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Performance characteristics of pavement sub-base containing steel slag

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ABSTRACT: A sub-base is normally a granular layer in a pavement and comprises of aggregates with a specified grading. Good quality aggregates mostly derived from natural stone resources are now a days getting scarce and are becoming too costly in several locations because of longer lead involved. In this regard, engineers and researchers are constantly working on replacing aggregates which constitute bulk of a pavement layer, with alternate and waste materials. This paper deals with utilisation of abundantly and locally available steel slag, an industrial waste of a local integrated steel plant in pavement sub-base, thus not only offsetting the problems such as cost of construction, solid waste disposal problems and environmental concerns, but also helping preservation of natural stone resources for other essential uses. The experimental programme includes grading of available steel slag and normal aggregates, blending of slag with aggregates to achieve the desired gradation, and compaction test to determine the optimum moisture content. The study also includes other important performance characteristics such as expansion potential and CBR besides verifying the hazardous effects of using slag in pavement sub-base. It is observed that the use of aged steel slag results in much better performance characteristics, besides satisfying the environmental requirements, thus providing a solution of building a sustainable pavement in sites not far from steel plants.

Keywords: Slag, XRD analysis, toxicity, CBR, expansion behaviour

1 INTRODUCTION

A sub-base in a pavement is normally a granular layer that bears some amount of stresses and strains caused due to the vehicular loads transmitted through upper layers, and also transmits small amount of stresses to the subgrade. A sub-base used in most of highways comprises of aggregates with a specified grading. Good quality aggregates mostly derived from natural stone resources are now a days getting scarce and are becoming too costly in several locations because of longer lead involved. At the same time, generation of a vast quantity of waste materials from different manufacturing industries like iron and steel, is facing a shortage of dumping space and is also creating severe environmental pollution. In this regard, engineers and researchers are constantly working on replacing aggregates which constitute bulk of a pavement layer, with alternate and waste materials. India is world's 2nd largest producer of crude steel. As on 2019, India produces 12 million tonnes of steel slag annually (IBM 2020). This paper is an attempt to explore replacement of costly conventional aggregates with steel slag produced in huge quantity as a waste from an integrated steel plant located nearby, in pavement sub-base course, as the amount of waste steel slag generated is so vast that it results in dumping problems because of lack of space, and can also be hazardous to the environment.

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2 BRIEF REVIEW OF LITERATURE ON USE OF SLAG IN PAVEMENTS

Basic oxygen furnace (BOF) steel slag mainly comprises of silicon, calcium and iron. However, it also contains some trace (potential toxic) elements, like chromium and vanadium, which needs to be verified for acceptable level of concentration (Chaurand et al. 2007). The steel slag aggregate (SSA) was utilised in road construction in Saudi Arabia, which is a by-product of the steel manufacturing process. Two types of SSA materials (0 – 5 mm) and (0 – 37 mm) were used in different combinations with locally available marl, marl fines, and sand, and the CBR values of the optimum blends were found to be very high (Aiban 2006). Pasetto and Baldo (2010) reported that ferrous slags such as blast furnace slag, steel making slag, manufactory and ferroalloy slags are the industrial by-products which can be used in pavement construction because of their wide convenience and scope of applications. The steel slag combined with limestone aggregates were used in different proportions to achieve the desired density and shear strength in Egyptian roads. The BOF slag as well as electric arc furnace (EAF) slag can also be used for road base as well as for road base asphalt concrete. As compared to blast furnace slag, steel slag usually has a higher bulk density and potential expansive nature where volume changes can be noticed up to 10 percent due to the presence of free calcium and magnesium oxides. Before use in construction, suitable ageing or treatment with acids or asphaltic coating should be done to avoid the potential long-term volume changes. The free lime content of steel slag is studied to analyse its expansion behaviour (Emery 1982). He also observed through different investigations that the mixtures of slag and asphalt showed better mechanical characteristics than those containing conventional aggregate and asphalt, satisfying the acceptable criteria for road construction. Wang et al. (2010a) developed a theoretical equation to determine expansion rate of steel slag subjected to load and climatic changes. Volume expansion test was carried out in laboratory and compared with theoretical volume expansion rate which can be deduced from free lime content, specific gravity and bulk specific gravity of slag. It can be seen that, expansion in volume can be absorbed to certain extent by the void volume present in steel slag, and sometimes potential expansion can be almost zero. Shen et al. (2009) aimed at preparing a mix of steel slag, fly ash and gypsum which can be used in base layer of a pavement. After conducting tests for different proportions, the mix having fly ash to steel slag ratio as 1:1, and phosphogypsum dosage as 2.5% makes the optimal mix which resulted in highest strength among other combinations.

2.1 *Objective and scope of study*

Through brief review of literature presented above, it is seen that, most of physical and engineering properties of slag are superior as compared with the natural aggregates. With controlled leaching and expansion characteristics, the use of steel slag in pavement bases/sub-bases can be beneficial from the point of economy, waste utilisation and environment. Keeping in view these facts, the main objective of this study is to explore possible utilisation of abundantly available steel slag for pavement sub-base replacing conventional aggregates to the extent possible. To achieve the above main objective the scope of the present study is as follows.

i. Collection of steel slag samples from waste dumps
ii. Characterisation and leachate analysis of steel slag sample
iii. Grading analysis of collected slag and aggregate samples, and blending of slag and aggregates to satisfy desired grading for subgrade
iv. Determination of physical properties slag, aggregate and slag-aggregate blends
v. Study of expansion potential of slag-aggregate blend

3 MATERIALS AND METHODS

The study is divided into three phases. In the first, the chemical composition, phase composition and toxicity characteristics of slag samples are studied. The second phase relates to the physical properties of slag, aggregates as well as the combination of slag and crushed aggregates to find its suitability for use in the sub-base layer of a pavement. The third phase is regarding free lime content of steel slag and study of its expansion behaviour.

3.1 *Characterisation of slag*

The dry slag samples were finely grounded to get a homogeneous mixture, and then the samples were analysed using an X-ray fluorescence spectrometer (XRF). The chemical composition of slag samples was analysed and the results are presented in Table 1. The mean chemical composition of 12 slag samples was expressed in terms of percentage of total weight. The chemical composition of slag gives some insight to the performace of the materials in a structural layer. The results show that the slag samples mainly have oxides of iron, aluminium, calcium and magnesium, which provide strength to the material.

Table 1. Chemical composition of slag.

SiO_2	FeO	Al_2O_3	CaO	MgO	MnO	S	TiO_2	K_2O
26-28	16-25	4.9-7.7	28-34	7.6-11.4	3.6-5.3	0.1	0.59-0.68	0.11-0.18

3.2 *XRD analysis*

The X-ray diffraction technique was used to determine the phase composition of slag samples. The slag samples were grounded (to pass a standard 75µm IS sieve) and homogenised before analysis. XRD analysis was performed on a PW 3020 Philips diffractometer using Cu Kα (λ=0.15405 nm) radiation. The phases present in the slag sample determined by XRD analysis are illustrated in Figure 1. The XRD patterns of slag sample are quite complex. It shows multiple overlapping of different peaks. This results in presence of a number of different types of minerals in it. As is seen from the figure, a large number of well-defined peaks represent the crystalline structure of the slag. It also represents slow cooling of slag. The intensity of peak also shows major and minor minerals present in it. Most abundant compounds present in this slag are Quartz (SiO_2), Alumina (Al_2O_3), Hematite (Fe_2O_3) and Calcium compounds. Overlapping of peaks and presence of oxides results in difficulty of determination of compounds.

3.3 *Scanning Electron Microscopy (SEM)*

A Scanning Electron Microscope (SEM) of make and model, JEOL JSM- 6480 LV, EDS was used to capture the micro-structure images of slag samples supplied. The SEM images, as presented in Figure 2 indicate that the steel slag is crystaline in nature. The surface textures of the steel slag are rough and angular. It is seen that some particles are elongated and some are flakey in shape.

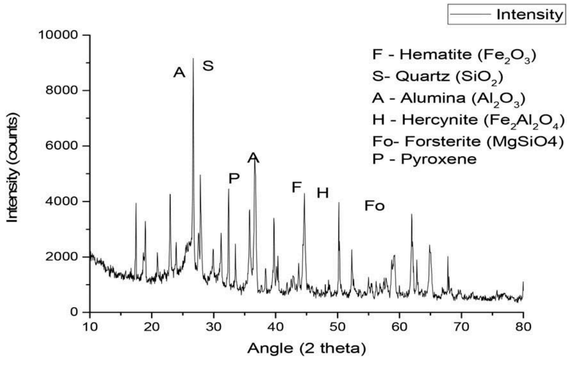

Figure 1. XRD pattern of slag sample.

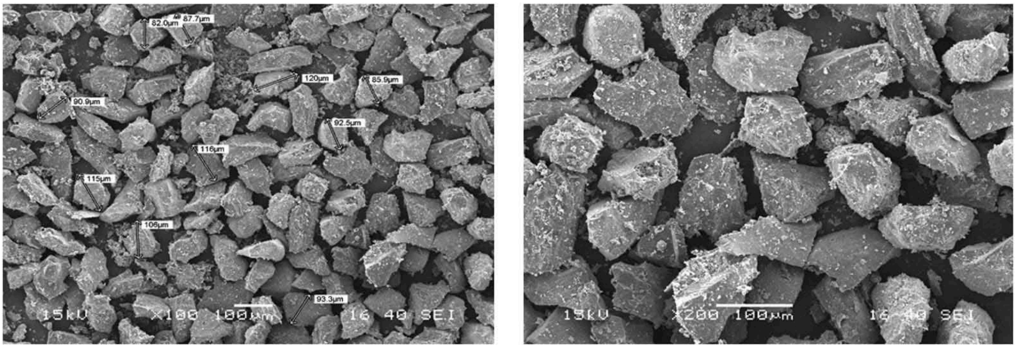

Figure 2. SEM images of steel slag samples.

3.4 *Toxic characteristic leaching procedure*

Toxicity Characteristic Leaching Procedure (TCLP) is conducted to determine the harmful metals present in slag samples in order to ensure safety in its use in the field. Necessary procedure of sample solution preparation, extraction and filtration has been folllowed (Environmental Protection Agency (EPA) of United States method 1311 1992, Aiban 2006). Finally, the metals are detected using Atomic Absorption Spectroscope (AAS). The results of quantity of important heavy metals in slag samples following the above procedure are presented in Table 2. It is seen that the results obtained are far below the corresponding permissible limits. In other words, the slag samples contained toxic components below permissible limits for which they can be used in pavement layer without any possible threat of harm to any living plants or organisms.

3.5 *Physical properties*

3.5.1 *Particle size distribution*

The gradations of the slag samples and crushed aggregate samples of different nominal sizes, 40 mm, 20 mm, 10 mm, 6 mm and dust were done by sieve analysis using Indian Standard (IS) sieves. The slag samples were blended with crushed aggregate samples for use in filter (lower) layer or drainage (upper) layer of granular sub-base (GSB) to satisfy the desired grading of MoRTH (Ministry of Road Transport and Highways, Govt. of India 2013). For the filter layer a close GSB grading II and for the drainage layer a relatively uniform GSB grading VI was taken as per the said specifications. The grading curves of crushed aggregates and steel slag as supplied are shown in Table 3.

Table 2. Concentration of heavy or toxic elements in leachate water of slag samples.

Toxic element	Pb (Lead) (mg/L)	Cr (Chromium) (mg/L)	Se (Selenium) (ug/L)	As Arsenic) (ug/L)	Hg (Mercury) (ug /L)
Observed concentration	0.127	0	0	0	0.728
Permissible limit	5	5	1	5	0.2

Table 3. Particle size distribution of steel slag and crushed aggregates.

Sieve size (mm)	Per cent passing					
	A40	A20	A10	A6	Stone Dust	Steel Slag
53	100	100	100	100	100	100
26.5	46.82	100	100	100	100	79.69
9.5	0.17	3.6	55.74	100	100	31.56
4.75	0.13	1.25	18.26	87.71	91.36	16.45
2.36	0.13	0.93	5.67	41.41	70.00	10.13
0.425	0.11	0.78	3.55	17.97	41.16	3.77
0.075	0.08	0.52	1.91	4.12	18.44	1.10

The physical properties of slag and crushed aggregates determined by the relevant Indian Standards for use in different layers of sub-base are listed in Table 4.

Table 4. Physical properties of steel slag and crushed aggregate samples.

Property	Steel Slag	Aggregate
Specific gravity (Bulk)	3.28	2.64
Specific gravity (Apparent)	3.5	2.70
Water absorption (%)	1.98	0.46
Liquid limit (%)	27.99	23.17
Aggregate impact value (%)	11.67	14.94
Aggregate crushing value (%)	14.8	14.7
Los Angeles abrasion value (%)	15.76	22.76

3.5.2 *Modified proctor test*

Modified Proctor test was conducted as per the IS: 2720 (Part 8) (1983) to determine the maximum dry density (MDD) and optimum moisture content (OMC) for a given slag-aggregate sample, so that the same may be used for achieving compaction in the field.

3.5.3 *California Bearing Ratio (CBR) test*

The CBR values of the combined blend of slag and crushed aggregates were determined as per IS: 2720 (Part 16) (1987).

3.6 *Expansion characteristics*

Though slag has excellent physical properties, it is the volume expansion that may make it unsuitable for construction applications. The expansion in slag normally occurs due to the presence of free lime. The expansion test was carried out by following the procedures reported in different studies (Emery 1982, Wang et al. 2010]. The mould containing compacted CBR sample was immersed in hot water bath (inside a large steel container). The temperature was maintained at $70\pm2^{\circ}$C with continuous supply of air, and the water level was maintained, with temperature readings taken for verification at continuous intervals for seven days.

Figure 3. Expansion test in progress.

4 RESULTS AND DISCUSSION

4.1 *Characterization of steel slag used*

From the chemical composition as presented in Table 1 and discussed in Section 3.1, it has been observed that the slag used in the study confirms to steel slag that has a principal amount of CaO, SiO2 and FeO (about 80% by weight) in relevant proportions. From XRD analysis discussed in Section 3.2, the phases are found to be in stable carbonate, hydroxide, silicate or aluminate form which may not cause threat of chemical actions. By using the AAS as dicussed in Section 3.4, the concentrations of toxic metals present in leachate water were found to be within the permissible limits of Environmental Protection Agency (EPA) of United States, hence may be considered as safe for use in pavements considering environmental issues.

4.2 *Performance characteristics*

4.2.1 *Blending of steel slag and aggregates*

The results of blending of steel slag and crushed aggregate samples determined by following usual theoretical approaches are shown in Table 5. The optimum percentages of steel slag were found to be 58.5% and 90% to satisfy GSB of grading II and grading IV, respectively as per MoRTH (2013), with rest comprising of aggregates of other nominal sizes.

Table 5. Blending of slag and crushed aggregates GSB Grading II and IV (MoRTH, 2013).

	Grading II		Grading IV	
Sieve Size (mm)	Specified Per cent Passing	Blending Proportion (Slag=58.5%+A6=41.5%), Per cent Passing	Specified Per cent Passing	Blending Proportion (Slag=90% +A10=5%+A6=5%) Per cent Passing
53	100	100	100	100.00
26.5	70-100	88.11	50-100	65.64
9.5	50-80	59.95	-	-
4.75	40-65	46.02	15-35	28.00
2.36	30-50	30.16	-	-
0.425	10-15	9.65	-	-
0.075	0-5	2.35	0-5	0.81

4.2.2 *Compaction characteristics and CBR of blended mix*

For use of materials in a structural layer of a pavement it is essential to ascertain the optimum moisture content (OMC) and compaction conditions (maximum dry density (MDD)) before actual construction. Similarly, in absence of advanced tests for assessment of strength of the granular layer, California Bearing Ratio (CBR) test of sample prepared at its OMC and MDD may be used. The results of optimum moisture content, maximum dry density and CBR values under both unsoaked and soaked conditions for different slag-aggregate blends according to GSB II and GSB IV gradations are given in Table 6.

Table 6. Performance characteristics of blended slag and crushed aggregate samples.

	Granular Sub-base Filter layer (GSB II)	Granular Sub-base Drainage layer (GSB IV)
Property	Slag 58.5% + A6 41.5%	Slag 90% + A10 5% + A6 5%
Optimum moisture content (OMC) (%)	6.24	4.62
Maximum dry density (MDD) (kN/m^3)	24.9	24.7
Un-soaked CBR (%)	128.2	164.4
Soaked CBR (%)	87.1	103.9

4.3 *Expansion characteristics*

Steel slags have some free lime content which reacts with water, even from atmosphere, to form oxides, as a result creating expansion during this slow reaction. These expansion characteristics cause development of internal stresses in the pavement layer. The amounts of expansion as discussed earlier in Section 3.6 are represented by expansion in percent or expansion ratio, which should be within minimum values for possible use in pavements. The expansion characteristics of slag-aggregate combinations (GSB-II and GSB-IV gradings) determined through the expansion tests are represented in Figure 4. It is to be noted that the top plot refers to the sample without surcharge indicating more expansion behaviour as compared with the bottom plot which refers to the sample with surcharge representing overburden in field situation. It is clearly seen that the expansion of the sample used is quite less for any concern in the field and the given slag-aggregate sample can be used in the pavement sub-base.

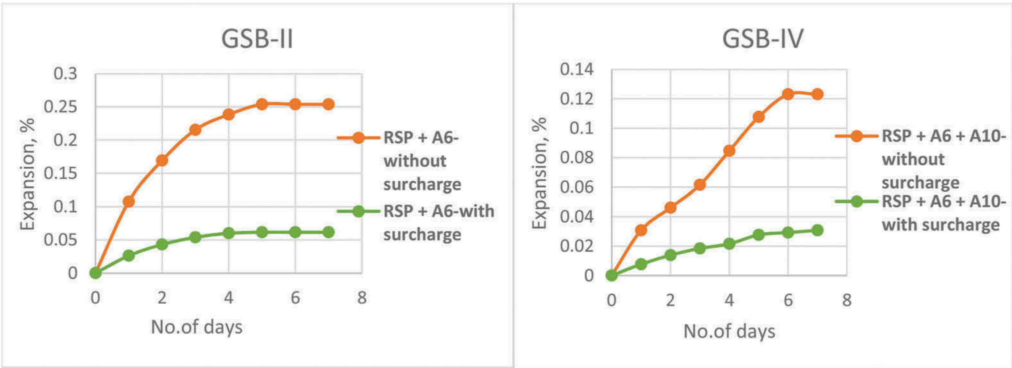

Figure 4. Expansion behaviour of slag-aggregate samples.

5 CONCLUSIONS

From the experiments conducted on the slag and slag-aggregate samples and from the analysis of results of various tests conducted, the following important conclusions are drawn.

i. The heavy and toxic metals present in the slag leachate water were either zero or negligible, and were within acceptable limits. Hence, there were no potential environmental and health hazards.
ii. For filter layer and drainage layer of GSB, the optimum concentrations of steel slag were found to be 58.5% and 90% (by weight) satisfying the desired gradings (GSB grading II and grading IV respectively as per the MoRTH specifications).
iii. Steel slag used was observed to contribute to higher CBR value of the blended sample for GSB.
iv. The expansion test result of the blended of steel slag-crushed aggregate sample was found to be much below 1% (the limiting value) and can be used in unbound pavement applications.

Considering the above test results obtained through experimental investigations, it is observed that the use of aged steel slag results in much better performance characteristics, besides satisfying the environmental requirements, thus providing a solution of building sustainable pavement sub-base in sites which are close to the steel plants.

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