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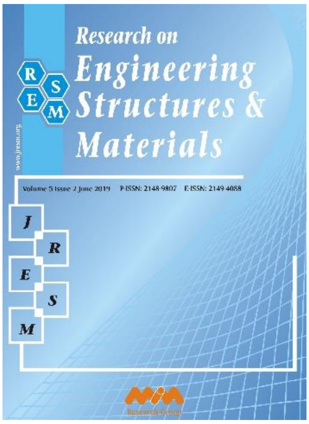

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Research Article

Experimental investigation on use of ferrochrome slag as an alternative to natural aggregates in concrete structures

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Abstract

In view of reducing the cost of concrete and to meet the demand of conventional raw materials used in concrete, various industrial and solid wastes are being studied for their utilization in concrete without affecting its fresh, hardened and durability properties. Ferrochrome slag is waste material obtained from manufacturing of high carbon ferrochromium alloy. Depending upon cooling process, two types of ferrochrome slag are produced i.e. air cooled by letting molten slag cooled down under normal temperature and water cooled ferrochrome slag by quenching molten slag. Presence of chromium in Cr+3 and Cr+6 state in ferrochrome slag is an area of concern towards its feasibility to be used as a constituent material in concrete. In this study, physical and chemical properties of both types of slags were evaluated to check the feasibility of replacing natural fine aggregates with water cooled ferrochrome slag and natural coarse aggregates with air cooled ferrochrome slag. In concrete mix designs, natural aggregates were replaced with ferrochrome slag at replacement levels of 30%, 60% and 100%. Mixes were prepared at two w/c ratios and were evaluated for different fresh, hardened and durability properties of concrete. It was concluded that 60% replacement of natural coarse aggregate with air cooled ferrochrome slag and 60% replacement of natural fine aggregate with water cooled ferrochrome slag in concrete is feasible.

1. Introduction

Concrete is the most commonly used structural material for majority of construction work taking place across the globe. Out of its total volume, aggregate (both coarse and fine combined) makes up for the 70% of its volume and thereby making them the principal component materials in concrete production. Rapid growth in population, urbanization and industrialization has led to huge increase in demand of housing, transportation and other infrastructural amenities which will require large amount of concrete. This has resulted in scarcity of conventional fine and coarse aggregates which are required for producing concrete. In view of reducing the cost of concrete and to meet the demand of conventional raw materials used in concrete, various industrial and solid wastes are being studied for their utilization in concrete without affecting its fresh, hardened and durability properties. The use of industrial solid waste as a partial replacement of conventional raw materials for preparation of concrete is a favorable way to reduce the environmental impact from the construction industry along with compensating the lack of natural resources and thereby reducing the demand for extraction of natural raw materials [1].

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The Ferrochrome slag is an important byproduct of ferrochromium industries and generated during the manufacturing of ferrochrome alloy. Ferrochrome alloy is manufactured in a submerged electric arc furnace by physiochemical process at the temperature of 1700ºC. The main constituents of ferrochrome slag are SiO2, Al2O3 and MgO with minor traces of ferrous/ferric oxides and CaO. Chromium is generally present in the form of partial altered chromite and entrapped alloy. Quartzite is added as fluxing material to reduce the melting temperature of slag. The slag production is 1.1-1.6 t / t Ferrochrome alloy depending on feed materials.

Depending upon the cooling process, two types of ferrochrome slag are produced i.e. air cooled by letting the molten slag cool under normal temperature and water cooled ferrochrome slag by quenching the molten slag. Since, the particle size of air cooled ferrochrome slag is in coarser range, it can potentially be used as replacement of natural coarse aggregate in concrete. Whereas, since the particle size of water cooled ferrochrome slag lies in finer range, it can potentially be used as replacement of natural fine aggregate in concrete. However, presence of chromium as Cr+3 which is not soluble in water (when oxidized turns into Cr+6) and Cr+6 which is soluble in water (hazardous), makes ferrochrome slag a potent threat to environment.

The Ferrochrome slag possesses physical properties similar to natural aggregates which makes it a suitable material for application in concrete as a replacement of natural aggregates. However, very limited research work and studies have been conducted to investigate presence of different forms of Chromium in ferrochrome slag and possibility of utilization of ferrochrome slag as replacement of conventional aggregates in concrete (especially reinforced cement concrete). In both water cooled and air cooled ferrochrome slag as determined by Nilamadhaba et.al [2], chromium is present in stable spinel phase and in the form of entrapped metallic granules. In molten slag, Cr is mainly in Cr+2, which is not stable at room temperature and therefore solidifies in most stable oxide i.e. Cr2O3 or Cr+3 which is insoluble in water and also not expected to oxidize at atmospheric temperature to highly soluble and carcinogenic Cr+6 form. The Chromium present in entrapped metallic granules is in dispersed state and therefore not expected to leach out when in contact with water. However, many researchers addressed the oxidation of Cr+3 to Cr+6 in the presence of strong oxidants which results in the possibility of slowly releasing Cr+6 to the environment in the long run. Leachability of heavy metals is the main environmental concern due to possible impacts on human health and environmental pacts.

Lind et. al [3] investigated that "leaching tests with salt seawater and pH adjusted water reveal low leachability from the slag for most elements. It was also reported that in road construction, there was a low migration of particles from the slag to the underlying soil and that the leaching from the Ferrochrome slag to the groundwater was low for the elements analyzed, with the exception of potassium. Al Jabri et al. [4] investigated the combined effects of fly ash as cement replacement and ferrochrome slag as a substitute of natural aggregate. Cement was replaced with fly ash at the ratio of 10, 20, and 30% whereas coarse limestone aggregates were replaced with coarse ferrochromium aggregate at replacement levels of 25, 50, and 75%. The results from the study revealed that inclusion of ferrochromium aggregates led to increase in the strength of concrete and also the abrasive wear resistance while it has negligible influence on the porosity and water absorption of concrete.

Panda et.al [5] investigated the environmental and mechanical properties of concrete containing ferrochrome slag. The concrete showed increased strength in comparison to control sample. The standard leaching experimental results showed that the leachable chromium remains well immobilized in the cement and concrete matrix with very low to non-detectable level of chromium leaching. Sathwik et. al [6] investigated the utilization of ferrochrome slag as replacement of coarse aggregate in concrete. They conducted the study on M50 grade of concrete. Their studies revealed that in concrete made with up to 75% replacement of natural aggregates with ferrochrome slag, the compressive and flexural strength was found comparable with that of the control sample. Zyranov et. al [7] investigated the possibility of low carbon ferrochrome slag into a dry slag and further recycling it into commercial product. Their study concluded that the strength of concrete under normal condition is less than the strength of concrete under steam curing as high temperature activates the process of slag hydration.

In view of the above mentioned studies, it becomes imperative to conduct studies and evaluate the performance of concrete mixes containing water and air cooled ferrochrome slag as replacement of natural aggregates in concrete and compare their performance with corresponding control concrete mixes made with 100% natural aggregates in terms of different fresh, hardened and especially durability properties of concrete, as very limited studies has been conducted on the durability parameters of concrete made with ferrochrome slag as a replacement of natural aggregates.

2. The Effect of Factors on Shear Force

In this study, Ferrochrome slag (both water cooled and air cooled) aggregates were evaluated for different physical characteristics as per IS: 2386 [8] (as applicable for manufactured sand and manufactured coarse aggregates). Both water and air cooled ferrochrome slag samples were subjected to chemical analysis as per IS 4032 [9] for evaluation of loss on Ignition, major constituents (Cr_2O_3, Al_2O_3, Fe_2O_3, CaO, SiO_2, reactive silica and MgO) and minor constituents (Na_2O, K_2O, SO_3, Cl^-, TiO_2 etc.). Total alkali content as Na_2O equivalent, total sulphate content as SO_3, acid and water soluble chloride content and total sulphur as S. Elemental analysis and leaching study as per Toxicity characteristic leaching procedure (TCLP) as per ASTM D5233 [10] for heavy metals was carried out for both ferrochrome slag samples. Both air and water cooled ferrochrome slag aggregates were evaluated for Alkali Silica reactivity using accelerated and long term mortar bar test. Other concrete making materials such as cement, natural aggregate and admixture were meeting the criteria as mentioned in relevant Indian Standards.

Two control concrete mixes were prepared using Ordinary Portland Cement (OPC) along with 100% natural fine aggregates and 100% natural coarse aggregates at two different water-cement ratios of 0.65 and 0.40. Then, mixes were prepared by replacing natural fine aggregates with water cooled ferrochrome slag at 30, 60 and 100% along with 100% natural coarse aggregates at both the water cement ratios. Further, mixes were prepared by replacing natural coarse aggregate with air cooled ferrochrome slag at 30, 60 and 100% along with 100% natural fine aggregates at both the water cement ratios. Thus, a total number of 14 concrete mixes were prepared. All the mixes were studied for fresh properties of concrete such as workability (in terms of slump at 30, 60, 90 and 120 minutes) and air content of concrete as per IS: 1199 [11]. Further, mixes were evaluated for different mechanical properties such as compressive strength, flexural strength, split tensile strength, density, drying shrinkage of concrete and modulus of elasticity of concrete at various ages. Mixes were also studied for different durability properties of concrete tests such as Rapid Chloride ion penetrability test (RCPT), Sulphate expansion test, Chloride migration test, accelerated carbonation test and sorptivity test.

3. Properties of Air Cooled Ferrochrome Slag and Water Cooled Ferrochrome Slag

3.1. Physical Properties of Ferrochrome Slag

Sieve analysis of water cooled ferrochrome slag (< 4.75mm) and air Cooled Ferrochrome slag (20 mm and 10 mm) samples were carried out as per IS 383:2016 [12] and the results are given in Table 1.

Table 1. Sieve analysis of ferrochrome slag samples

IS Sieve Size	Water Cooled Ferrochrome slag (<4.75mm) % Passing	Air Cooled Ferrochrome slag, 20mm, % Passing	Air Cooled Ferrochrome slag, 10mm, % Passing
40 mm	-	100	-
20 mm	-	100	-
12.5 mm	-	-	100
10 mm	100	28	100
4.75 mm	100	1	23
2.36 mm	98	-	5
1.18 mm	79	-	-
600 μm	46	-	-
300 μm	28	-	-
150 μm	15	-	-

The physical properties of Ferrochrome slag samples are given in Table 2 below. The physical properties of water cooled and air cooled ferrochrome slag meets the various requirements of IS: 383-2016. The specific gravity of slag samples was observed to be higher than that of natural aggregates. Water absorption and material finer than 75 μm were found to be comparable with natural aggregates. The water cooled ferrochrome slag lies in zone 2 of grading as per IS: 383-2016. The low values of abrasion, crushing and impact reflects the stronger nature of air cooled ferrochrome slag.

Table 2. Physical properties of ferrochrome slag samples

Test Carried out	Water Cooled Ferrochrome slag (<4.75mm)	Air Cooled Ferrochrome slag, 20mm	Air Cooled Ferrochrome slag, 10mm
Specific gravity	2.87	2.99	2.98
Water absorption, %	0.74	0.33	0.31
Material finer than 75 μm % (wet sieving)	3.97	0.10	0.1
Soundness , MgSO4 %	2.68	1.28	1.91
Organic impurities %	Nil	Nil	Nil
Clay Lumps %	Nil	Nil	Nil
Total deleterious material, % (excluding coal & lignite)	Nil	Nil	Nil
Loose Bulk Density, Kg/lit	1.09	1.61	1.43
Compacted Bulk Density, Kg/lit	1.21	1.71	1.56
Abrasion value	-	14	-
Crushing Value	-	19	-
Impact Value	-	15	-

3.2. Chemical Properties of Ferrochrome Slag Samples

Both type of ferrochrome slag samples (water cooled and air cooled) were studied for several chemical parameters as per IS 4032. The chemical properties of ferrochrome slag samples are tabulated in Table 3 below.

Table 3. Chemical properties of ferrochrome slag samples

Test Carried out	Water Cooled Ferrochrome slag (<4.75mm), %	Air Cooled Ferrochrome slag, (>4.75mm), %
Gain on Ignition, %	+1.51	+0.93
Silica	25.73	31.54
Iron Oxide	3.59	5.23
Alumina	35.3	28.67
Calcium Oxide	2.8	3.68
Magnesium Oxide	22.36	19.22
Sulphuric Anhydride	0.12	0.06
Chloride	0.015	0.01
Alkalis (as Na2Oeq)	0.23	0.55
Titanium Dioxide	1.06	1.44
Total Sulphur	0.25	0.44

As per IS 383: 2016, the prescribed limit of total alkali content is 0.3%. The observed value of alkalis equivalent is 0.23% in case of water cooled ferrochrome slag which lies within the limit specified. However, the value obtained in case of air cooled ferrochrome slag is higher than the prescribed limit. The observed values of chloride content, calcium oxide, iron oxide and total Sulphur are well within the limits specified in IS 383: 2016.

3.3. Elemental Analysis of Ferrochrome Slag Samples

Both water cooled and air cooled ferrochrome slag samples were subjected to elemental analysis. The results of elemental analysis of ferrochrome slag samples are tabulated in Table 4 below.

Table 11 of IS: 383-2016 quotes limits for environmental safety and quality standards for using iron, steel and copper slag aggregates. The values obtained for cadmium, lead, selenium and hexavalent chromium are within limits.

Table 4. Results of elemental analysis of ferrochrome slag samples

Element	Water Cooled Ferrochrome slag (<4.75mm), %	Air Cooled Ferrochrome slag, (>4.75mm), %
Barium	0.027	0.098
Beryllium	0.001	0.0005
Bismuth	Below detection Limit	Below detection Limit
Cadmium	0.002	0.001
Cobalt	0.012	0.012
Chromium	8	8.86
Copper	0.175	0.42
Gallium	Below Detection Limit	Below Detection Limit
Manganese	0.219	0.185
Molybednum	0.011	0.008
Nickel	0.032	0.04
Lead	0.013	0.008
Selenium	Below Detection Limit	Below Detection Limit
Strontium	0.088	0.008
Tellurium	Below Detection Limit	Below Detection Limit
Thallium	Below Detection Limit	Below Detection Limit
Zinc	0.029	0.061
Vanadium	0.012	0.013
Chromium, Cr+3	-	-
Chromium, Cr+6	0.0002	0.0003

3.4. Leaching Study for Heavy Metals on Ferrochrome Slag Samples

Leaching study on air and water cooled ferrochrome slag was conducted as per TCLP procedure. The results of concentration of heavy metals in slag sample is tabulated in Table 5 below.

Table 5. Results of leaching study on ferrochrome slag and natural aggregates

Sl No.	Constituents	Water cooled FS Slag FA	Air-cooled FS Slag CA	Limits as per TCLP procedure
1	Chromium	0.486	0.727	5
2	Copper	0.005	*BDL	25
3	Manganese	1.298	1.215	10
4	Nickel	0.831	0.774	20
5	Lead	0.020	BDL	5
6	Zinc	0.208	0.209	250
7	Iron	45.37	53.93	-
8	Titanium	0.012	0.011	-

As per the leachable concentration limits given in ministry of environment [13], forest and climate change guidelines, the observed values are lower than the prescribed limits.

3.5. Petrographic Examination of Ferrochrome slag Sample

Air cooled and water cooled ferrochrome slag samples were subjected to petrographic examination and their results are as mentioned below in sub sections 3.5.1 and 3.5.2.

3.5.1. Petrographic Examination of Air Cooled Ferrochrome Slag

This is a medium grained textured partially weathered random sample of the coarse aggregate. The major mineral constituents are spinel, olivine and clinopyroxene. Accessory minerals are quartz and iron oxide. Micro globular glass grains with corroded margins present as clusters are uniformly distributed in the sample. Majority of glass grains are in the size range of 7μm to 53μm. Subhedral to euhedral spinel grains with sharp grain margins are also uniformly distributed in the aggregate. Euhedral olivine grains with sharp grain margins are partially fractured and shattered. Grain size of olivine varies from 55 μm to 1052 μm with an average of 502 μm. Subhedral to anhedral clinopyroxene grains with corroded margins are fractured and shattered. Subhedral quartz grains with sharp grain margins are randomly distributed in the sample. Anhedral iron oxide grains are also randomly distributed in the sample. Microphotographs are given in Fig 1.

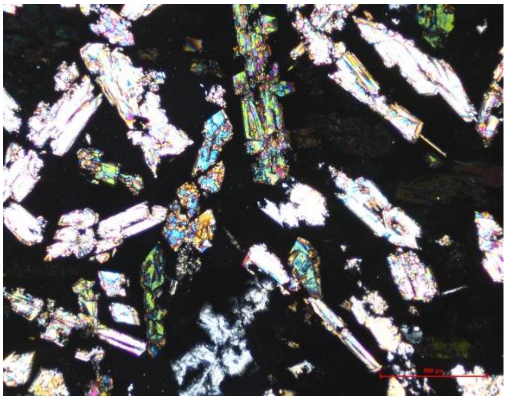

Fig. 1 Micrograph of air cooled Ferrochrome slag using optical microscope showing distribution of mineral grains in the sample (5x, x-nicols)

3.5.2. Petrographic Examination of Water Cooled Ferrochrome Slag

This is a fine grained textured partially weathered random sample of the fine aggregate. The predominant phase in the sample is glass. Subhedral to anhedral glass grains with sharp grain margins are uniformly distributed in the sample. Few elongated shaped glass grains are also observed in the fine aggregate. Grain size of glass varies from 15 μm to 408 μm with an average of 167 μm. Majority of glass grains are in the size range of 150μm to 170μm. Other mineral phases are quartz, orthoclase-feldspar, muscovite and iron oxide. Subhedral quartz grains with sharp grain margins are randomly distributed in the sample. Majority of quartz grains are in the size range of 100μm to 140μm. Subhedral orthoclase grains with rounded grain margins are also randomly distributed in the sample. Needle to lath shaped muscovite grains are mostly fresh in nature. Anhedral to subhedral iron oxide grains with corroded margins are uniformly distributed in the sample. Microphotographs are given in Fig 2.

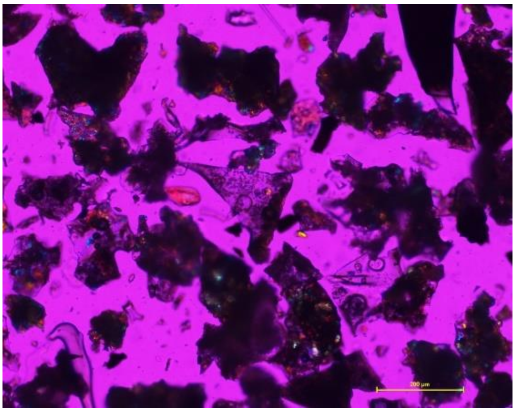

Fig. 2 Micrograph of water cooled ferrochrome slag using optical microscope showing distribution of mineral grains in the sample (5x, x-nicols)

3.6. Accelerated Mortar Bar Test

Accelerated mortar bar test was conducted on both water and air cooled ferrochrome slag aggregates as per ASTM C-1260 [14] for following compositions:

- 0% replacement of natural aggregates with ferrochrome slag
- 100% replacement of natural sand with water cooled ferrochrome slag samples.
- 100% replacement of natural coarse aggregate with air cooled ferrochrome slag samples.

The accelerated mortar-bar test as per ASTM 1260 consists of preparing mortar-bar in the same way as for conventional tests as per IS: 2386 i.e., by proportioning one part of Ordinary Portland Cement (OPC) to 2.25 parts of graded aggregates by mass, a fixed water to cement ratio of 0.47. The sample after 24-hours was de-moulded and then cured in hot water at 80ºC for 24-hours. Finally, the specimen was stored in 1N NaOH solutions at 80ºC for 14 days. The length change observations were taken in hot condition i.e., within 15+5 seconds after taking out from the solution. The samples were stored in plastic containers. As per ASTM criteria, the aggregate showing expansions less than 0.10% at 16 days after casting are classified as innocuous, whereas the aggregates showing more than 0.20% expansion are classified as potentially reactive. For aggregates showing expansion between 0.10% and 0.20%, the results are to be supported by other tests. Test results are given in Table 6. For all types of compositions, aggregates showed innocuous behaviour as expansion in all the cases were reported below 0.10%.

Table 6. Accelerated mortar bar test (ASTM C1260)

S.No.	Sample Type	1N NaOH 800C 14 Day Expansion %	Remarks
1	Fine Aggregate (0% replacement)	0.07	innocuous
2	Fine Aggregate (100% replacement)	0.03	innocuous
3	Coarse Aggregate (100% replacement)	0.09	innocuous

3.7. Mortar-Bar Test

Mortar-bar test was conducted at normal regime of 380 C and accelerated regime of 600 C as per IS: 2386. The test at 380 C was conducted to bring out the effect of metastable silica minerals present in aggregates, if any, and tests at 600 C was conducted to bring out the effect of slowly reactive strained quartz type of aggregates. The test was conducted using two reference OPC samples i.e. OPC-1 having alkali content (Na2O eq.) of 1.56% and OPC-2 having alkali content of 0.59%. The results of the mortar-bar tests are presented in Fig. 3 and 4. On perusal of mortar bar test results in Fig. 3 and 4, it can be seen that the expansions are within the permissible limits of 0.05% at 90 days and 0.06% at 180 days with all combinations. Therefore, ferrochrome aggregate samples were classified as innocuous as per IS: 2386.

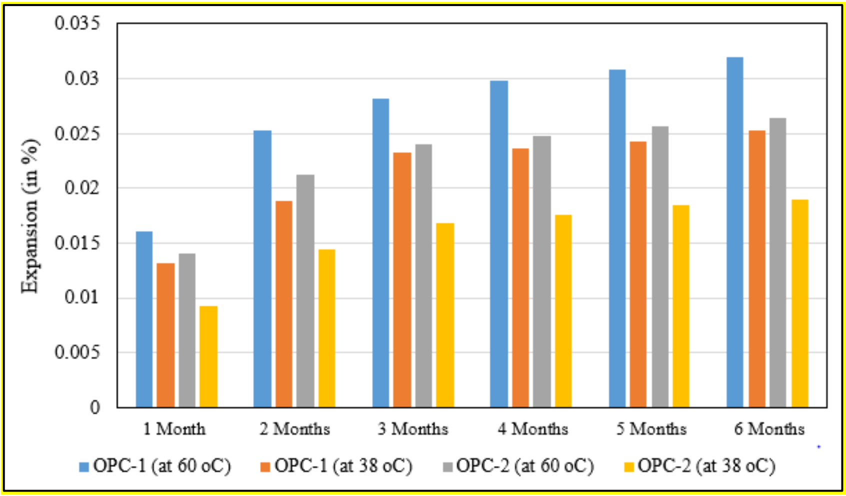

Fig. 3 Alkali aggregate reactivity as per IS: 2386 part VII for water cooled ferrochrome slag as 100% replacement of natural sand

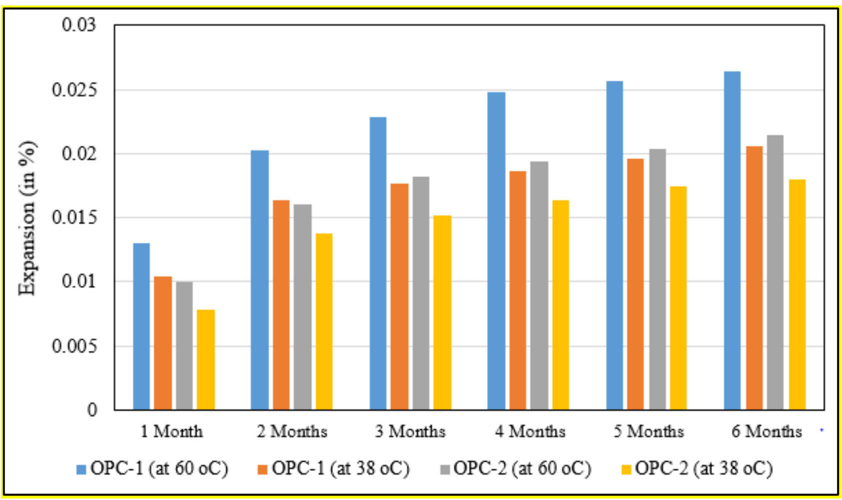

Fig. 4 Alkali aggregate reactivity as per IS: 2386 part VII for air cooled ferrochrome slag as 100% replacement of natural coarse aggregate.

4. Studies on Fresh, Hardened and Durability Properties of Concrete Mixes

4.1. Concrete Mixes Containing Water Cooled Ferrochrome Slag as Replacement of Natural Fine Aggregate

Two control concrete mixes (M4 and M0) were prepared using OPC along with 100% natural fine aggregates and 100% natural coarse aggregates at two water-cement ratios of 0.65 and 0.40. Then, mixes were prepared by replacing natural fine aggregate with water cooled ferrochrome slag at 30, 60 and 100% along with 100% natural coarse aggregates at both the water cement ratios

Therefore, a total of 8 mix designs (2 no. of control mixes + 3 x 2 = 6 number of mixes containing water cooled ferrochrome slag as fine aggregate) were carried out. The concrete mixes were designed for initial slump value of about 150 mm. Mix design details of concrete mixes are tabulated in Table 7.

Table 7. Concrete mix design details of mixes containing water cooled ferrochrome slag as replacement of natural fine aggregate

S. No.	Mix	Ferrochrome slag as fine Aggregates (%)	Cement (Kg/m3)	Water (Kg/m3)	Ferrochrome slag as fine aggregates (Kg/m3)
1	M0	0	300	195	0
2	M1	30	300	195	287
3	M2	60	300	195	573
4	M3	100	300	195	957
5	M4	0	425	170	0
6	M5	30	425	170	254
7	M6	60	425	170	507
8	M7	100	425	170	847

Table 7. (Con.) Concrete mix design details of mixes containing water cooled ferrochrome slag as replacement of natural fine aggregate

S. No.	Natural Fine Aggregate (Kg/m3)	Natural Coarse Aggregate (10 mm) (Kg/m3)	Natural Coarse Aggregate (20 mm) (Kg/m3)	Admix (%)
1	874	414	623	0
2	611	413	622	0.2
3	349	413	621	0.7
4	0	413	622	0.2
5	773	439	661	0.2
6	541	439	661	0.3
7	309	439	660	0.5
8	0	439	661	0.2

4.1.1. Fresh Concrete Properties

Fresh concrete properties such as workability (in terms of slump at 0 minutes, 30 minutes, 60 minutes and 120 minutes after preparation of mix) and air content were evaluated for all the 8 mixes and test results are given in Table 8.

Table 8. Fresh concrete properties of mixes containing water cooled Ferrochrome slag as replacement of natural fine aggregate

S. No	W/c Ratio	Mix ID	Ferrochrome slag as fine Aggregates (%)	Natural Sand
1	0.65	M0	0	100
2	0.65	M1	30	70
3	0.65	M2	60	40
4	0.65	M3	100	0
5	0.4	M4	0	100
6	0.4	M5	30	70
7	0.4	M6	60	40
8	0.4	M7	100	0

Table 8. (Con.) Fresh concrete properties of mixes containing water cooled ferrochrome slag as replacement of natural fine aggregate

S. No	Workability of concrete (mm):				Air Content, %	Remarks
	0 Min	30 Min	60 Min	120 Min		
1	145	135	125	100	1.8	Homogeneous mix
2	150	120	100	55	1.9	
3	160	110	85	30	2	
4	140	120	90	40	2.1	Segregation and bleeding
5	150	140	120	90	1.7	Homogeneous mix
6	150	110	80	40	1.9	
7	145	100	60	30	2.1	
8	150	110	80	40	2.4	Segregation and bleeding

Concrete mixes containing Ferrochrome slag showed significantly higher slump loss after 60 and 120 minutes in comparison to the control concrete mixes. Air content of all 8 mixes were similar and comparable (around 2%). It was observed that when replacement of natural coarse aggregate with air cooled ferrochrome slag goes beyond 60%, mixes showed signs of segregation and bleeding due to high specific gravity of ferrochrome slag.

4.1.2. Hardened Concrete Properties

Hardened concrete properties were evaluated for the eight concrete mixes. Compressive strength test was conducted on concrete cubes (150 mm × 150 mm × 150 mm) as per IS: 516 [15]. Flexural strength test was conducted on concrete beam (size 500mm x 100mm x 100mm) as per IS: 516. Split strength test and Modulus of Elasticity were conducted on concrete cylinder (150mm diameter and 300mm height) as per IS:5816 [16] and IS:516 respectively. Drying shrinkage test was conducted on concrete beam (75 x 75 x 300 mm) as per IS:1199. The test results are in Table 9.

Table 9. Hardened concrete properties containing of mixes containing water cooled ferrochrome slag as replacement of natural fine aggregate

W/c	Mix ID	Ferrochrome slag as fine Aggregates (%)	Compressive Strength, MPa				Flexural Strength, MPa	
			1 Day	3 Day	7 Day	28 Day	7 Day	28 Day
0.65	M0	0	4.54	12.5	18.1	26.22	4.07	5.05
0.65	M1	30	6.33	14.5	20.2	30.14	4.4	5.3
0.65	M2	60	7.38	16.5	22.95	38.05	5.07	5.37
0.65	M3	100	8.67	18.8	24.46	41.89	5.45	6.01
0.4	M4	0	15.95	32	41.86	49.79	6.4	8.07
0.4	M5	30	19.05	27.2	43.01	46.75	6.37	9.77
0.4	M6	60	20.84	29.3	42.89	53.08	7.17	10.3
0.4	M7	100	23.76	27.8	44.78	56.89	8.5	11.4

Table 9. (Con.) Hardened concrete properties containing of mixes containing water cooled ferrochrome slag as replacement of n atural fine aggregate

W/c	Mix ID	Split Tensile Strength, MPa	Dry Density Kg/m3	Drying Shrinkage	MOE (N/mm2)
		28 Day	28 Day	28 Day	28 Day
0.65	M0	2.42	2450	0.0171	28204
0.65	M1	2.67	2470	0.0168	30651
0.65	M2	2.72	2550	0.0164	32982
0.65	M3	3.21	2502	0.0179	34876
0.4	M4	4.51	2478	0.0191	37144
0.4	M5	4.75	2494	0.018	38013
0.4	M6	5.1	2520	0.0175	38885
0.4	M7	5.26	2560	0.0173	40016

Compressive, flexural and split tensile strength at age of 28 days for experimental mixes (containing water cooled ferrochrome slag as replacement of fine aggregates) at both w/c were found to be either higher or comparable to their control mix. Due to higher specific gravity of ferrochrome slag, dry density of the concrete mixes containing water cooled ferrochrome slag were higher than control mixes. The drying shrinkage values for all the concrete mixes were found satisfactory and comparable with their corresponding control mixes. Modulus of Elasticity (MOE) of the concrete mixes containing ferrochrome slag as replacement of natural fine aggregates were found to be either higher or comparable to corresponding control mixes.

4.1.3. Durability Properties of Concrete mixes

Durability parameters of concrete such as Rapid Chloride ion penetrability test (RCPT) as per ASTM C-1202 [17], Sulphate expansion test as per ASTM C-1012 [18], Chloride migration test as per NT Build 492 [19], accelerated carbonation test as per ISO 1920 part 12 [20] and sorptivity test as per ASTM 1585 [21] were evaluated for all the eight concrete mixes. Test results are presented in Table 10.

Table 10. Durability properties of concrete mixes containing water cooled ferrochrome slag as replacement of natural fine aggregate

W/c	Mix ID	Ferrochrome slag as fine Aggregates (%)	RCPT, Coulomb	Chloride Migration, NT Build Diffusion coefficient (x 10-12 m2/s)		
			28 Day	28 Day	56 Day	90 Day
0.65	M0	0	3542	8.31	6.99	3.34
0.65	M1	30	3133	7.49	5.42	3.21
0.65	M2	60	3268	6.61	4.76	3.05
0.65	M3	100	2255	3.44	4.12	2.68
0.4	M4	0	1525	7.49	5.56	3.65
0.4	M5	30	1862	8.13	4.73	3.55
0.4	M6	60	1375	6.78	4.1	3.21
0.4	M7	100	1378	4.64	3.56	2.87

Table 10. (Con.) Durability properties of concrete mixes containing water cooled ferrochrome slag as replacement of natural fine aggregate

W/c	Mix ID	Sulphate expansion (%)			Carbonation Depth, mm	Sorptivity	
		28 Day	56 Day	90 Day		Initial	Secondary
0.65	M0	0.002	0.006	0.008	8.74	0.0057	0.0024
0.65	M1	0.003	0.005	0.007	7.33	0.0080	0.0028
0.65	M2	0.003	0.006	0.007	7.50	0.0062	0.0030
0.65	M3	0.002	0.005	0.009	7.10	0.0070	0.0038
0.4	M4	0.003	0.006	0.009	Nil	0.0032	0.0008
0.4	M5	0.003	0.005	0.007	Nil	0.0038	0.0009
0.4	M6	0.002	0.007	0.009	Nil	0.0005	0.0002
0.4	M7	0.004	0.006	0.008	Nil	0.0010	0.0006

In case of RCPT, it was observed that experimental mixes containing water cooled ferrochrome slag as replacement of natural sand show comparable performance to corresponding control concrete mixes. All the mixes having w/c of 0.65 fall under the permeability class “moderate” and mixes having w/c ratio of 0.40 fall under permeability class “low” as defined in ASTM 1260.

Similarly, performance of experimental mixes (containing water cooled ferrochrome slag as replacement of natural sand) in case of chloride migration test as per NT build 492 is similar and comparable to their corresponding control mixes. In case of accelerated carbonation test, mixes prepared at water to cement ratio of 0.65 (both experimental and control mix) showed similar carbonation depth (of around 8 mm) and mixes prepared at water to cement ratio of 0.40 (both experimental and control mix) showed nil carbonation depth. Sulphate expansion results for all the concrete mixes are well within the maximum limits prescribed by ASTM C 1012. Sorptivity test results of experimental mixes containing water cooled ferrochrome slag as replacement of natural sand are similar and comparable to their corresponding control mixes.

This shows that replacement of natural fine aggregates with water cooled ferrochrome slag aggregates in a concrete mix does not have any negative or detrimental effect on the durability properties of concrete.

4.2. Concrete Mixes Containing Air Cooled Ferrochrome Slag as Replacement of Natural Coarse Aggregate

Along with two control concrete mixes (M4 and M0), mixes were prepared by replacing natural coarse aggregate with air cooled ferrochrome slag at 30, 60 and 100% along with 100% natural fine aggregates at both the water cement. Thus, six experimental mixes (containing air cooled Ferrochrome slag) were prepared along with two control mixes (M0 and M4). All the concrete mixes were designed for initial slump value of around 150 mm. Mix design details of concrete mixes are tabulated in Table 11.

Table 11. Concrete mix design details of mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

Mix	Ferrochrome slag as coarse Aggregates (%)	Cement (Kg/m3)	Water Kg/m3	Natural Fine aggregate (Kg/m3)	Ferrochrome slag as coarse Aggregate (10mm) (Kg/m3)
M0	0	300	195	874	0
M8	30	300	195	863	116
M9	60	300	195	863	233
M10	100	300	195	862	387
M4	0	425	170	773	0
M11	30	425	170	759	123
M12	60	425	170	759	245
M13	100	425	170	759	409

Table 11. (Con.) Concrete mix design details of mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

Mix	Ferrochrome slag as coarse aggregates (20mm) (Kg/m3)	Natural Coarse Aggregate (10 mm) (Kg/m3)	Natural Coarse Aggregate (20 mm) (Kg/m3)	Admix (%)
M0	0	414	623	0
M8	217	286	431	0
M9	433	164	246	0
M10	721	0	0	0.6
M4	0	439	661	0.2
M11	229	302	454	0.3
M12	457	172	260	0.3
M13	762	0	0	0.3

4.2.1. Fresh Concrete Properties

Fresh concrete properties such as workability and air content were evaluated for all the 8 mixes. Test results are given in Table 12.

Table 12. Fresh Concrete properties of mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

S. No	W/c Ratio	Mix ID	Ferrochrome slag as coarse Aggregates (%)	Natural coarse aggregates
1	0.65	M0	0	100
2	0.65	M8	30	70
3	0.65	M9	60	40
4	0.65	M10	100	0
5	0.40	M4	0	100
6	0.4	M11	30	70
7	0.4	M12	60	40
8	0.4	M13	100	0

Table 12. (Con.) Fresh Concrete properties of mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

S. No	Workability of concrete (mm):				Air Content, %	Remarks
	0 Min	30 Min	60 Min	120 Min		
1	145	135	125	100	1.8	Homogeneous mix
2	150	140	120	80	1.7	
3	150	130	110	50	1.8	
4	150	120	70	50	2	Segregation and bleeding
5	150	140	120	90	1.7	Homogeneous mix
6	150	135	110	70	1.6	
7	140	125	90	40	1.9	
8	145	90	60	50	2.1	Segregation and bleeding

Concrete mixes containing air cooled ferrochrome slag showed significantly higher slump loss after 60 and 120 minutes in comparison to the control concrete mixes. Air content of all 8 mixes were similar and comparable (around 2%). It was observed that when replacement of natural coarse aggregate with air cooled ferrochrome slag goes beyond 60%, mixes showed signs of segregation and bleeding due to high specific gravity of ferrochrome slag.

4.2.2. Hardened Concrete Properties

Hardened concrete properties were evaluated for all the six concrete mixes (M8 to M13) along with the control mixes (M4 and M0). Specimen size, test method and age of testing for all the tests were kept same as discussed in 4.1.2. Test results have been tabulated in Table 13.

Table 13. Hardened concrete properties of mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

W/c	Mix ID	Ferrochrome slag as coarse Aggregates (%)	Compressive Strength, MPa				Flex Strength, MPa	
			1 Day	3 Day	7 Day	28 Day	7 Day	28 Day
0.65	M0	0	4.54	12.5	18.1	26.22	4.07	5.05
0.65	M8	30	4.91	16.7	19.11	27.96	4	4.83
0.65	M9	60	3.61	9.93	16.01	24.69	3.87	4.73
0.65	M10	100	6.57	16.4	21.68	28.55	3.89	4.97
0.4	M4	0	15.95	32	41.86	49.79	6.4	8.07
0.4	M11	30	14.42	30.9	33.04	47.44	5.67	7.03
0.4	M12	60	9.58	29.6	38.19	45.44	5.87	7.7
0.4	M13	100	11.92	29.9	37.18	45.39	4.73	6.93

Table 13. (Con.) Hardened concrete properties of mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

W/c	Mix ID	Split Tensile Strength, MPa	Dry Density Kg/m3	Drying Shrinkage	MOE (N/mm2)
		28 Day	28 days	28 days	28 Days
0.65	M0	2.42	2450	0.0171	28204
0.65	M8	2.41	2470	0.0175	28508
0.65	M9	2.17	2460	0.0159	26588
0.65	M10	2.54	2580	0.0170	28486
0.4	M4	4.51	2478	0.0191	37144
0.4	M11	3.46	2490	0.0174	34140
0.4	M12	3.57	2515	0.0171	34395
0.4	M13	3.87	2560	0.0167	33854

Compressive, flexural and split tensile strength at age of 28 days for experimental mixes (containing air cooled ferrochrome slag as replacement of coarse aggregates) at both w/c were found to be similar and comparable to their control mix. Due to higher specific gravity of ferrochrome slag, dry density of the concrete mixes containing air cooled ferrochrome slag were higher than control mixes. The drying shrinkage values for all the concrete mixes were found satisfactory and comparable with their corresponding control mixes. Modulus of Elasticity (MOE) of the concrete mixes containing ferrochrome slag as replacement of natural coarse aggregates were found to be similar and comparable to corresponding control mixes.

4.1.3. Durability Properties of Concrete Mixes

Durability parameters of concrete such as Rapid Chloride ion penetrability test (RCPT) as per ASTM C-1202, Sulphate expansion test as per ASTM C-1012, Chloride migration test as per NT Build 492, accelerated carbonation test as per ISO 1920 part 12 and sorptivity test as per ASTM 1585 were evaluated for all the eight concrete mixes. Test results have been presented in Table 14.

Table 14. Durability properties of concrete mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

W/c	Mix ID	Ferrochrome slag as coarse Aggregates (%)	RCPT, Coulomb	Chloride Migration, NT Build Diffusion coefficient (x 10-12 m2/s)		
			28 Day	28 Day	56 Day	90 Day
0.65	M0	0	3542	8.31	6.99	3.34
0.65	M8	30	2331	9.03	5.88	4.27
0.65	M9	60	3574	8.54	6.24	2.6
0.65	M10	100	4259	6.48	3.98	3.12
0.4	M4	0	1525	7.49	5.56	3.65
0.4	M11	30	2189	6.81	5.29	3.68
0.4	M12	60	3490	9	5.44	3.71
0.4	M13	100	2876	8.52	5.90	3.58

Table 14. (Con.) Durability properties of concrete mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregate

W/c	Mix ID	Sulphate expansion (%)			Carbonation Depth, mm	Sorptivity	
		28 Day	56 Day	90 Day		Initial	Secondary
0.65	M0	0.002	0.006	0.008	8.74	0.0057	0.0024
0.65	M8	0.001	0.004	0.007	7.65	0.0021	0.0010
0.65	M9	0.002	0.005	0.008	12.55	0.0033	0.0017
0.65	M10	0.003	0.005	0.009	10.55	0.0023	0.0013
0.4	M4	0.003	0.006	0.009	Nil	0.0032	0.0008
0.4	M11	0.004	0.006	0.008	Nil	0.0011	0.0004
0.4	M12	0.003	0.005	0.008	Nil	0.0010	0.0003
0.4	M13	0.005	0.007	0.009	Nil	0.0013	0.0004

In case of RCPT results, it was observed that experimental mixes containing water cooled ferrochrome slag as replacement of natural sand show comparable performance to corresponding control concrete mixes. Similarly, performance of experimental mixes (containing air cooled ferrochrome slag as replacement of natural coarse aggregates) in case of chloride migration test as per NT build 492 is similar and comparable to their corresponding control mixes. In case of accelerated carbonation test, mixes prepared at water to cement ratio of 0.65 (both experimental and control mix) showed similar carbonation depth (of around 8 to 12 mm) and mixes prepared at water to cement ratio of 0.40 (both experimental and control mix) showed nil carbonation depth. Sulphate expansion results for all the concrete mixes are well within the maximum limits prescribed by ASTM C 1012. Sorptivity test results of experimental mixes containing air cooled ferrochrome slag as replacement of natural coarse aggregates are similar and comparable to their corresponding control mixes.

This shows that replacement of natural coarse aggregates with air cooled ferrochrome slag aggregates in a concrete mix does not have any negative or detrimental effect on the durability properties of concrete.

4.3. Leaching Studies on Selected Concrete Mixes

Leaching study was also conducted on few selected concrete samples made with replacement of natural aggregates with corresponding ferrochrome slag aggregates, as per Toxicity Characteristic Leaching Procedure (TCLP) to detect the presence of different heavy metals constituents. The results of concentration of heavy metals ions leached out from concrete samples are given in Table 15.

Table 15. Results of Leaching study on concrete samples

Sl No.	Constituents	M0	M4	M1	M5	M6	Limits as per TCLP procedure
1	Chromium (Cr)	0.1341	0.010	0.119	0.169	0.187	5
2	Copper (Cu)	0.009	0.006	0.047	0.12	0.007	25
3	Manganese (Mn)	0.002	0.002	0.025	0.002	0.002	10
4	Nickel (Ni)	0.013	BDL	0.023	0.007	BDL	20
5	Lead (Pb)	BDL	BDL	BDL	BDL	BDL	5
6	Zinc (Zn)	0.039	0.035	0.053	0.028	0.034	250
7	(Fe) Iron	BDL	0.048	0.032	0.010	0.001	-
8	Titanium (Ti)	0.054	0.003	0.92	0.028	0.053	-

As per the leachable concentration limits given by ministry of environment, forest and climate change guidelines, the observed values of heavy metal ions are lower than the prescribed limits.

5. Conclusions

Based on the results and observations of above mentioned studies following conclusions are drawn:

- Physical properties of water and air cooled ferrochrome slag meets the various requirements of IS: 383-2016. Specific gravity of slag samples was observed to be higher than that of natural aggregates. Water absorption and material finer than 75 µm were found to be comparable with natural aggregates. The low values of abrasion, crushing and impact reflects the stronger nature of air cooled ferrochrome slag.
- The results of elemental analysis of ferrochrome slag samples showed that concentrations of elements are within limits.
- Concrete mixes were prepared at two w/c ratios by replacing natural fine aggregates with water cooled ferrochrome slag and natural coarse aggregates with air cooled ferrochrome slag. Concrete mixes containing Ferrochrome slag showed significantly higher slump loss after 60 and 120 minutes in comparison to the control mixes. It was observed that when replacement of natural aggregates with ferrochrome slag goes beyond 60%, mixes showed signs of segregation and bleeding due to high specific gravity of ferrochrome slag. Hardened properties of concrete mixes containing ferrochrome slag were found to be higher or comparable to their corresponding control mixes at the age of 28 days. In terms of different durability related parameters, experimental mixes containing ferrochrome slag aggregates showed comparable performance in comparison to their corresponding control concrete mixes containing 100 % natural aggregates.
- Leaching study was conducted on water and air cooled Ferrochrome slag as per Toxicity Characteristic Leaching Procedure (TCLP) to detect the presence of different heavy metals constituents such as Cr, Fe, Zn, Cu, Mn, Ni, Pb and Ti. The observed values of heavy metal ions are lower than the prescribed limits. Leaching study was also conducted on few selected concrete samples made with replacement of natural aggregates with corresponding ferrochrome slag aggregates and the observed values of heavy metal ions are lower than the prescribed limits.

Based on the above conclusions, following recommendations are being made:

Water cooled Ferrochrome slag can be used as replacement of natural fine aggregate up to 60% by weight along with 100 % with natural coarse aggregates for making concrete. Air cooled Ferrochrome slag can be used as replacement of natural coarse aggregate up to 60% by weight along 100 % with natural fine aggregates for making concrete.

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