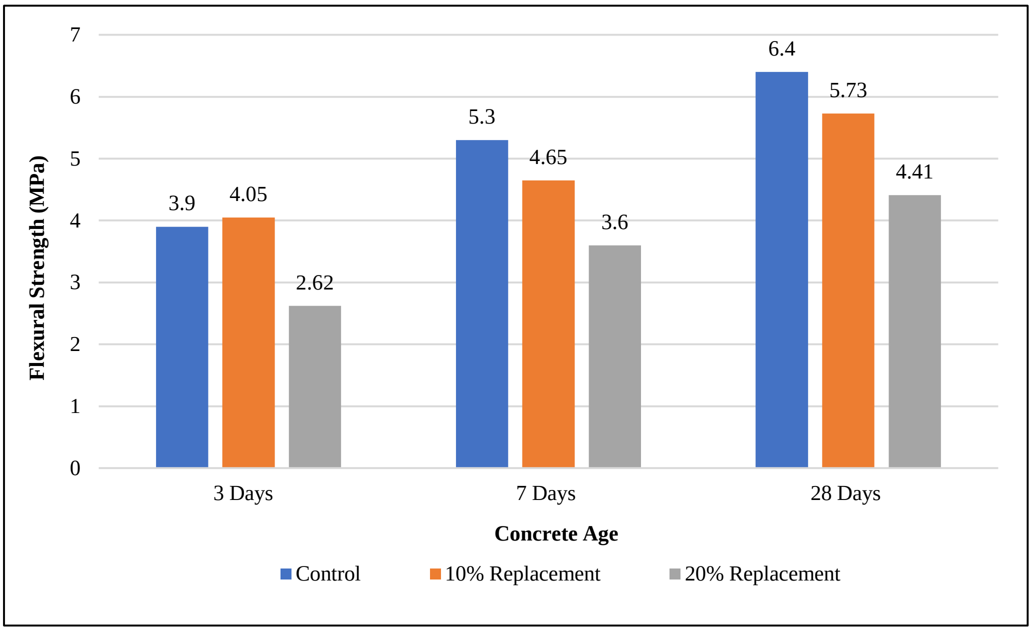

Figure 11. Flexural strength

Above mentioned results show that flexural strength reduces from 104% of that of control specimen to 89.5% at 28 days for 10% replacement. Flexural strength remains almost constant at 68% of that of control specimen at all ages for 20% replacement. The split cylinder tensile and flexure strengths as a function of compressive strength are shown in Table 9. The results show that tensile strength is 10% whereas flexure strength is approximately 20% of the compressive strength for all the specimens at all ages.

Table 9. **Split cylinder tensile and flexure strength as a function of compressive strength**

Relationship	Specimen	3 Days	7 Days	28 Days
σ_t/σ_c	Control	0.095	0.10	0.10
	Industrial Slag 10 % Replacement	0.09	0.09	0.11
	Industrial Slag 20 % Replacement	0.10	0.11	0.1
$\sigma f/\sigma c$	Control	0.20	0.18	0.20
	Industrial Slag 10 % Replacement	0.21	0.18	0.2
	Industrial Slag 20 % Replacement	0.20	0.18	0.18

At the end, the strength activity index was determined using more fine slag particles i.e. particles passing through sieve # 200. The same composition was used as given in Table 8. The results are shown in Table 10.

Table 10. **Strength Activity Index with slag particles passing sieve #200**

Sr. No.	Specimen	7 Days Strength (MPa)	28 Days Strength (MPa)
1	Control Mortar	285.36	295.20
2	Industrial Slag Mortar	295.20	373.92

The results of Table 10 are promising and show that the slag particles if ground to the size of the cement could provide a very good replacement of cement. The finer the particle, more is the area per unit volume, available for hydration.

4. Conclusion

Industrial slag used in this experiment mainly possesses silica and can be classified as a siliceous pozzolanic material. The pozzolanic activity increases with the decrease in the quantity of industrial slag. The pozzolanic activity is dependent on the particle size of the industrial slag, finer the particle more is the strength for a given partial replacement of cement. Split cylinder tensile strength test is about 10% of the compressive strength for all control, 10% and 20% partial replacement samples at all 3,7 and 28 days of age. Flexural strength test is about 20% of the flexural strength for all control, 10% and 20% partial replacement samples at all 3,7 and 28 days of age. The industrial slag particles have irregular shape with sharp angles requiring more water to attain a certain workability of the control specimen. Most importantly, the finer slag powder (passing ASTM sieve #200) gives compressive strength even higher than the control specimen. The 20% replacement of cement by the slag powder (passing through ASTM sieve #200) used in this study could save the amount of cement in the future projects of the locality and could provide an environment friendly construction.

5. Acknowledgements

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6. Conflicts of Interest

The authors declare no conflict of interest.

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