ABRASION RESISTANCE OF SUSTAINABLE WASTE STEEL SLAG MIXED CONCRETE

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Since the exploration of natural aggregate for construction is leading to environmental concerns, the development of sustainable construction materials, such as steel slag, is being promoted. Ecology gets threatened by the disposal issue of steel slag, as million tonnes of steel slags are produced as a by-product in steel industry. This investigation, analyze the potential of steel slag as a partial and complete replacement for coarse aggregates in cement concrete. It is seen that the inclusion of steel slag improves the abrasion resistance property of cement concrete. This study is strengthened by Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy analysis which is carried out on the basis experimental fallouts. It is concluded that, the use of steel slag improved compressive strength and the abrasion resistance property of cement concrete, that is applicable in flooring, pavements or in places where concrete surface being in contact with external forces and environment.

Keywords: *Abrasion Resistance, Indian Standards 9284, Compressive strength, Steel slag mixed concrete*

1. Introduction

Cement concrete is a major construction material used in almost all types of construction projects like pavements, buildings, hydraulic structures, etc. Large quantity of concrete is being produced in the world, which consumes large quantities of ingredients (i.e., cement, fine aggregate, coarse aggregate and water etc.). Quality of concrete is governed by its ingredients properties [1,2]. Aggregates occupy about 70 percentage of the volume of concrete. Limited natural resources are only available for aggregates in India and other parts of the world. Governments are imposing restrictions on explorations of natural aggregates, due to its threatening effect on the environment. So, it is high time for researchers and engineers to find a suitable replacement for aggregates.

Use of artificial industrial slag instead of natural aggregate is achieving popularity in producing sustainable concrete [1] [3]. Steel slag may found suitable with regards to strength, durability of concrete; if its sulphate as SO_3 and water absorption are limited to 0.5 percentage and 10 percentage respectively [4]. The percentage of CaO present in steel slag aggregate can be used as a portion of binder, or as binder itself. Steel slag satisfactorily proved the improvement in bearing capacity, when used as cement bound base coarse [5]. The replacement of coarse aggregate using steel slag up to 75 percentages shows significant results against workability and mechanical strengths [6,7]. Steel slag mixed in concrete up to 60 percentages in replacement of coarse aggregates improved compressive strength of M20, M30, M40 and M50 grades by 4 to 7 percentage [8]. Steel slag aggregates are showing lower water absorption and light weight than brick aggregates.

Concrete mixed with steel slag aggregate shows improved workability, modulus of elasticity, tensile strength and UPV properties compared to the concrete with brick aggregates. Modulus of elasticity of different concrete mixes vary with type of steel slag aggregates [9]. Workability of steel slag mixed concrete is similar to the controlled concrete when it is mixed in 45 percentages to coarse aggregates. Slight change in compressive strength after sulphate attack was noted due to porous surface nature of steel slag aggregates. Sorptivity and water absorption properties have no effect when concrete mixed with steel slag [3][10]. No negative effect on short term properties of hardened concrete when it's mixed with steel slag up to 20 percentages [11].

Lower slump observed in greater percentage of steel slag aggregate mixed concrete, slump value decreased to if fine ingredients replaced by SS due to existing of non-finer grains of SS [12]. Decrease in the slump is noted in use of steel slag increased in concrete but intended to segregation; 12 percentage of workability increased when added silica fumes without adding superplasticizer. Steel slag mixed concrete attributed to high unit weight in proportionate with increased percentage of SS in concrete due to specific gravity of steel slag is more than natural aggregates [13].

Maximum compressive strength noted at 25 percentage of replacement of fine aggregate by steel slag [14] and remarkable mechanical properties observed when steel slag replaced to fine aggregates [15]; properties significantly improved in 25 percent to 30 percent replacement of fine aggregate by steel slag. Compressive

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strength of steel slag mixed concrete increased by 1.1 times than natural stone aggregate concrete in any mix grades of M20, M30, M40 and M50[10]. Addition of 30 percent of steel slag coarse aggregate showed up to 40 percentage and 36.67 percentage improvement in compressive and flexural strength respectively[16]. Use of 75 percentage of steel slag as coarse aggregate showed significantly changes in mechanical as well as acid attack properties, this study also commented that use of waste as a aggregates saves up to 10 percentages of cost of concrete[6]. Steel slag aggregates possess an expansion in most conditions. Experiment resulted in no change in length or slightly changes in length about 0.034% after 120 days in 100 percentages replacement of steel slag in concrete [17]. Un-hydrated free lime and magnesium oxides present in steel slag are having potential to expand in hydration reaction when comes in contact with humid environment. Weight loss after acid resistance test was lesser in 30% steel slag coarse aggregates mixed concrete and 40% steel slag fine aggregates. Dehydration rate of steel slag mixed concrete was high in sulphuric acid than hydrochloric acid which resulted into weight loss [12]. Reduction in pores could be achieved by using steel slag as pore filler which resulting fine and discontinuous pore concrete, ultimately increased impermeability [18].

Many concrete surfaces are exposed to environmental effects, loading, abrasive actions etc. especially in case of concrete pavements. But only limited information is available on durability properties and abrasion resistance of concrete, particularly when steel slag is included in concrete for flooring or pavement purpose. Concrete surfaces expose to several abrasive actions which may lead to failure of concrete pavement [19,20].

This paper investigates the compressive strength, abrasion resistance and microstructure of concrete with steel slag as a replacement option to coarse aggregate to defeat environmental concerns.

2.Materials and Mix Design

General purpose cement manufactured by ACC, Ordinary Portland Cement of 53 grades, confirming to IS 12269: 1989 with specific gravity 3.15 and normal consistency 32 % was used in this research, manufacturer's properties of cement used is given in Table 1 [21]. River sand used was confirming to zone II as per IS 383: 1970 [22]. Coarse aggregate of 20 mm nominal maximum size derived from stone crushing was used to produce concrete.

Crystalline steel slag of size below 20 mm with 4.98 of fineness modulus produced in EAF process from steel manufacturing plant was collected for investigations from ISMT, Steel Manufacturing Unit, Pune (India). Aggregates (fine and coarse) used for production of concrete possessed physical properties and chemical properties of steel slag observed at steel manufacturing plant are shown in Table 2. Physical properties of steel slag aggregates are similar characterized with natural stone aggregates and within the limits of Indian Standards. ISMT, Pune chemical analysis is carrying at laboratory in plant, Table 2 shows the data used for chemical analysis of 20 steel slag samples (or 20 batches). The steel slag produced is containing CaO, MgO, SiO_2 and FeO which ranges from 35.58 % to 42.06 %, 8.06 % to 10.48 %, 15.76 % to 20.10 % and 18.56 % to 28.28 % respectively. Alkalinity (Basidity) of steel slag ranges from 1.95 to 2.54 which is fallen into medium alkalinity slag in

Table 1

Cement properties

Sr. No.	Parameters	Results	Requirement as per IS 269: 2015 (Variety OPC 53)
1	Chemical Composition		
A	Lime Saturation Factor $CaO – 0.7\, SO_3 / (2.8\, SiO_2 + 1.2\, Al_2O_3 + 0.65Fe_2O_3)$	0.90	Not greater than 1.02 and not less than 0.80
B	The ratio of % Alumina to that of Iron Oxide Al_2O_3 / Fe_2O_3	1.29	Not less than 0.66
C	Insoluble Residue (% by mass)	0.4	Not more than 5.0 %
D	Magnesia (% by mass)	0.9	Not more than 6.0 %
E	Sulphuric Anhydride (% by mass)	3.0	Not More than 3.5 %
F	Total loss on Ignition (%)	1.8	Not More than 4.0 %
g	Chloride Content (%)	0.020	Not More than 0.1 % for general purpose but not more than 0.05 % for pre-stressed structures
2	Physical Analysis		
A	Fineness Blaine's Specific Surface Area (m^2 / kg)	290	Not Less than 225
B	Compressive Strength (MPa) 72 ± 1h (3 Days) 168 ± 2h (7 Days)	 37.5 47.8	 Not less than 27.0 Not less than 37.0
C	Setting Time (Minutes) Initial Final	 125 175	 Not less than 30 Not more than 600
D	Soundness Le-Chatelier Expansion (mm) Auto-Clave Expansion (%)	 1.0 0.07	 Not more than 10.0 Not more than 0.8

Table 2

Physical of aggregates and chemical properties of steel slag

Sr. No.	Property	Fine Aggregate	Natural Stone Aggregates	Steel Slag	Remark
1	Specific Gravity [23]	2.665	2.67	2.61	
2	Water Absorption [23]	1.25 %	1.2 %	1.14 %	
3	Silt Content [24]	4.03 %	-	-	
4	Sieve Analysis [25]		FM= 4.39	FM= 4.98	
5	Impact Value [26]	-	7.89 %	16.93 %	Should not Exceed 30 %
6	Abrasion: Los Angeles [26]		23.43 %	25.86 %	Maximum permissible; 30 %

Heat No	Grade	Slag Type	Chemicals in oxide form (% by weight)				Basidity (EAF)
			CaO	MgO	SiO_2	FeO	
1257N	Gr-3	EAF TAPPING	39.1	8.06	16.4	22.38	2.38
1360N	SAE-52100	EAF TAPPING	41.28	9.06	16.24	28.28	2.54
1265N	40cr4	EAF TAPPING	39.88	9.01	15.8	22.56	2.52
1274N	16MnCr5	EAF TAPPING	38.76	8.84	16	21.82	2.42
1287N	ISMT-5	EAF TAPPING	38.7	8.16	16.2	22.16	2.39
1289N	ISMT-5	EAF TAPPING	39.28	8.84	15.8	22.5	2.49
1298N	SAE-1020	EAF TAPPING	39.1	9.06	15.76	23.98	2.48
1300N	ST-52	EAF TAPPING	38.82	8.96	15.9	23.8	2.44
1304N	STR-525	EAF TAPPING	35.58	9.02	15.88	23.88	2.43
1311N	SAE-52100	EAF TAPPING	39.01	8.85	16	21.8	2.44
1322N	S53C	EAF TAPPING	39.2	9.16	16.26	21.56	2.41
1326N	20MnCr5	EAF TAPPING	40.28	8.06	15.88	23.44	2.54
1334N	SAE-52100	EAF TAPPING	42.06	10.08	18.36	21.67	2.29
1335N	Gr-3	EAF TAPPING	41.5	8.86	18.5	20.95	2.24
1345N	SAE-52100	EAF TAPPING	40.93	9.29	19.1	21.67	2.14
1351N	SAE-52100	EAF TAPPING	41.5	10.48	18.8	23.15	2.21
1373N	SAE-1035	EAF TAPPING	40.15	9.9	17.85	20.06	2.25
1374N	SAE-1010	EAF TAPPING	41.06	10	16.96	21.45	2.42
1387N	SAE-52100	EAF TAPPING	39.25	8.85	20.1	18.56	1.95
1390N	SAE-52100	EAF TAPPING	39.81	9.06	19.1	21.87	2.08

Table 3

Mix proportions of M30 grade concrete (kg/m^3)

Sample Name	Cement (Kg.)	Water (Kg.)	Fine Aggregate (Kg.)	Coarse Aggregate (Kg.)	Steel Slag (Kg.)	Remark
S1	387.5	186	680	1110	-	Control mixture
S2	387.5	186	680	832.5	277.5	25 % replacement of coarse aggregate by steel slag
S3	387.5	186	680	555	555	50 % replacement of coarse aggregate by steel slag
S4	387.5	186	680	277.5	832.5	75 % replacement of coarse aggregate by steel slag
S5	387.5	186	680	0	1110	100% replacement of coarse aggregate by steel slag

significant to use in concrete. Free CaO observed in steel slag is ranges from 2.00 to 2.62 % which also provides significant use of SS in concrete in orientation of non-forming $CaCO_3$ after age of steel slag.

The mix was designed for M30 grade as per IS 10262:(2009) [27] in consideration with good degree of supervision, concrete in mild exposure and 50 mm slump value of workability in direct placing conditions. The proportions adopted for all mixes by weight was 1-Cement: 1.75- Fine aggregate: 2.86- Coarse Aggregate. Coarse aggregate was partially and fully replaced (in weight percentage) by steel slag in different proportions (0 %, 25 %, 75 % and 100 %). The water cement ratio of control mix and steel slag added concrete were 0.48. Water to solid ratio was 11.71. The same cement content was used for all samples. Only coarse aggregate was replaced by steel slag, maintaining the same quantity of fine aggregates and the effect of addition of steel slag on the total volume and weight were ignored. The nomenclatures of different samples used in this study and the corresponding mix proportions are presented in Table 3.

3.Test specimen and procedure

Test for compressive strength and abrasion were performed to assess the performance of steel slag mixed concrete. Three test specimens of 150 mm cube and 100 mm cubes were casted and tested according to Indian Standards to test compressive strength and abrasion resistance respectively [4,28]. Specimen casted of mix after checked for workability of fresh concrete with slump cone test and within the permissible limit of stipulations made in concrete mix design. Slump cone used to assess the workability with 300 mm height, 200 mm base diameter and 100 mm top diameter and standard procedure adopted as per IS 1199 [29].

Three concrete specimens of every mix for each test at 28 days age were used. Tests were carried out on electrically operated, four piller model, digital compression testing machine of maximum capacity of 2000 kN with 1kN accuracy which shows compression strength with accuracy of 0.01 N/mm^2 with permissible error of +/- 2 percent of maximum load when feeded with dimensions of specimen, as shown in Figure 1. Load was applied axially on specimen without shock till the specimen was crushed.

Fig. 1 - Compression testing on concrete specimen.

The abrasion test (Surface wear) was performed at Indian Institute of Technology, Mumbai (IIT Bombay) according to IS: 9284: 2002 [30] on 28 days cured concrete cube specimen of 100 mm. Four surfaces of one specimen were exposed for testing to analyze the surface

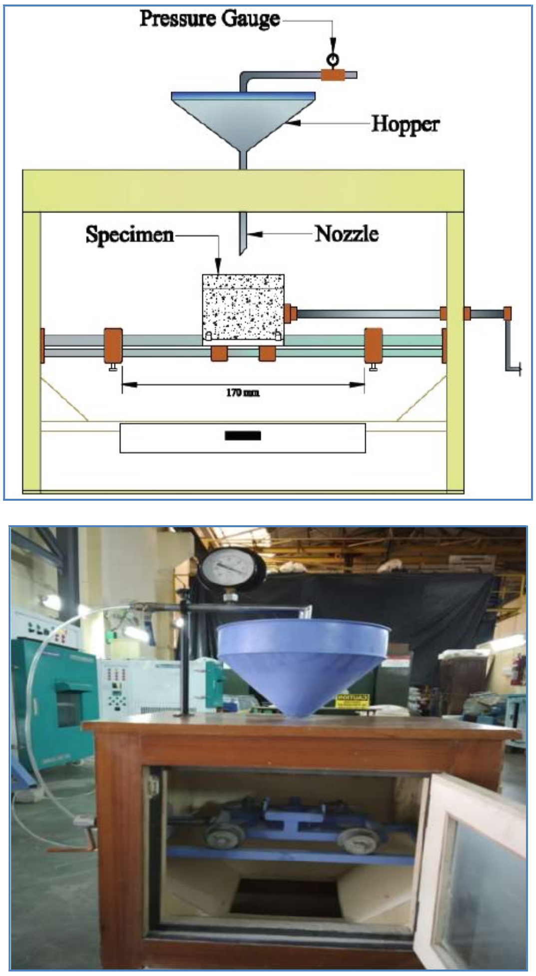

Fig. 2 - Abrasion of concrete (IS 9284) test set up.

behaviour of concrete when mixed with steel slag. Three specimens were casted for each grade of concrete to test compressive strength and abrasion resistance. The dry, rubbed and weighed specimen was placed on carrier provided in wooden cabinet. Cabinet was attached with cradle which allow specimen to slope about 10^0 verticals while testing. Four surfaces (vertical surfaces at time of casting) with 0^0 angle and 180^0 angle were subjected to impingement of 4000 grams of abrasive charges at air pressure of 0.14N/mm^2 at each time. Abrasive charge used was confirming to IS 650 but graded to pass 1.00 mm IS sieve and retained on 0.50 mm IS sieve [30]. Testing set up is shown in Figure 2 while surface of specimen after impingement is shown in Figure 3.

Weight of specimen after each test is recorded, percentage difference between final and initial weight of specimen after tested four surfaces denoted the percentage abrasion loss. Average of 12 surfaces (four surfaces of three cubes) from same grade of concrete represents the abrasion loss for the grade of concrete. This standard suggested maximum value of percent abrasion loss of concrete pavement with mixed tyre and iron tyre is 0.16, with pneumatic tyre is 0.24, factory and dockyard is 0.16, railway platfroms is 0.24,

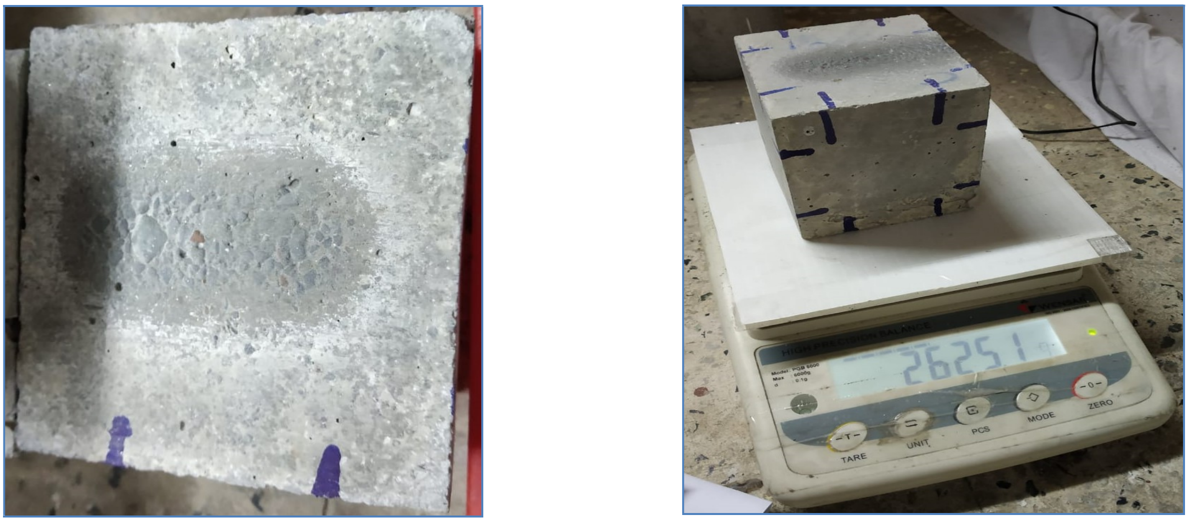

Fig. 3 - Abraded concrete surface after.

and footpath is 0.40.

Field emission scanning electron microscopy (FESEM) of concrete is carried on the Ultra High Resolution low voltage imaging and unique low vacuum capabilities with 1.0 nm at15 kV, 1.4 nm at 1 kV &1.8 nm at 3 kV and 30 Pa resolution (make: FEI Nova NanoSEM 450) and Energy Dispersive Spectroscopy (EDS) is carried on 123 eV at Mn Kα and 45eV at C Kα) & element detection range from 4 Be to 95 Am resolution (make: Bruker XFlash 6I30). xT microscope Control and Espirit 1.9 are software used to interpret the data.

4.Result and discussion

This study is intended to find compressive strength and abrasion resistance properties of M30 grade of concrete when mixed with different percentage of steel slag. Compressive strength is increasing when steel slag added in replacement of coarse aggregate; except a compressive strength for S2 sample (25 % of addition of steel slag) as shown in Table 4. This is might be an effect of workmanship and compaction even applied a same methodology for all samples. Compressive strength which is attributing to concrete is varying from 37.4 N/mm^2 to 45.32 N/mm^2. Concrete mix with 75% of replacement of aggregate with steel slag is valued 45.32 N/mm^2 as compressive strength, which is more in all mixes.

Abrasion of concrete surface can be caused by many physical actions, and results from the experiment are presented in Table which 5 indicates the weight (before and after testing) in grams for all four surfaces of one specimen. This table also indicates the nature of abrasion on each surface of concrete cube while end abrasion loss calculates from initial and final weight difference.
Average percentage of each surface is 0.23 % with variation 0.178 % to 0.319 % which observed that the concrete with stone aggregates and steel slag aggregates can used for concrete pavement with pneumatic traffic, railway platform and footpath.

Compressive strength is varying with steel slag percentage where direct effect of compressive strength has been observed on abrasion also. Abrasion resistance of sample with compressive strength 45.32 N/mm^2 is showing maximum abrasion resistance.

Concrete specimens (Natural stone aggregates and steel slag mixed concrete) are observed in SEM as shown in Figure 4 which observe that the equal distribution of water cement paste covered the aggregates, extra presence of Ca can observe in Figure 4 a in which micro pores are filled and surface become denser. Denser surface leads to abrasive resistance surface. Stone aggregate mixed concrete is showing pores at surface which will be the victim of unequal distribution abrasive load on surface and prone to

Table 4

Compressive strength and Average percentage abrasion loss

Concrete Mix Sample	Compressive Strength (N/mm^2)	Average % abrasion loss
S1 (0% SS)	42.66	0.254
S2 (25% SS)	37.40	0.233
S3 (50% SS)	41.33	0.220
S4 (75% SS)	45.32	0.213
S5 (100% SS)	44.00	0.233

Table 5

Abrasion loss of concrete surfaces

Sr. No.	Concrete Grade Sample	Specimen	% abrasion loss for specimen surface after testing at 0^0 and 180^0	Avg % abrasion loss of 3 specimen (Test on Surface 1)	% abrasion loss for specimen surface after testing at 0^0 and 180^0	Avg % abrasion loss of 3 specimen (Test on Surface 2)	% abrasion loss for specimen surface after testing at 0^0 and 180^0	Avg % abrasion loss of 3 specimen (Test on Surface 3)	% abrasion loss for specimen surface after testing at 0^0 and 180^0	Avg % abrasion loss of 3 specimen (Test on Surface 4)	Average % Abrasion (Test Completed)
1	SS00	28_1	0.274	0.269	0.264	0.238	0.235	0.263	0.280	0.245	**0.254**
		28_2	0.248		0.222		0.325		0.227		
		28_3	0.283		0.228		0.229		0.229		
2	SS25	28_1	0.223	0.214	0.228	0.211	0.205	0.266	0.244	0.241	**0.233**
		28_2	0.224		0.221		0.300		0.240		
		28_3	0.194		0.183		0.293		0.239		
3	SS50	28_1	0.174	0.173	0.175	0.164	0.272	0.316	0.235	0.225	**0.220**
		28_2	0.192		0.160		0.324		0.197		
		28_3	0.154		0.158		0.353		0.241		
4	SS75	28_1	0.166	0.184	0.166	0.179	0.246	0.224	0.271	0.265	**0.213**
		28_2	0.178		0.182		0.196		0.268		
		28_3	0.210		0.188		0.229		0.255		
5	SS100	28_1	0.260	0.221	0.186	0.194	0.272	0.280	0.243	0.237	**0.233**
		28_2	0.217		0.200		0.249		0.215		
		28_3	0.187		0.195		0.319		0.254		

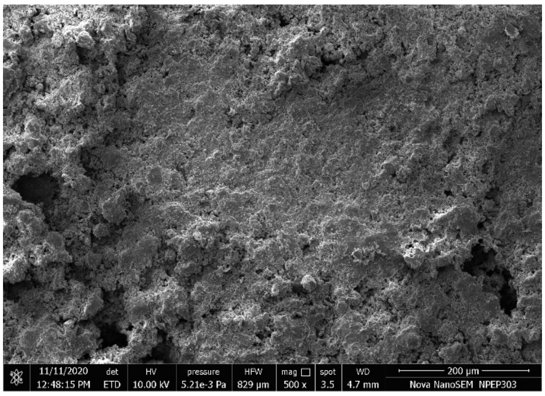

Fig. 4 a) - Steel slag mixed concrete surface

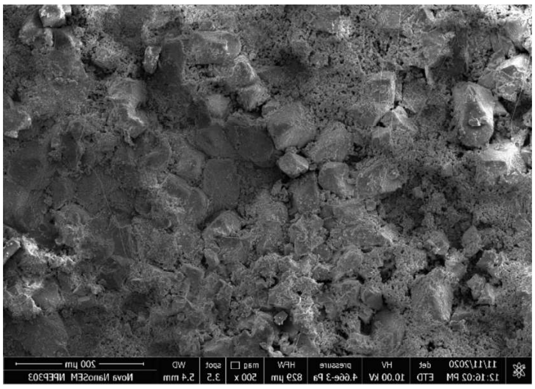

Fig. 4 b)- Stone aggregates mixed concrete surface

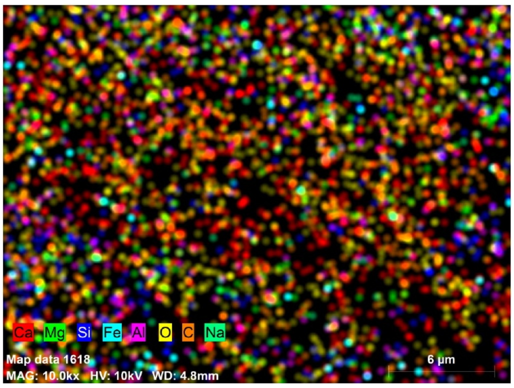

Fig. 5 a) - Steel slag mixed concrete surface

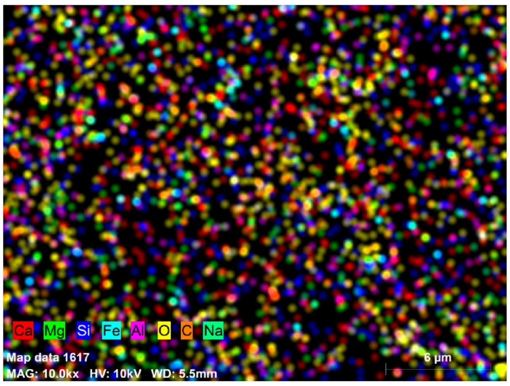

Fig. 5 b) - Stone aggregates mixed concrete surface more abrasive than steel slag mixed concrete. Distribution of chemical ingredients on concrete surface which is undergoing under abrasive forces can be observed in EDS imaging in Figure 5. Calcium (Ca) present in steel slag mixed concrete is 26.83 % where in stone aggregate mixed concrete is 24.24 %, this would be resulted from presence of CaO in steel slag. Presence of Carbon (C) at 13.70 % by weight in steel slag mixed concrete where Carbon (c) at 9.22 % by weight in stone aggregate mixed concrete may leads to form $CaCO_3$ which effect on pH of concrete.

5. Conclusions

This experimental study on replacement of coarse aggregate by steel slag aggregates culminates followings:

- An increase in the compressive strength and abrasion resistance properties of steel slag mixed concrete which were prepared by replacing 75% of coarse aggregate with a steel slag aggregate. Compressive strength increased by 6.23 % where abrasion loss decreased by 16.14 %. The steel slag mixed concrete can be utilized as a general-purpose concrete in line with a requirement of IS 10262.
- Percentage abrasion loss for all mixes studied ranges from 0.213 to 0.254; thus, it can be utilized for concrete pavement with pneumatic tyred traffic, railway platform and footpaths as per IS 9284.
- The addition of steel slag (over a range of steel slag proportion) in concrete does not significantly affect the abrasion resistance but the concrete prepared using steel slag was good in compressive strength, uniformity in ingredients and non-porous. The chemical composition and its distribution do not affect microstructure of concrete when produced with steel slag mixed concrete.

This study is limited to the scope stated but researcher can explore but not limited to whole or discrete effect of occurrence and radioactivity of SS, presence of toxic elements or heavy metals in SS and microstructural analysis of SS on concrete for sustainable construction.

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