Physico-chemical Characterization of Steel Slag as Railway Ballast Material

Pawan Kumar Chamling[1][0000-0003-1816-0910] Sumanta Haldar[1]

and Shantanu Patra[1]

[1] Department of Civil Engineering, School of Infrastructure, Indian Institute of Technology Bhubaneswar, Jatni, Odisha – 752050

pkc11@iitbbs.ac.in; sumanta@iitbbs.ac.in; shantanupatra@iitbbs.ac.in

Abstract. Steel slag is an industrial by-product generated during steel making process. At present, rate of utilization of this by-product is too low and it has an enormous potential to use as a ballast material. Understanding of physical and chemical characteristics of this by-product is essential for its proper use as a ballast material by railway industry. In present study, the crushing and abrasion characteristics of steel slag has been experimentally investigated. Along with physical properties, total concentration of As, Cd, Cu, Cr, Pb, Ni and Zn from it using acid digestion testing method has also been carried out. Results show that total extractable metals are within the limits prescribed by the United States Environmental Protection Agency (USEPA) regulating limits. The crushing and abrasion values are also found within the Research Designs and Standards Organization (RDSO) specifications.

Keywords: Steel Slag, Railway Ballast; Industrial Waste; Environmental Regulations.

1 Introduction

Steel slag is an industrial by-product generated during steel making process. The Indian steel producing industries generate more than 17 million tons of steel slag every year (Indian minerals yearbook 2018). Recently, India replaces Japan as second top steel producer. With increase in steel production, steel slag generation is also expected to increase at an alarming rate. At present, rate of utilization of this by-product is too low. The reason of the low utilization is mainly due to potential leaching of harmful elements and competition from easily available natural raw materials (Das et al. 2007). Due to large scale new constructions in Indian railways industry such as semi-high-speed railways, high-speed railways, dedicated freight corridors and upgradation of existing tracks, demand of natural crushed aggregate is increasing (National rail plan 2030, Ministry of Railways, Government of India). However, mining of natural aggregate becomes difficult due to environment legislation. Steel slag has an enormous potential to use as a ballast and sub-ballast material in Indian Railways

(Chamling et al. 2018, Koh et al. 2018). The use of steel slag as railroad construction materials will be an enthusiastic outcome for the waste management hierarchy, provided that the use takes into account the required environmental and engineering concerns. Based on this circumstantial, a better understanding of the physical, chemical and mineralogical properties of steel slag is required. The objective of current laboratory investigation is to study the environmental and physical properties of the coarse steel slag particles. A series of physical and chemical tests are performed. Physical tests such as Los Angeles abrasion test, impact test, crushing test, water absorption test, particle shape test, soundness test and specific gravity test are performed. For chemical tests such as X-ray diffraction and flame atomic absorption spectrometry test are performed.

2 Material and Methods

2.1 Material

The steel slag used in the present study are provided by the Rourkela Steel Plant, Odisha. Received samples have been sieved through different IS sieve size to obtained the representative samples for further laboratory testing. Figure 1 shows the visual appearance of the collected steel slag. Maximum particle size of the sample is obtained as 90 mm. No pre-treatment has done on the collected samples. The particle size distribution of the collected steel slag is shown in Fig. 2. The fine content of the collected steel slag is found as around 10%.

Fig.1 Visual appearance of steel slag

2.2 Methods for characterization

Chemical characterization

Mineralogy composition of the steel slag has been determined by using X-ray diffractometer Bruker D8 ADVANCE device (Bruker, Massachusetts). X-ray diffraction

(XRD) device is operated at 40 kV and 40 mA and Kα radiation has been generated with the help of Cu anode. Data has been collected for 2θ interval 10–90° with step increment size of 0.02°. Energy-dispersive X-ray spectroscopy (EDS) of the steel slag is performed to get the atomic percentage of elements. INCA version 7.0 software integrated with the EDS has been used to obtain the elemental data generally present in steel slag as reported by Indian mineral yearbooks 2018.

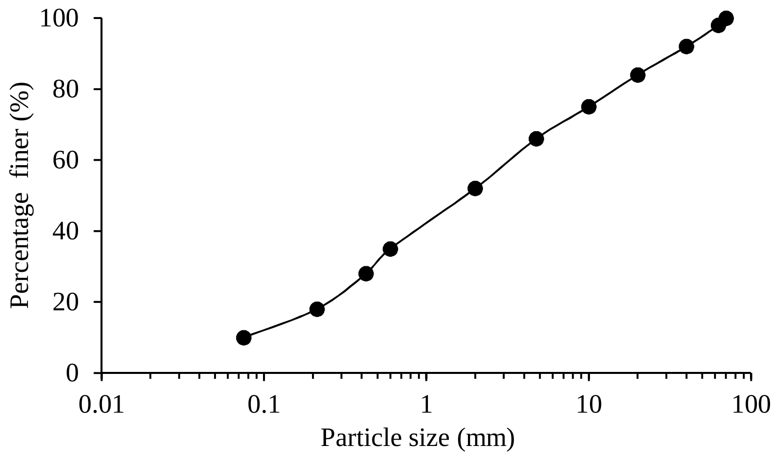

Fig. 2 Particle size distribution curve of the collected steel slag

Leaching tests are often performed to assess the worst case environmental scenario (Rondi et al. 2016). A number of leaching methods such as acid digestion, toxicity characteristic leaching procedure (TCLP), synthetic precipitation leach procedure (SPLP), multiple extraction procedure (MEP) etc., are used to remove the soluble components from the solid matrix (Tiwari et al. 2015). In present study, acid digestion technique is used to generate the leachate that will dissolve almost all environmentally available elements. Steel slag samples are digested according to EPA Method 3050B which is a very strong acid digestion method.

Physical characterization

In present study, Los Angeles test has been performed in order to measure the steel slag aggregates resistance to abrasion by using Los Angeles Test Machine in accordance with IS 2386-part IV standard. The resistance to degradation of steel slag is measured under combination of abrasion and impact during the rotation of steel drum containing 12 steel spherical balls with total mass of around 5 kg. For this test, 10 kg sample is taken from steel slag ballast materials whose gradation is harmonious with grade F of IS 2386 standard. The machine is rotated with a speed of 30 rpm for 1000 revolutions (IS 2386 Part IV (1963)). After the completion of the test, the material is removed from the machine and the material coarser than 1.7 mm has been separated out by sieving through 1.7 mm IS sieve. After that coarser materials has been washed properly and oven dried at 105° C. The mass loss percentage has been calculated by subtracting the obtained mass from the original mass of test sample.

Crushing value test has been performed to measure the resistance of steel slag aggregate to crushing under a gradually applied compressive load. The test has been performed on aggregate passing from 12.5 mm sieve and retained on 10 mm sieve which is in accordance with IS 2386 standard. The appropriate quantity has been taken from steel slag ballast materials to fill the 150 mm cylindrical mould in three layers, each layer being tamped 25 times with the rounded end of the tamping rod. The load is applied with the help of a plunger at a uniform loading rate of 4 tonne/min up to a total load of 40 tonnes. After the completion of the test, the material is removed from the mould and has been sieved through 2.36 IS sieve properly to get finer fraction. The crushing value has been calculated by the ratio of the mass of fine fraction to the total sample mass.

Impact test has been performed to find out the relative measure of the resistance of the steel slag aggregate to sudden shock. In the present study, steel slag aggregate passing through 12.5 mm sieve and retained on 10 mm sieve has been taken which is in accordance with IS 2386 Part IV (1963) standard. Material has been filled in the cylindrical steel cup in three layers, each layer being tamped 25 times with the tamping rod. The test sample has been subjected to total of 15 blows with the 50 kg hammer from a height of 35 cm each being delivered at an interval of around one second. After the completion of the test, the material is removed from the mould and has been sieved through 2.36 IS sieve properly to get finer fraction. The Impact value is calculated by the ratio of the mass of fine fraction to the total sample mass.

To get an idea on the internal structure of coarse aggregate, generally water absorption test is performed. Aggregates with the higher water absorption have more porous structure and are commonly considered inappropriate as construction materials, unless found to be satisfactory based on strength, and mass stability tests. In current study, 2 kg steel slag aggregate passing through 63 mm sieve and retained on 6.3 mm sieve has been taken and placed in the wire mesh basket and immerged in distilled water with a cover of 50 mm of water above the top of the basket at temperature 27 ± 3 °C. Steel slag aggregate has been jolted for 25 times and weighed after immersion of steel slag aggregate for 24 hours. After that, aggregate has been taken out and gently surface dried with cloth and kept in air until it appears to be completely surface dry and mass has been taken. Then aggregate kept in oven for 24 hours at 105 °C and again dry mass has been taken.

Soundness test of steel slag aggregate is performed to check the resistance to weathering action and to judge the durability. This test is performed according to IS 2386 Part V (1963) standard.

3 Results and Discussion

3.1 Chemical composition of steel slag

Energy-dispersive X-ray spectroscopy (EDS) of the steel slag has been performed and the atomic percentage of elements is obtained. After that, the weight percentage of chemical composition is calculated which are generally present in steel slag as identified by Indian mineral yearbook 2018. It is observed that the major chemical compounds present in steel slag are CaO, SiO_2 and FeO. The results of percentage composition of various elements measured using EDS technique are shown in Table 1.

Table 1. Chemical composition of steel slag collected from RSP

Element	Weight (%)	Indian Minerals Yearbook 2018
CaO	53.35	44.4
FeO	21.03	22.6
SiO_2	16.9	13.7
P_2O_5	3.58	-
MgO	3.25	6.7
Al_2O_3	1.79	1.82
S	0.1	0.09

3.2 Particle mineralogy of the steel slag

X-ray Diffraction (XRD) analysis is performed using D8 ADVANCE XRD device (Bruker, Massachusetts). XRD patterns of steel slag shows a mixture of various crystalline phases with many overlapping peaks (Fig. 3). The most common crystalline phases present in steel slag are larnite [Ca_2SiO_4], wustite [FeO], mayenite [$12CaO.7Al_2O_3$], srebrodolskite [$Ca_2Fe_2O_5$] and portlandite [$Ca(OH)_2$]. Free lime hydrates in presence of water and forms portlandine and its presence suggests that the majority of free lime present on surface gets hydrated. Wustite is observed as one of the major mineral phase due to high iron oxide contents present in steel slag.

3.3 Physical properties of the steel slag

The physical property tests results show the stability of steel slag aggregate at different type of action namely rotary action, impact action and crushing action. These tests results are shown in Table 2. A good value of these tests are obtained for the steel slag due to high strengths of the existing compounds in their microstructure. All the obtained values are within the Research Designs and Standards Organization (RDSO, IRS-GE-1-2004) specification except the water absorption. Water absorption obtained as 1.7 % which is higher than the recommended value of 1% but within the specification for exceptional case value of 2.5 %. Specific gravity is found as 3.21 which is greater than the specific gravity of conventionally used aggregates as ballast materials. Due to higher specific gravity of steel slag, steel slag ballast may provide higher lateral resistance to the rail track. Soundness value is obtained as less than 7 %.

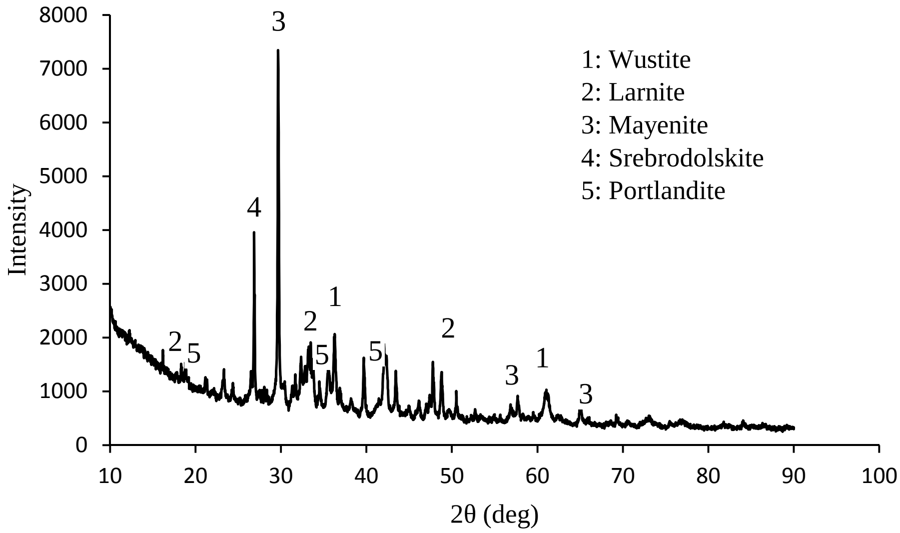

Fig.3 X-ray Diffraction pattern of the investigated steel slag

Table 2. Physical properties of steel slag collected from RSP

Testing	Steel Slag Ballast Value	Standard Test Method	RDSO Specification
Impact test	18%	IS:2386 Part IV (1963)	< 20% (25% in exceptional case)
Crushing test	23%		-
Abrasion test	16%		< 30% (35% in exceptional case)
Specific Gravity	3.21	IS:2386 Part III (1963)	-
Water Absorption	1.7%		< 1% (2.5 % in exceptional case)
Soundness	6.3%	IS:2386 Part V (1963)	-
Particle Shape	Sub-angular	IS:2386 Part I (1963)	-

3.4 Total concentration of heavy metals

It is important to know the total content of hazardous substances present in steel slag. The toxic effects of solid wastes are known to be influenced by their heavy metal contents. The total composition of each material are analyzed by flame atomic absorption spectroscopy (FLAA). As the result of FLAA test, heavy metals such as As, Cd, Cu, Cr, Pb, Ni, Zn are detected. The detected concentration of heavy metals is relatively less as shown in Table 3. All the concentration values are within the allowable values of Environmental Protection Agency (US-EPA, 2009) requirement for solid inert waste. Koh et al. (2018) has also reported very small amounts of heavy metals present in the steel slag. Hence, it can be used as ballast material. The less concentration values of heavy metals may be obtained if chemical reaction occurred in presence of water.

Table 3. Results of FLAA test of steel slag collected from RSP

Constituents	**Average Concentrations (mg/l)**	**Concentration (mg/l) (Koh et al, 2018)**	**EPA (US-EPA, 2009) allowable limits for hazardous waste classification (mg/l)**
Arsenic (As)	0.1197	0.001	5
Barium (Ba)	0.583	-	100
Cadmium (Cd)	0.0117	0.006	10
Copper (Cu)	0.038	0.007	25
Chromium (Cr)	0.0673	-	5
Lead (Pb)	0.6199	-	5
Nickel (Ni)	0.0321	-	20
Zinc (Zn)	0.2914	-	5

4 Conclusions

A series of physical and chemical tests are performed on the steel slag collected from the Rourkela Steel Plant. From this investigation the following conclusions are reached.

- Larnite, wusite, mayenite, srebrodolskite and portlandite are the major crystalline phases which are identified in the steel slag. The physical properties of steel slag which are observed, is due to the presence of these crystalline phases.
- Steel slag aggregates are found to have good resistance against rotary action, impact action, crushing action and weathering action indicating that this material is ideal for usage as railway ballast.

- The total concentration of heavy metals, present in steel slag are within the permissible limits according to USEPA specification and therefore have minimal environmental risks for their use as a ballast material.

All the obtained physical properties are found within the Research Designs and Standards Organization (RDSO) specification. Simultaneously steel slag categorized as inert solid wastes according to EPA specification. Thus, it is possible to use steel slag as railway ballast material instead of natural crushed aggregate.

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