MECHANICAL PERFORMANCE OF BITUMINOUS CONCRETE INCORPORATING STEEL SLAG WITH NATURAL AGGREGATE

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ABSTRACT

India has world's second largest road network in terms of length with a total road length of 4.24 million km. Hot mix bituminous pavement contributes around 50% road length to this vast road network. Large scale highway construction in India, emanating from rapid development, has caused massive depletion of scarce natural aggregate. This paper addresses this problem by investigating the influences of the utilization of steel slag as a coarse aggregate on the properties of hot mix bituminous concrete. Physical characteristics of bituminous mix ingredients i.e natural aggregate, steel slag aggregate and bituminous binder were determined to find out their compliance with Ministry of Road Transport and Highway Specification for Road and Bridge Works in India. Mechanical characteristics of bituminous mixes i.e Unmodified (having natural aggregate) and Modified (having steel slag as coarse aggregate) were determined using Marshall Method of mix design.

Unmodified and Modified mixes were subjected to an array of performance tests to check out the suitability of steel slag aggregates for the preparation of high performance bituminous concrete mix. The performance tests includes, retained Marshall Stability, indirect tensile strength, static creep test, wheel-tracking test and resilient modulus test. The laboratory study confirmed the improvement in various mechanical properties of steel slag modified mixes besides reduction in temperature and moisture susceptibility.

Key Words: Steel Slag Aggregate, Natural aggregate, Bituminous Mix, Bituminous Pavement.

INTRODUCTION

The development of the highway construction industry in India under the aegis of National Highway Development Program (NHDP), has posed great demand of natural aggregates for road construction. As the resources for naturally occurring aggregates diminished at an ever increasing rate, road industries are keen to utilize recycled and waste materials in road construction in harmony with sustainable development. Steel slag, a waste product from the steel making industry, is one of the recycled materials reported to exhibit great potential to replace naturally occurring aggregates in bituminous mixes.

Metallurgical waste particularly steel slag, generated in India is mostly collected by the waste producers themselves and partly by the companies doing separate collection of waste as their primary activity. The generated steel slag waste is partly recovered and returned to the production process (reuse) and part of the waste is sometimes used by other industries as secondary raw material (recycling), whereas the largest part still ends on often non-regulated landfills as industrial waste in adjoining areas. Disposal of steel slag as landfills are particularly hazardous for the environment.

Steel slag, a by-product from the steel making process had been reported to exhibit great potential as a replacement for natural aggregates in road construction (Bagampadde U., et al,1999; Juan M. M., et al,2005; Hunt L., et al,2000). Besides having better mechanical properties than natural aggregates, steel-slag aggregates have been reported to retain heat considerably longer than natural aggregates (Hamzah O. M., et al,2008). The heat retention characteristics of steel-slag aggregates can be advantageous for HMA construction, as less gas (energy) is used during the execution of asphaltic concrete works. Mladen F.,et.al. 2010, explored the possible utilization of Basic Oxygen Furnace (BOF) slag in asphalt concrete. Their study confirmed that the asphalt produced with BOF slag exhibit good resistance to permanent deformation, high stability with good flow properties and high stiffness modulus.

India is the 4th largest steel producer in the world with total steel production of 72 MT per annum. Steel slag generated in steel manufacturing industries obtained from Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF), is another waste from iron and steel industries in India. It is non-hydraulic and crystalline in nature and rich in Fe_2O_3 content (20-30 percent). The limited use of steel slag in Indian steel plants (less than 30%, mainly used in sinter plant as lime substitute) and use of recovered metallic's in steel making remains a matter of concern for steel industries (CPCB Report,2006-07). In contrast in developed countries, the use of steel slag as construction material ensuring 100% utilization. Harsco India Private Limited which deals in Slag Co Products approached CSIR-CRRI for laboratory evaluation of processed steel slag aggregates to find out its suitability in road construction. Steel slag generated in Electric Arc Furnace (EAF) is considered for laboratory evaluation.

OBJECTIVES

Most projects in India involving steel slag aggregates as construction material are using this recycled aggregate in lower quality applications such as road bases rather than wearing course. The aim of this research is to study the performance of steel slag as road pavement aggregates compared to the conventional use of silicious aggregates for the same purpose. The detailed objectives are outlined below:

- (1) To assess the physical and mechanical characteristics of steel slag aggregate to find out its suitability in high performance bituminous concrete mix.

- (2) To assess the performance of bituminous concrete mix prepared using steel slag aggregate with siliceous natural aggregate and bituminous concrete mix having 100 % natural siliceous aggregates.
- (3) To evaluate the effect of moisture and temperature on the performance of mixes incorporating steel slag.
- (4) To compare the performance of Steel slag modified mix and Unmodified mix having natural aggregates.

MATERIALS AND METHODS

The study is divided into three main phases. The first is related to the physicochemical characterization of the steel slag aggregate, natural aggregate and bitumen. The second phase deals with bitumen mix designs which were two mixes; One with an integrated slag-natural aggregate matrix (Steel slag modified mix) and one with only natural aggregates (Unmodified Mix) used as a control mix. Third phase covers the various performance tests carried out to assess mechanical characteristics of steel slag modified and unmodified mix.

Material Used

The processed steel slag aggregates used in the study was supplied by HARSCO India Private Limited. Steel Slag was generated as a melt at about 1650°C during steelmaking from hot metal, direct reduced iron or scrap. It consisted of oxidized co-elements of the hot metal and other metallic charges which reacted with the added limestone and dolomite. Depending on the process technology, one could distinguish Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) slag. The chemical composition of EAF steel slag used in the study is given in Table 1.

Calcium oxide (CaO), iron oxide (FeO) and silica (SiO₂) are the three major chemical constituents of both EAF and BOF slags. Due to the presence of unstable phases in its mineralogy, steel slag can show volumetric instability, caused mainly by the presence of free CaO. In the presence of water, free lime hydrates and forms portlandite (Ca(OH)₂). Portlandite has a lower density than CaO and hence, hydration of free CaO results in volume increase (Irem Z. Y. et al, 2011).

In order to reduce the expansibility of steel slag aggregate, several aging methods can be used like air aging, hotwater aging and steam aging; under first method steel slag is left out in the open for 1 month for weathering through air (air aging), in the second method i.e hot water aging steel slag is immersed in hot water at 80 ± 3 °C temperature for 1 day or 3 days and the last method exposes steel slag aggregate to steam at 100⁰C for over 3 days (steam aging) (Han Y. M., et al, 2002) .

Table 1: Chemical Composition of Steel Slag

S.No.	Type of Oxide	Oxide Content %
1)	Calcium - CaO	42.0
2)	Iron - FeO	17.7
3)	Silica - SiO ₂	17.2
4)	Magnesium - MgO	7.2
5)	Aluminium - Al ₂ O ₃	7.1
6)	Manganese - MnO	4.3
7)	Phosphorous - P ₂ O ₅	< 1
8)	Sulphur - SO ₃	< 1
9)	Potassium - K ₂ O	< 1
10)	Sodium - Na ₂ O	< 1
11)	Chromium - Cr ₂ O ₃	< 1

Physico-Mechanical properties of natural aggregates and steel slag aggregates were determined through laboratory tests to assess the suitability of aggregates in bituminous mixes. Table 2 reports the physical and mechanical properties of aggregates as well as specific test protocol adopted.

For the preparation of bituminous mix, Viscosity Graded bitumen binder (VG 30) was considered. To find out the suitability of bitumen binder for preparation of bituminous mix, various physical properties of bitumen were determined as per relevant Indian standard specifications. Properties of bitumen binder obtained from laboratory testing are reported in Table 3.

Table 2: Physical-Mechanical Properties of Aggregates

Properties Tested	Test Results		Specified Limits in MoRTH Specification	Testing Specifications
	Natural Aggregates	Steel Slag Aggregates		
Los Angles Abrasion Value	14.23%	12.06%	30 % max	IS 2386 (Part-V)
Aggregate Impact Value	21.64%	16.67%	27% max	IS 2386 (Part IV)
Soundness				
i) Sodium Sulphate	5.60%	4.30%	Max.12 %	IS 2386 (Part-V)
ii) Magnesium Sulphate	4.80%	5.10%	Max 18 %	
Combined Elongation and Flakiness Index	25.20%	8.95%	30% max	IS 2386 (Part I)
Water Absorption Value	0.70%	0.80%	2% max	IS 2386 (Part III)
Specific Gravity	2.75	3.06	2.5 – 3.0	IS 2386 (Part II)
Stripping (Retained Coating %)	99.00	99.50	Minimum retained coating 95%	IS 6241

Table 3: Bitumen Characterization

Physical Properties	BIS Test Methods	Type of Binder VG-30	Requirements of IS 73:2006 for VG 30
Penetration 25°C ,100 g, 5 sec, 0.1mm	IS 1203-1978	62	50-70
Softening point (R & B),°C	IS1205-1978	49	Min. 47
Ductility, cm at 27°C (5 cm/min pull)	IS 1208-1978	78	Min.75
Specific gravity at 27°C	IS 1202-1978	1.01	Min. 0.99
Absolute Viscosity, at 60°C, (Poise)	IS1206 (Part 2)	2570	2400-3200

Mix Design

Two fractions of natural aggregates and processed steel slag aggregates i.e 0-10mm and 10-20mm, Stone Dust and hydrated lime are combined together to obtain desired aggregate blend meeting the gradation requirements of MoRTH specification for Road and Bridge work for bituminous concrete (BC). Stone dust collected from aggregate crusher is used as fine aggregate with natural and processed steel slag aggregates.

Hydrated lime is primarily used as an anti-stripping agent to inhibit moisture damage. Gradation of natural aggregates, processed steel slag aggregates, stone dust and hydrated lime along with their respective concentration in all in one aggregate blend, adopted for preparation of bituminous concrete (BC) mix is given in Table 4.

Table 4: Proportioning of Aggregates

Sieve Size in mm	Individual Gradation (Percentage Passing)						Designed Blend		MoRTH Specified Limits
	Natural Aggregate 0-10mm (A)	Natural Aggregate 10-20mm (B)	Stone Dust (C)	Hydrated Lime (D)	Steel Slag Aggregate 0-10mm (E)	Steel Slag Aggregate 10-20mm (F)	Natural Aggregate A:B:C:D	Steel Slag E:F:C:D	
	0.2	0.5	0.28	0.02	0.1	0.6	20:50:28:2	10:60:28:2	
26.5	100	100	100	100	100	100	100	100	100
19	100	100	100	100	100	100	100	100	79-100
13.2	100	42.13	100	100	100	60.90	71.07	76.54	59-79
9.5	85.60	32.16	100	100	88.97	40.77	63.20	63.36	52-72
4.75	62.43	10.13	99.83	100	78.57	2.30	47.50	39.19	35-55
2.36	19.23	3.46	92.47	100	25.17	0.00	33.47	30.41	28-44
1.18	10.87	0.00	73.50	100	4.57	0.00	24.75	23.04	20-34
0.6	4.10	0.00	51.20	100	0.00	0.00	17.16	16.34	15-27
0.3	0.00	0.00	41.40	1.41	0.00	0.00	11.62	11.62	10-20"
0.15	0.00	0.00	28.70	8.63	0.00	0.00	8.21	8.21	5-13"
0.075	0.00	0.00	8.33	92.57	0.00	0.00	4.18	4.18	2-8'

For both the mixes the grading distribution was optimized with reference to designed grading envelop of MoRTH specification. An aggregate gradation curve along with reference grading envelopes for bituminous concrete wearing course is shown in Figure 1.

Figure 1: Gradation Curves of Bituminous Concrete Wearing Course

Optimum bitumen content of steel slag modified and unmodified bituminous mixes were determined through Marshall Procedure as stipulated in ASTM D 1559. It is known that the optimum bitumen content is sensitive to aggregate type as well as gradation. The optimum bitumen content was determined based on maximum stability, maximum density, and 4% air voids as recommended in MoRTH specification.

Performance Test Program

The performance of the mixes optimized in the mix design was studied with respect to the basic mechanical properties of bituminous mixes and in relation to the principal causes of pavement failure. Both mixes were evaluated for indirect tensile strength, resilient modulus, resistance to permanent deformation, fatigue resistance and moisture damage.

Indirect Tensile Strength

Since fatigue failures are the result of cyclic tensile strains or stresses it was postulated by numerous researchers that tensile stiffness would correlate best with fatigue. Indirect tensile strength test is used to assess the tensile strength of modified and unmodified bituminous mixes. The test was carried out according to ASTM 4867M-04 test method by loading a Marshall specimen with compressive load acting parallel to and along the vertical diametric-loading plane. The tensile strength is calculated as follows:

$$S_t = \frac{2P}{\pi tD} \quad \text{Eq. (1)}$$

Where S_t = tensile strength, P = maximum load, t = specimen height immediately before test, D = specimen diameter.

The tensile strength ratio of moisture conditioned and dry subset was also calculated to find out the moisture susceptibility of modified and unmodified mixes. Following formula was used to find out the tensile strength ratio of unmodified and modified bituminous mixes

$$TSR = \left(\frac{S_{tm}}{S_{td}} \right) * 100 \quad \text{Eq. (2)}$$

Where TSR = tensile strength ratio, S_{tm} = average conditioned tensile strength of the moisture conditioned subset, S_{td} = average tensile strength of the dry subset.

Resilient Modulus

The resilient modulus is an important parameter to determine the performance of pavement and to analyze pavement response to traffic loading. Moreover the resilient modulus can be considered as a synthetic indicator of the structural properties of the mixes (Hamzah O. M., et al, 2008; Pasetto M. et al, 2011). A non destructive test protocol was adopted according to ASTM D 4123-82. The test was conducted at four different test temperatures: 25°C, 30°C, 35°C and 40 °C for modified and unmodified mixes. The specimens were conditioned at the selected test temperature for 4 hours prior to testing. Repeated haversine load with a pulse width of 0.1 second and a pulse repetition period of

3 seconds was used in all resilient modulus testing in order to avoid impact loading to specimens. The total resilient modulus (E_{rt}) is defined as:

$$E_{rt} = \frac{P(v_{RT} + 0.27)}{t \cdot \Delta Ht} \quad (3)$$

Where E_{rt} = Total resilient modulus of elasticity (MPa),

P = Repeated load (N),

v_{RT} = Total resilient Poisson's ratio (a value of normally 0.35 used),

t = the thickness of specimen (mm),

ΔHt = total recoverable horizontal deformation (mm).

Rutting Resistance

Rutting is a longitudinal surface depression in the wheel paths. Rutting displaces the bituminous mixture in the wheel path and created channels. Rut resistance of unmodified and modified mixes were investigated through Wheel Tracking Test. Test was carried out as per AASHTO specification T-324 on bituminous concrete slab of 300×300×50mm size. Test samples were prepared at optimum binder content for unmodified and steel slag modified bituminous mixes. Bi-directional loading is applied with the help of a steel wheel with a solid rubber tire subjected on a total load of 31 kg and producing mean normal pressure of 5.6 kg/cm². Loading was applied at the rate of 42 passes per minute along the length of the slab at 40 °C test temperature. Two specimens were tested for each mix and average rut depth after 10000 cycles (20000 passes) were calculated.

Resistance to Permanent Deformation

The resistance to permanent deformation has been investigated by static creep test. In the static creep test, a constant axial load is applied to the test specimens throughout the duration of the test. All specimens were subjected to a seating load of 78.5 N for ten minutes before being loaded with a constant axial load of 785.4 N for 60 minute duration. Strain recovery was noted for all specimens for 60 minute duration after the removal of the axial load. The static creep test was performed on universal testing machine. Test results are presented in Figure 4. Various other creep related parameters which clearly define the creep nature of the binder such as total deformation, permanent deformation and elastic recovery, are also calculated and presented in Table-7 for unmodified and steel slag modified mixes respectively.

RESULTS AND DISCUSSION

Material Characterization and Mix Design

Test results in table 2 shows that EAF steel slag aggregates found to meet out all important physical-mechanical characteristics of aggregates laid down in MoRTH specification for Road and Bridge Work, 2001 for preparation of bituminous concrete

mixes. Steel slag aggregates found to offer higher resistance to abrasion and impact loading compare to natural aggregates. The SiO_2/CaO ratio characterizes the steel slag aggregate as substantially alkaline aggregate, and ensures improved affinity with the weakly acid bitumen (Pasetto M et al, 2011). EAF steel slag aggregates found to satisfy volumetric stability criteria while subjected on soundness test to simulate harsh weather conditions. Neither the natural nor steel aggregates exhibit the poor affinity with bitumen, while tested for striping after 24 hour immersion in water at 25°C .

For both the mixes the aggregate grading were optimized with reference to the design grading envelop of MoRTH specification (Figure 1). The design grading curves are within the reference grading envelopes (MoRTH Specification, 2001) for bituminous concrete wearing course of 19 mm nominal maximum size aggregate. For both the mixes three Marshall Specimens were prepared at varying binder content of 0.5 %, in the range of 4.5 – 6%. The results of Marshall Mix design are summarized in Table 5.

Table 5: Volumetric Properties and Marshall Test Results

Type of Mix	Air voids (%)	Optimum Binder Content (%)	Bulk Density (g/cc)	Marshall Stability at 60°C (kN)	Flow (mm)	VFB (%)
Unmodified Mix (With Natural aggregate)	4.0	5.1	2.57	13.2	3.0	71.7
Modified Mix (With Processed Steel Slag aggregate)	4.0	5.0	2.91	14.85	3.1	77

The optimal bitumen content of the mix resulted as being slightly lower for the steel slag modified mix may be due to higher specific gravity aggregates (Bagampadde U., et al, 1999). The mix with steel slag showed better Marshall results than the mix with 100% natural aggregates, with a net increment of Marshall stability of 12.5 % and reduced flow. Steel slag modified mix meet out the requisites specified in MoRTH standard for bituminous concrete mixes thus acceptable for road construction in India.

Indirect Tensile Strength

The tensile strength, tensile strength ratio and retained Marshall stability of steel slag modified and unmodified mixes are reported in Table 6. Indirect tensile strength test revealed that steel slag modified bituminous mix showed improvement in tensile strength of the moisture conditioned and dry subset of bituminous mix by 7.5 % and 3.5 % respectively. Higher tensile strength is an indicator of improved resistance for fatigue

cracking. Moisture susceptibility is typically a problem that can cause the bitumen binder to strip from the aggregate, leading to raveling and disintegration of the mixture. Resistance against moisture susceptibility was assessed by comparing the tensile strength ratio and retained Marshall Stability of modified and unmodified mix. Higher tensile strength ratio (86.40%) and better retained Marshall Stability (84%) were found in steel slag modified mixes. It indicates that modified mix having steel slag aggregate can resist moist weather conditions.

Table 6: Results of Indirect Tensile Strength Test

Type of Mix	Average tensile strength of conditioned subset, S_{tm} , (MPa)	Average tensile strength of the dry subset, S_{td} , (MPa)	TSR (%)	Retained Marshall Stability, (%)
Unmodified Mix (With Natural Aggregates)	1.04	1.26	83.00	74.00
Modified Mix (With Steel Slag Aggregate)	1.12	1.30	86.40	84.00

Resilient Modulus

Indian specifications don't specify minimum threshold of resilient modulus for the acceptance of the mixtures, therefore the results can be considered useful only for a performance analysis to compare both the mixtures considered. It can be seen that from figure 2 that the bituminous mixes with steel slag showed better mechanical properties, with values of resilient modulus that were always higher than those of the mixture with natural aggregate, varying from 26 to 33 % with respect to the temperature.

Figure 2: Resilient Modulus of Bituminous Mix with Steel Slag and Natural Aggregate

Rutting Resistance

Figure 3 shows the results for the rutting potential of bituminous concrete with steel slag and natural aggregates. Average rut depths after 10000 cycles were found to be 4.08 mm and 3.11 mm in unmodified and steel slag modified bitumen mixes respectively. The results showed that the final rut achieved in slab made with steel slag aggregate as compared to that made with natural aggregate is about 23.77% less. The reduced rutting in steel slag mixture can be attributed to higher specific gravity of steel slag aggregates and better interlocking that steel slag interlocks well within the mixture, which is undeniably essential for deformation resistance. Thus steel slag aggregates can replace the natural aggregates in high performance bituminous mixes on high volume traffic corridors due to its greater adhesion ability and rut resistance.

Figure 3 : Development of Rut vs Number of Cycles

Resistance to Permanent Deformation

Figure 4 reports the evolution of the creep curve and elastic recovery of the unmodified and steel slag modified bituminous mixes. The integration of steel slag in bituminous mixture clearly improves the resistance to permanent deformation. Permanent deformation for the steel slag mixture is 0.0537 mm, while for the conventional mixture it is 0.289 mm. Elastic recoveries (after the removal of the load) as indicated in Table 7, is 52.89 % in case of steel slag modified mix while it is limited up to 23.54 % in unmodified mix. The steel slag mix has good interlocking and adhesion, thus the modified mix can resist greater deformation and can last longer when compared to conventional mixture.

Figure 4: Axial Deformation Vs. Time
Table 7: Static Creep Test Results

Temp. (°C)	Total Deformation (mm)		Permanent Deformation (mm)		Elastic Recovery (%)	
	Unmodified Mix	Modified Mix	Unmodified Mix	Modified Mix	Unmodified Mix	Modified Mix
35	0.378	0.114	0.289	0.053	23.54	52.89

CONCLUSIONS

The results obtained by laboratory testing of aggregates shows that EAF steel slag aggregate meets the Indian specifications for the use in bituminous mixes. Steel slag aggregates possess requisite physical and mechanical properties which are comparable with the natural aggregate produce from igneous rocks of silicate composition.

Mix design results are quite satisfactory for bituminous mix containing steel slag aggregates with good values of Marshall Stability and Retained Marshall Stability. Steel slag mix shows significant improvement in resistance to moisture damage and high resistance to permanent deformation. Improved resilient modulus at higher temperature and reduced susceptibility for rutting in steel slag modified mix pave the way for thinner bituminous layer as wearing course.

In conclusion the study found that the use of EAF steel slag in bituminous mixes may be a technically satisfactory option which can preserve rapidly depleting natural aggregate. Further the laboratory study reported in the paper is required to be complemented by field

trial of steel slag aggregate bituminous mixes to establish beneficial effects for formulation of national specification.

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