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Steel Slag as A Road Construction Material

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Abstract

Steel slag is a byproduct obtained from steel industry. It is generated as a residue during the production of steel. Because of the high disposal cost as a waste material and the overall positive features of steel slag, it has been declared a useful construction material, not an industrial waste by most of the developed countries. Successively, it is recycled as an aggregate for the construction of roads, soil stabilization, and base and for the surfacing of flexible pavement. Despite this, a large amount of steel slag generated from steel industries is disposed of in stockpiles to date. As a result, a large area of land is being sacrificed for the disposal of this useful resource. Many researchers have investigated the use of steel slag as an aggregate in the design of asphalt concrete for the road construction. The best management option for this by product is its recycling. This leads to reduction of landfills reserved for its disposal, saving the natural resources and attaining a potential environment. The purpose of this paper is to review the engineering properties of steel slag and its utilization for road construction in different ways.

Keywords: Steel slag, recycle, skid resistance, soil stabilization, industrial waste material, sustainability

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1.0 .INTRODUCTION

Aggregate is obtained from natural rocks. Mining of the aggregate, leads to the reduction of natural resources. The countries having limited resources of natural aggregate are thinking to save their natural resources for their future generation. A large area of land is utilized for the disposal of such solid wastes, producing by industries. Factors like environmental, economic, technical and deficiency of proper construction material have diverted the attention of researchers to other alternatives [1]. As a result, they have explored variety of recycled materials which can be used as an aggregate.

According to Geiseler (1996), in 350 BC Aristotle has indicated that during the purification of iron, a byproduct is generated like a stone called iron slag [2]. It has number of advantages but very effective for drying the injuries. The byproduct generates from the melting of scrape to produce steel by an electric arc furnace (EAF), and through the conversion of iron to steel by a basic oxygen furnace (BOF). The steel slag obtained from these furnace looks like similar but the properties may differ based on the grade of steel produced and the furnace, while the chemical composition remains within the range. As compare to electric arc furnace, the main problem with basic oxygen furnace is the excess quantity of its free lime and free magnesia contents. Particular expertise are needed to handle it in a proper way to avoid the volumetric expansion otherwise it may result pavement failure [3].

According to National Slag Association iron and steel slags have been used in engineering constructions for more than 150 years. It is being used as aggregate in replacement of natural aggregate, for bounding applications (BFS) instead of Portland cement, fill material, rail road ballast and sub grade soil stabilization. According to John Emery iron slag were used for the construction of roads during the Romans Empire also [4]. In 1998 up to 97% of the total generated steel slag has been used in different ways for the construction of high trafficked roads by Germany. It is utilized as aggregate for surface layer, road base and sub base. It is also utilized in earthworks and hydraulic structures as well [5]. Because of significant amount of free iron, steel slag becomes hard and dense to provide high abrasion resistance [6]. It is a rough textured, sufficient angular, vesicular and porous material. After compaction it provides a satisfactory particle interlock and high stability. There is not any standard for the proportioning of steel slag with natural aggregate but if partially replaced at the percentage of about 20% to 100% provides satisfactory results. Previous experimental studies show that the use of steel slag may improve the performance pavement. The rough textured surface of steel slag provides high skid resistance. The high specific gravity and the proper interlocking due to angularity of steel slag result better stability and resistance against rutting as well.

2.0 PRODUCTION AND UTILIZATION OF STEEL SLAG

During the production of three tons stainless steel around one ton of steel slag is generated [7]. It has been noticed that per year fifty million tons of steel slag is generated from different steel industries throughout the world. Only in Europe, around twelve millions of steel slag is generated every year [5]. Steel slag is a residual material that generates during the production of stainless steel by different resources either from the melting of scrape to produce steel in electric arc furnace (EAF), or by converting iron to steel in basic oxygen furnace (BOF). Hot liquid metal, scrape and fluxes together with lime and dolomite lime processed in basic oxygen furnace. The impurities like carbon monoxide and silicon, manganese, phosphorous and iron in liquid state combines with lime is and dolomite lime are separated by injecting oxygen with high pressure to form steel slag. Electric arc furnace is a kettle shaped arrangement used to process cold steel scrape instead of hot liquid metal. The scrap is melted through high electric current passing through graphite electrodes by forming an arc. Some other metals like Ferro, alloys are added to balance the required chemical composition of steel and oxygen is blown to purify the steel. At the end, the floating steel slag is separated from the surface of molten steel [8]. The residual steel slag is then crushed into 8 inches with the help of a large steel ball or a solid steel cylinder by dropping it to the slags. The process for crushing and grading is repeated until to get the required grade of aggregates. Recovery of metallic particles is carried out through conveyer belts electromagnetically in the same plant. Then supplied in the form of construction aggregate to the construction agencies. It is competing with natural aggregate, where high performance aggregate is limited. This indicates the importance of alternative aggregates like steel slag are valuable products not the wastes, also providing environmental benefit [3].

3.0 ENGINEERING PROPERTIES OF STEEL SLAG

Engineering properties influence the level of performance and suitability of the material being used for road construction [9]. As far as the engineering properties of steel slag are concerned. Sufficient research has been done on the chemical and mineral composition as compare to the physical and mechanical properties of steel slag. Geotechnical properties of steel slag like the bearing capacity, compaction and shear strength have been neglected.

3.1 Chemical and Mineral Composition of Steel Slag

Generally steel slags consist of CaO, MgO, SiO_2 and FeO oxides, which found within the range of about 88% to 90 %. The total concentration of these oxides in liquid slags is in the range of 88%–92%. Though these oxides fluctuate based on the material used, type of steel being manufactured and condition of furnace [8]. Use of dolomite instead of lime as a flex, highly influence the chemical composition which provides higher content of MgO [10]. The chemical composition of steel slag are given in Table 1.

Both BOF and EAF slags are dicalciumsilicate, dicalciumferrite and wustite. Dicalciumsilicate provides stability, which prevents disintegration of steel slag. Several studies show that the dissolved lime and MgO does not affect the volume of steel slag, but the excess amount of “spongy free lime” and MgO may cause the volume instability [2]. The mineralogical composition is given in Table 2.

Table 1 Chemical properties of steel slag

Steel slag	CaO	SiO_2	Al_2O_3	FeO/Fe_2O_3	MgO	MnO	TiO_2	SO_3	P_2O_5	Free Cao	Reference
BOF	39.30	7.75	0.98	-/38.06	8.56	4.24	0.94	0.02	-	-	Shen et al , (2009) [11]
EAF	35-40	9-20	2-9	15-13/-	5-15	0-8	-	0.08-2.3	.01-2.5	-	Shi (2004) [8]
BOF	47.5	11.8	2.00	-/22.6	6.3	1.90	0.50	-	2.70	-	Mahieux et al., (2009) [12]
EAF	30-40	10-20	<10	15-35/-	<10	10	~/	<0.25	<2	<1.5	Miklos, (2000)[13]
BOF	41.30	12.50	2.40	-/31.20	4.3	6.10	0.8	-	1.10	-	Chaurand et al., (2007) [14]
EAF	25-40	10-17	4-7	-/-	4-15	<6	-	-	<1.5	<3	Motz and Geseler, (2001) [5]
BOF	47.88	12.16	1.22	26.30/-	0.82	0.28	-	0.28	3.33	-	Das et al., (2007) [15]
EAF	40.78	17.81	4.23	9.25/3.97	8.53	9.79	-	0.3	0.74	-	Nicolae et al., (2007) [16]
BOF	40.1	17.80	2.04	12.92/6.58	6.32	6.52	-	0.46	1.13	3.9	Nicolae et al., (2007) [16]
EAF	45.5	32.2	3.7	3.3/1	5.2	2	-	-	-	-	Tossavainen et al., (2007) [17]
BOF	41.3	15.60	2.20	-/-	6.90	8.90	0.50	-	-	3.3	John Emery, (1984) [4]
EAF	32.1	19.4	8.6	-/-	9.4	6.8	0.4	0.6	-	-	Lekakh et al., (2008) [18]
BOF	41.44	15.26	4.35	13.95/9.24	8.06	5.2	0.72	-	1.15	3.9	Poh et al., (2006) [19]
EAF	35.7	17.53	6.25	-/26.36	6.45	2.5	0.76	-	-	-	Tsakiridis et al., (2008) [20]
BOF	45.41	13.71	3.8	21.85/3.24	6.25	3.27	-	-	1.42	-	Xue et al., (2006) [21]
EAF	29.49	16.11	7.56	-/35.26	4.96	4.53	0.78	0.63	0.55	-	Barra et al., (2001) [22]
BOF	45	11.10	1.90	10.70/10.90	9.6	3.10	-	-	-	-	Tossavainen et al., (2007) [17]
EAF	23.9	15.3	7.4	-/-	5.1	4.5	-	0.1	-	0.45	Manso et al., (2006) [23]
EAF	52.3	15.30	1.30	-/-	1.10	0.39	-	-	3.10	10.0	Reddy et al., (2006) [24]
EAF	24.4	15.35	12.21	34.36/-	2.91	5.57	0.56	-	1.19	-	Luxan et al., (2006) [25]

Table 2 Mineralogical composition of steel slag

Slag	Mineralogical composition	References
EAF	$CaCo_3$, FeO, MgO, Fe_2O_3,$Ca_2Al(AlSiO_7)$, Ca_2SiO_4	Barra et al, (2001) [22]
--	$2CaO.SiO_2$, $3CaO.SiO_2$, $2CaO.Fe_2O_3$, FeO, (Ca.Fe)O	Geilseler, (1995) [2]
EAF	Ca_2SiO_5, $Ca_2Al(AlSiO_7)$, Fe_2O_3,$Ca_{14}Mg^2(SiO_4)_8$, $MgFe_2O_4$, Mn_3O_4, MnO_2	Luxan et al, (2000) [25]
BOF	2CaO. Al_2O_3.SiO_2,Fe_2O_3,CaO,FeO	Nicolae et al, (2007) [16]
EAF	MnO_2, MnO, Fe_2SiO_4, Fe_7SiO_{10}	Nicolae et al, (2007) [16]
BOF	2CaO.Fe2O32CaO.P2O5, 2CaO. SiO2, CaO	Reddy et al, (2006) [24]
BOF	β-Ca2SiO4, FeO-MnO-MgO solid solution, MgO	Tossavanien et al ,(2007) [17]
EAF	Ca3MgSiO4)2, β-Ca_2SiO_4 spinal solid solution (Mg,Mn)(Cr,Al)$_2$O$_4$wsuite-type solid solution ((Fe,Mg,Mn)O),$Ca_2(Al,Fe)_2O_5$	Tossavanien et al , (2007) [17]
EAF	Ca_2SiO_4,$4CaO.Al_2O_3.FeO_3$, $Ca_2Al(AlSiO_7)$, Ca_3SiO_5, $2CaO.Al_2O_3SiO_2$, FeO, Fe_3O_4, MgO, SiO_2	Tsakiridis et al (2008) [20]

3.1.1 Affinity of Steel Slag with Binder

The aggregate should have affinity with binder to provide an adequate adhesion to the mix design. This property of aggregate having affinity with binders is known as "hydrophobic" and the aggregates which are not having such a property called "hydrophilic". Steel slags are hydrophobic (strong affinity with binder), basic or alkaline in nature having pH value of around 12. Whereas the bitumen binder normally acidic, having a naturel chemical affinity with steel slags and the pH value of bitumen binder is less than 7. This property of steel slag provides a good adhesion and helps to resist against the stripping. A simple test is conducted by putting the sample into boiling water and the degree of stripping is evaluated [3].

3.2 Physical and Mechanical Properties of Steel Slag

Roads are subjected to static and dynamic forces, including the harsh environment like rain, temperature, freezing and thawing. The proposed material should provide adequate physical and mechanical properties to resist and perform well. The physical and mechanical properties are given as: aggregate crushing value, loss angles abrasion, aggregate impact value, soundness, polished stone value, water absorption, surface texture, stripping, specific gravity and flakiness. The physical and mechanical properties of steel slag productively meet the requirements of a high class material. As compare to natural aggregate, it provides an ideal durability, permeability, stability and resistance against abrasion, cracking and permanent deformation. The physical and mechanical properties of steel slag are given in Table 3.

Table 3 Physical and mechanical properties of steel slag

Steel slag	G_s	Bulk Density (Kg/m^3)	Water absorption (%)	LAA (%)	Soundness	ACV (%)	AIV	Polished stone value	CBR	Stripping (%)	Reference
EAF	3-3.7	1800 to 2000	0.2-2	20-25	<12	-	-	-	-	-	Alizadeh et al., (1996) [26]
-	3.69	-	-	15	2.2	15	11	-	<400	>97	Aiban and Abdul Wahab, (1999) [27]
-	-	-	-	20-25	<12	-	-	-	300	-	Noureldin and Mc Daniel, (1990) [28]
EAF	3.38	-	-	24	-	-	-	0.05	-	0	Pasetto and Baldo, (2012) [29]
EAF	3.91	-	-	15.5-21.5	-	-	-	0.05	-	0	Pasetto and Baldo, (2012) [29]
-	3.5	>1900	0-2	14	0-1.5	20	14	-	>200	-	Holliday (1997) [3]
WCS	3.4	-	1.6	13	0.4	-	-	-	-	-	Sofilic(2010) [30]
ACS	3.3	-	1.8	16	0.8	-	-	-	-	-	Sofilic(2010) [30]

3.2.1 Specific Gravity

Steel slag contains sufficient amount of iron oxide, therefore it has greater value of specific gravity as compare to the natural aggregates. Number of researchers have evaluated the specific gravity of other construction materials and that of steel slag fall within the range of 3 to 4 [31]. Steel slag is about 20 % heavier than the lime stone and granite. This may be an economic disadvantage, but is not considered, as it provides more advantages like high strength and durability.

3.2.2 Grain-Size Distribution

Grain size distribution, an important factor which is highly influenced the mechanical properties of the material. It is difficult to break it in to particles of different sizes during its generation in the steel mill. During the cooling process, it breaks down into different particle size containing larger size as boulders up to the sizes of silt. Further it is processed to obtain proper grade of steel slag by crushing plants as discussed earlier.

The coarse gradation particles found in the range of about 64mm to 200mm, similarly the medium size particles are up to 64mm. The fine gradation is like well graded sand consisting of varying sizes of gravel up to the silt size particles, retained at No. 4 sieve;

4.75mm and passing through No 200 sieve ;0.075mm. the silt size particle %age remains within the range of 10% to 15% [22, 32].

3.2.3 Compaction Characteristics

Limited studies have been carried out on the compaction of general steel slag. The results of previous researches show higher values of maximum dry unit weight of steel slag then natural aggregate. Rohde et al., (2003) have studied the compaction characteristics of EAF steel slag of different grades by standard proctor compaction test method [32]. The optimum moisture content and maximum dry weight of EAF steel slag were in the range of 3%-6% and 23-26kN/m^3.

3.2.4 Shear Resistance

Steel slags are rough in surface texture, cubical and angular as compare to the natural material. It provides better interlocking and friction which results stability, resistance to rutting and higher skid resistance. The friction angle of steel slag is reported 40^0 to 50 [28]. Because of its better shear resistance, can be use all the layers of pavements.

3.2.5 Thermal Properties

It has been noticed that steel slag, has a potential to retain the heat as longer than natural aggregate. The heat retention property of steel slag aggregate is an advantage. It helps to prepare hot mix asphalt concrete to coat the aggregates properly specially repairing of pavements surface in cold weather [28].

■4.0 UTILIZATION OF STEEL SLAG IN THE CONSTRUCTION OF ROADS

Steel slags have been successfully utilized for the construction of roads in wearing course, base and sub base as well. Especially Europe, Canada, Australia and USA have not treated it as an industrial waste but a useful construction material, and successfully using steel slag as aggregate in surfacing and base of flexible pavements [6, 33]. Steel slag is produced in 29 states of United States by 17 companies. Special specification, sufficient record of its uses and performance on major projects around the world indicate that both steel (BOF or EAF) slag is a material of choice. In Batlimore according to Khan et al., (2002) the outstanding characteristics demonstrating one of the advantages of using steel slag bituminous concrete is high skid resistance (under wet or dry conditions) provided throughout the service-life of the pavements [34-38]. SSA and asphalt mixtures were used to provide 1 to 1.25 inch thick surface layer for a number of roadways in Indiana between 1979 and 1981 [28]. Bituminous test sections were constructed using six different combination of coarse and fine aggregate to produce mixtures with a wide range of gradations and proportions of steel slag coarse aggregates. Skid resistance numbers measured using ASTM E274 indicate that the use of steel slag aggregate in asphalt surface mixtures provide pavement surfaces with good skid resistance. Asphaltic paving mixtures using steel slag aggregate displayed exceptionally high stability, which may improve the rut resistant when used in pavement surface layers. Mix produced utilizing steel slag aggregate and natural sand displayed exceptionally large stiffness modulus values. A large stiffness value is an indicator of the possibility of using a reduced pavement thickness [39]. This thinner layer plays an important role in compensating for the high-density disadvantage of steel slag asphalt mixtures. Stock and Ibberson, (1996) reported the use of steel slag in bituminous road construction in South Yorkshire and its environs for the past 60 years [40]. Above 300,000 tons of steel slag per year was utilized for road construction. As an assessment of skid resistance of asphalt surfaces incorporating steel slag, side force coefficient Routine Investigation Machine (SCRIM) was measured on various categories of roads (100 mm and 14 mm surface dressings). The surveys show that steel slag road surfaces have at least as good long-term skid resistance properties as those of comparable natural aggregate road surfaces under similar traffic conditions [40]. SSA has also been successfully utilized in countries with high ambient temperatures that cause major problems in asphalt surfaces. Amongst the various countries around the world with hot climates, such as Singapore, Malaysia, Australia, South Africa, Saudi Arabia and Italy, have already realized the superior properties of steel slag asphalt [41]. Permanent deformation can occur at a very early stage in the life of asphalt surfacing material, when the road surface temperature begins to approach the softening point of the bitumen [42-46]. The high surface temperature causes the asphalt to become plastic and then deform very easily resulting in rutting.

It is observed that the use of EAF steel slag for low volume roads economical as compare to the natural aggregates. Properly weathered EAF steel slag has been investigated for the construction of low volume roads as a base material. Satisfactory results of resilient modulus were obtained from EAF steel slag as compare to the natural aggregates [32]. Aiban and Abdul Wahhab (2006) incorporated a mixture of marl and sand with 30% to 85% of steel slag by weight for road base and obtained CBR values up to 455% [27]. For the use of base and sub base courses, properties of cement stabilized steel slag also have been studied as well. The results exhibited high values then natural aggregate cement stabilization [47]. A mixture of fly ash and phosphogypsum with steel slag designed for road base. When the properties of this mix investigated, the resulted values of long term shear strength and water stability indices were much higher than cement stabilized granular materials [11]. It is also proposed by Mymrin et al., (2005) that the construction cost of road base can reduced by the use of cement activated steel slag with natural soil mix, because it provides maximum strength and stability with a shorter thickness as compare to the conventional material [48].

■5.0 CONCLUSION

This paper reviewed the engineering properties of steel slag. Steel slag has a number of advantages with high engineering properties. It has been declared a useful construction material not an industrial waste. The overall conclusion drawn based on the literature review is as followed; previous studies have emphasized on utilization of steel slag in cement and concrete industry.

Hence, most of the experimental studies explored the chemical composition not the physical or mechanical properties of steel slag. The study further, steel slag mixture requires higher value of bitumen content, which does not meet the guidelines of optimum bitumen content for natural aggregate. There is not any guideline or specification in general for steel slag to be followed, for the different proportions of steel slag blended with natural aggregate to obtain adequate mix design. Literature showed that steel slag has enough potential and can be utilized in subgrade or embankments, but very rare research have been done in this area. It is concluded based on chemical and mineralogical composition, the properties of steel slag are different compared to the natural aggregate. So, the guidelines of natural aggregate are being followed for steel slag is not appropriate. Economically the steel slag may be cheaper if utilized in urban roads but it would be expensive for rural roads due to the transportation charges.

6.0 FUTURE RESEARCH RECOMMENDATIONS

This current study reviewed literature on the engineering properties and the utilization of steel slag in the construction of roads. However, more research work is needed in this area. For this purpose, researchers need to explore the geotechnical properties of steel slag needs some attention, because the shear strength parameters and the compaction characteristics have not been studied properly.

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