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Characteristics and Utilization of Steel Slag in Road Construction

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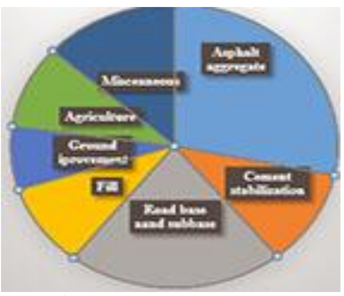
Graphical abstract



Uses of steel slag

Abstract

Presently, the rate of utilization of steel slag in Malaysia is rather too low compared to some advanced countries. Many studies focused on the better way to increase the usage of industrial by-products in order to ease disposal problems. Enormous quantities of steel slag were deposited in yards, causing environmental pollution. Like other metallurgical slags, steel slags exhibit a great potential to be used as aggregate in highway construction. The assessment and evaluation of this material should be based on environmental, economic and technical factors before it can be used in road construction. In terms of technical perspective, steel slags must met the required test requirements that are needed for natural aggregates used for similar purposes. The degree of slag utilization needs to be improved as an important measure to these problems. The physical and chemical properties of slag were reviewed and the various areas of its applications are highlighted. The principal setback of its use; volumetric instability which results from hydratable oxides can be checkmated through appropriate methods like aging and steam test. In order to sustain its uses, microstructure analysis that can identify any harmful materials present in it is suggested. There is also an urgent need of standard methods to assess its suitability as highway construction material.

Keywords: Steel slag; volumetric instability; pavement; industrial by-product

1.0 INTRODUCTION

Over the years, steel slag has been utilized in various construction activities. According to Godfrey and Nie [1], enormous quantity of steel slag was used for wall making and road construction during the period of Roman Empire. It was later used in the production of cement in the early 19th century. Its application as rail ballast and in bridges construction has been encouraging. Also, during that period blast furnace slag was used in the production of bricks and mortar and the production of slag wool Kalyoncu [2].

Steel slag is one of the by-products in metallurgical industry. In terms of pretreatment, it can be grouped as Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF) and Ladle Refining (LF) slags [3]. According to the type of steel, steel slags can either be stainless steel slag or carbon steel slag. It can also be processed into aggregate (fine or coarse) which is useful in both dense and open graded hot mix asphalt concrete pavements [4-6]. Steel slag aggregate is also used in cold mix or surface treatment of pavement [7].

Currently, only BOF and EAF steel making process are predominant. Iron is converted into steel in the BOF steel making process while EAF process recycles mainly steel scraps. The steel from BOF and EAF can be processed into high grade steels, by passing them through a ladle refining unit. Different types of slags were produced from each of these processes. A flow chart that illustrates the kinds of slag produced for each process of iron and steelmaking is shown in Figure 1.

This paper critically examines utilization of steel slags for road construction in both developing and developed countries. Besides, characterization of steel slags in terms of mechanical, chemical and mineralogical properties was also examined. The problem and challenges associated with slag were also critically analyzed.

2.0 CHARACTERISTICS OF STEEL SLAG

2.1 Physical Properties

Unlike the chemical and mineralogical properties of steel slag, the available information on the physical properties of steel slags in the literature is very limited. Table 1 shows the physical properties of steel slag and the Malaysian specification for road works. Except for water absorption, the steel slag satisfies the requirements in terms of strength and shape. It was observed that the flakiness index value for slag was generally low, which can be attributed to the rounded shape of steel slags. The shape improved its interlocking properties when blended with bitumen compared to granite aggregates. The steel slag Los Angeles Abrasion

Value(LAAV) and its Aggregate Crushing Value (ACV) were all within the aggregate standard specifications for Malaysian road works. This implied that the material possesses adequate strength for utilization as highway aggregate material. The excellent soundness results indicated that steel slag would not disintegrate under the destructive action of the nature. The stripping test results indicated no evidence of stripping indicating a strong bond strength the binder and steel slag aggregate.

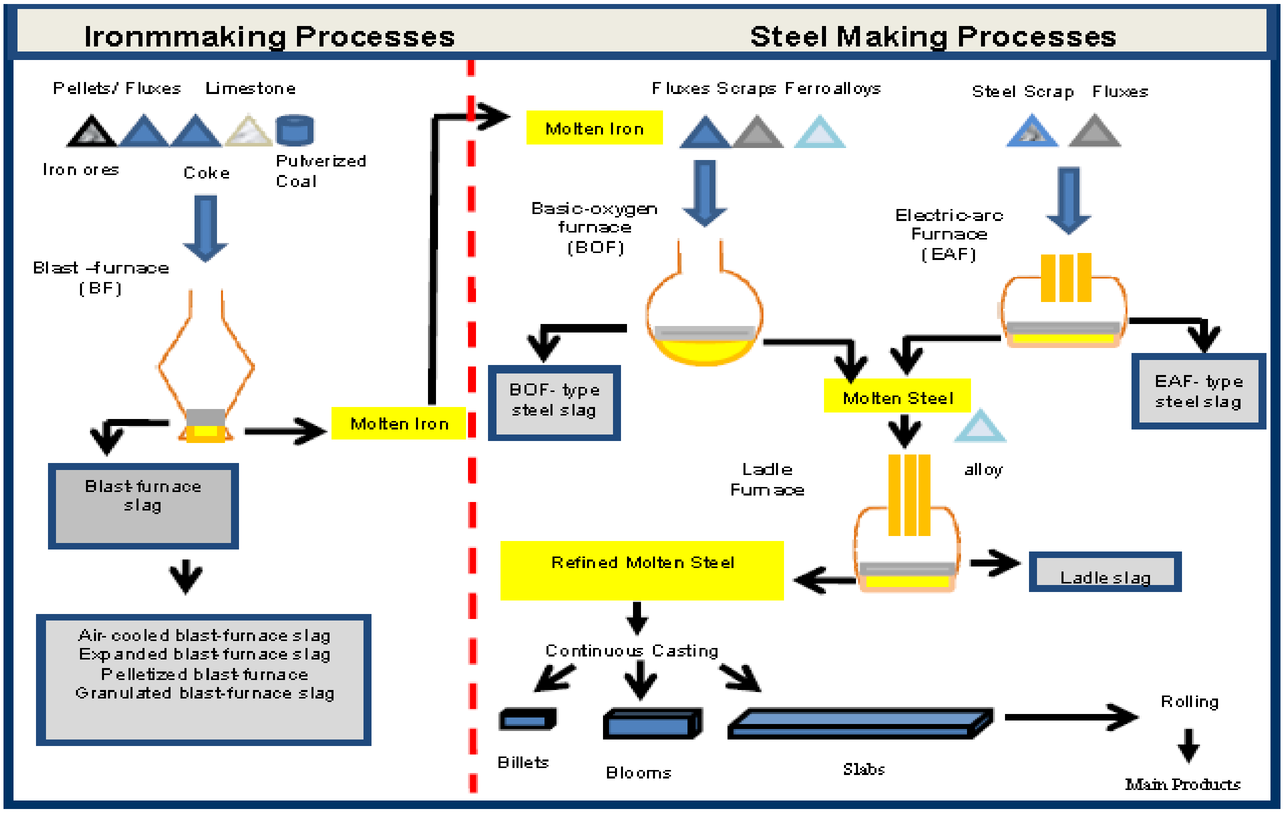


Figure 1 Flowchart of iron and steelmaking processes [8]

2.2 Chemical Properties

The two major types of slag were produced during steel production. Thus, they are expected to have similar chemical composition. Tables 2a and 2b show the major chemical composition from different literatures of chemical composition of BOF and EAF slag respectively. The BOF slag has silica (SiO_2) content ranges from 8-22%. The iron oxide (FeO/Fe_2O_3) of the BOF slag has a high value of 35%; this can be described as the amount of iron that has been oxidized and cannot be recovered into the steel during its production from molten iron.

As noted in Table 2b, the compositions of both BOF EAF slags are quite similar. Due to its mode of production, its chemical composition depends mainly on the recycled steel properties. In view of this, both EAF and BOF slags differ in their basic chemical compositions. For example, the FeO, CaO, SiO_2 and Al_2O_3 values of EAF slags were 3.3-30%, 23-60%, 8-32.2% and 2-18% respectively.

2.3 Mineralogical Properties

Cooling rate and chemical composition determine slag crystallization. Steel slag samples subjected to X-ray diffraction analysis indicates a complex structure with various peaks overlapping showing the phases of crystalline that present in steel slag [9]. The types of mineral that were reported in the literature for slags were presented in Table 2c. The common mineral phases are olivine ($2MgO.2FeO.SiO_2$), β-C_2S ($2CaO.SiO_2$) α-C_2S, C_4AF ($4CaO.Al_2O_3.FeO_3$), C_2F($2CaO.Fe_2O_3$).CaO (free lime), ($3CaO.MgO.2SiO_2$), FeO, MgO, C_3S ($3CaO.SiO2$), RO phase and CaO-FeO-MgO-MnO [10].

3.0 UTILIZATION OF STEEL SLAG

The mineralogical composition of steel slags plays a significant role in its utilization for various construction purposes. Since steel consumption is proportional to slag production, the recent increase in the steel consumption has greatly increased slag volume which has a positive impact on developing various methods of steel slag utilization.

Unlike mined material, its production data for the globe are relatively unavailable. The ratios of iron and steel to slag output were used to estimate annual world iron and steel slag output. For instance, in Malaysia about 750 tons of steel were produced daily and approximately 7.5 tons of slag were produced. From the research carried out in the Asian country, approximately 10% of steel slag was produced from the production of steel.

Table 1 Physical properties of steel slag [11] *, [12] **

Testing	Granite*	Steel slag*	Steel slag**	JKR Specification
Aggregate Crushing Value	26.10%	26.05%	23.00%	<30%
Los Angeles abrasion	9.80%	9.80%	24.00%	<30%
Aggregate Impact value	20.54%	17.20%	23.00%	-
Flakiness	19.00%	4.00%	2.00%	<30%
Soundness	5.20%	ND	2.07%	<18%
Polished stone value	52.70%	56.60%	54.00%	>40%
Water absorption	0.51%	1.20%	5.40%	<2%
Stripping	-	>95%	>95%	>95%

Table 2a Chemical composition of basic oxygen furnace slags

References	% Composition of Oxide									
	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	FeO	MnO	P_2O_5	TiO_2	Free CaO
Yi *et al*.[13]	45-60	1-5	10-15	3-13	3-9	7-20	2-6	1-4	-	-
Belhadj *et al*.[14]	40-45	1-2	8-13	4-8	28-32	-	2-4	1-2	0.5-1	-
Ameri *et al*.[15]	50-57	0.7-1.4	9-11	1-2	10-13	-	4-5	2.3-3.2	-	-
Zhu *et al*.[16]	40-58	2.3-4.9	12-16	6-9	17-28	-	-	1.4-1.8	-	-
Li *et al*. [17]	41-43	2.7-2.9	19-20	5-6	7-8	11-13	-	-	-	-
Wang [18]	35-41	2.4-3	12-18	8-11	-	-	4-5	0.5-0.8	-	-
Wang *et al*. [19]	30-55	1-6	8-20	5-15	-	10-35	2-15	0.2-3	0.4-2	-
Mahieux *et al*. [20]	47-50	2.00	11.80	6.30	22.60	-	1.90	2.70	0.50	-
Shen *et al*.[21]	39.3	0.98	7.75	8.56	38.06	-	4.24	-	0.94	-
Shen *et al*. [22]	30-55	1-6	8-20	5-15	-	10-35	2-8	0.2-2	0.4-2	-
NSA 2008 [23]	41.30	2.20	15.60	6.90	-	-	8.90	-	0.50	3.3
Nicolae [24]	40.10	2.04	17.80	6.32	6.58	12.92	6.52	1.33	-	3.9
Das *et al*. [25]	47.88	1.22	12.16	0.82	-	26.30	0.28	3.33	-	-
Chaurand *et al*.[26]	41.30	2.40	12.50	4.30	31.20	-	6.10	1.10	0.80	-
Xue *et al*. [27]	45.41	3.80	13.71	6.25	3.24	21.85	3.27	1.42	-	-
Reddy *et al*. [28]	53.30	1.30	15.30	1.10	-	-	0.39	3.10	-	-
Tossavainen *et al*. [29]	45.00	1.90	11.10	9.60	10.90	10.70	3.10	-	-	-
Poh *et al*.[30]	40-52	1-4	10-15	5-8	9-10	13-17	2-5	0.9-1.3	0.5-0.7	3-10

Table 2b Chemical composition of electric arc furnace slags

References	% Composition of Oxide									
	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	FeO	MnO	P_2O_5	TiO_2	Free CaO
Yi *et al*.[13]	30-50	10-18	11-20	8-13	5-6	8-22	5-10	2-5	-	-
Pasetto and Baldo [31]	29.60	9.30	13.02	3.65	-	32.84	5.09	-	0.35	-
Wang *et al*. [19]	35-60	2-9	9-20	5-15	-	15-30	3-10	0.1-2.0	-	-
Lekakh *et al*. [32]	32.1	8.6	19.4	9.4	-	-	6.8	-	0.4	-
Tsakiridis *et al*. [33]	35.7	6.25	17.53	6.45	26-36	-	2.5	-	0.76	-
Nicolae [24]	40.78	4.23	17.81	8.53	3.97	9.25	9.79	0.74	-	-
Tossavainen *et al*. [29]	45.5	3.7	32.2	5.2	1.0	3.3	2.0	-	-	-
Tossavainen *et al*. [29]	38.8	6.7	14.1	3.9	20.3	5.6	5.0	-	-	-
Manso *et al*.[34]	23.9	7.4	15.3	5.1	-	-	4.5	-	-	-
Manso *et al*. [35]	23-32	3.5-7.0	8.15	4.8-6.6	11-40	7-35	2.5-4.5	-	-	0.45
Shi [36]	35-60	2-9	9-20	5-15	-	15-30	3.0-8.0	0.01-0.25	-	0-4.0

Table 2c Mineralogical phases of slags

Reference	Type	Mineralogical Phases
Gahan *et al* [37]	EAF	$CaFe_2O_4$, $Ca_2MgO_2AlFeO_6SiO_2O_5$, Ca_2SiO_4, FeO
Gahan *et al* [37]	BOF	$Ca_2Fe_2O_5$, $Ca_xMn_{(1-x)}O$, Ca_2SiO_4, FeO
Tsakiridis *et al*. [33]	EAF	$CaSiO_4$, $4CaO.Al_2.Al_2O_3.Fe_2O_3$, $Ca_2Al(AlSiO_7)$, Ca_3SiO_5, $2CaO.Al_2O_3SiO_2$, FeO, Fe_3O_4, MgO, SiO_2
Tossavainen *et al*. [29]	EAF	$Ca_3Mg(SiO_4)_2$, β-Ca_2SiO_4, (Mg, Mn) $(Cr,Al)_2O_4$, (Fe, Mg, Mn)O), $Ca_2(AL, Fe)_2O_5$
Tossavainen *et al*. [29]	BOF	B-Ca_2SiO_4, FeO-MnO-MgO , MgO solid solution
Nicolae [24]	BOF	$2CaO.Al_2O_3.SiO_2$, Fe_2O_3,CaO,FeO
Nicolae [24]	EAF	MnO_2, MnO, Fe_2SiO_4, Fe_7SiO_{10}
Reddy *et al*. [28]	BOF	$2CaO.Fe_2O_3$, $2CaO.P_2O_5$, 2CaO, SiO_2, CaO
Belhadj [14]	BOF	C_2S, C_2F, Ca $(OH)_2$, CaO, (Fe $_{(1-x)}$ O, $CaCO_3$, MgO, SiO_2, Fe_3O_4.
Qian *et al*.[10]	EAF	ϒ-Ca_2SiO_4, CMS_2, CFMS, FeO-MnO-MgO solid solution

Table 3 shows the estimated slag generated in recent years while Figure 2 shows the various applications of steel slag for a particular year, 2006.

Globally, steel slag has been extensively used in the following areas of Civil Engineering works:

3.1 Asphalt Aggregates

Provided adequate quality control measures were put in place during the production of steel slag, it can perform credibly well as asphaltic aggregates. Many research works have proved it to be a high quality aggregates for asphaltic concrete. There is a natural temperature dependent viscosity for each grade of bitumen. Thus it will become soft and flow beyond a given temperature and become brittle and crack under load below a given temperature [38]. In view of this the tropical climates binders need to be stiffer at a given temperature. Tropical climate countries like Singapore had utilized steel slag as asphalt aggregates.

Ahmedzade and Sengoz [39] researched on the influences of steel slag utilization as coarse aggregate on hot mix asphaltic concrete properties. The incorporation of steel slag into the mixes produced better Marshall Stability and flow test results than mixtures with limestone. This implies that using steel slag as a coarse aggregate in asphaltic concrete mixtures reduces flow values and increased stability which indicates resistance to permanent deformation and high stiffness.

Table 3 Slag generation [40, 41]

Year	US Output	World Output
1994	9-14Mt	-
1995	9-14Mt	-
1996	15Mt	-
1997	17Mt	-
1998	17Mt	-
1999	11Mt	-
2000	13Mt	-
2001	-	-
2002	9-14Mt	90-135Mt
2003	9-14Mt	96-145Mt
2004	11-16Mt	115-118Mt
2005	10-14Mt	113-170Mt
2006	10-15Mt	124-186Mt
2007	-	135-194Mt
2008	-	134-189Mt
2009	-	121-180Mt
2010	-	141-201Mt

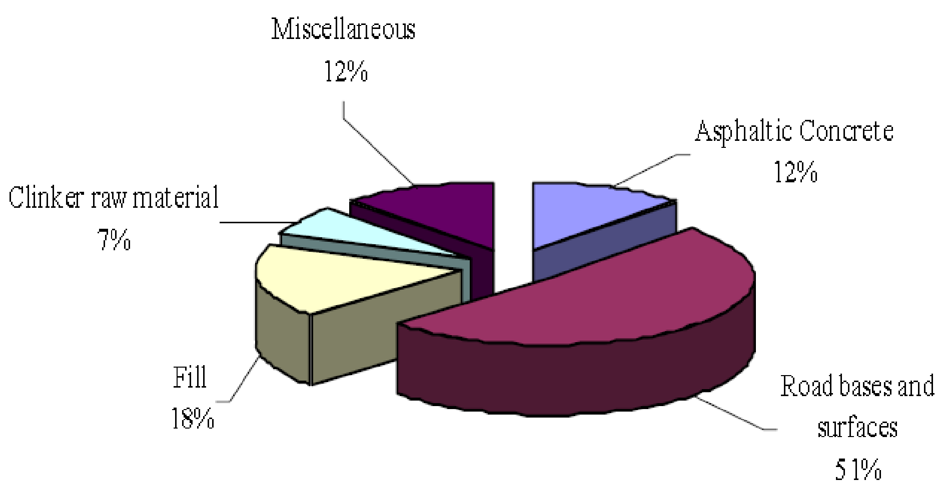


Figure 2 Use of steel slag in 2006 [40]

3.2 Cement Stabilization

Cement stabilization is one of the methods used in building pavement layers. Steel slag can be mixed effectively with other by product materials to produce an excellent cement stabilization product. BOF slag has been successfully mixed with Blast Furnace Slag and Fly ash to produce a semi rigid structure; it does not deform under traffic load and not flexible enough to resist cracking.

The major chemical composition of cement (C_2S, C_3S and C_4AF) that presents in steel slag qualifies it as cementitious materials. The basicity of steel slag generally increased with its cementitious properties. In view of this powdery steel slag can be used as concrete admixtures and cement additives [42]. Research carried out by Arabani and Azarhoosh [43] where a mixture of powdered steel slag, cement clinker and fly ash were used to prepare composite cement and it was observed that quantity of steel slag admixture present in cement can improve pore distribution, enhance the consistency of cement and also reduce the porosity. Altum, *et al.* [44] confirmed that 30% powdered steel slag added to the cement satisfied the Turkish Portland Cement standard requirements.

3.3 Sub base

Steel slag has very good internal friction, free draining ability and good compactability. Besides, it will not pump from the high water table due to its low water absorption. These qualities qualify it as a good sub base material. It has been used in Chile for decades under reinforced concrete roads as a sub base material and its long term performance has been sustained.

The study carried out by Pasetto and Baldo [45] on evaluating the performance of base course and road base asphaltic concrete incorporating electric arc furnace steel slags shown that EAF slags exhibits substantially equivalent physical and mechanical characteristics to those of natural aggregates normally used in pavement layers construction. Without violation of workability and densification of the mixes, mix designs with EAF slags gave good values of Marshall quotient and Marshall stability. Mixes with EAF slags also exhibit low water damage thereby showing a good durability application. All the mixes with EAF slags satisfied the conditions for acceptance of the Italian road standards and thus suitable for road construction.

3.4 Ground Improvement

It can be successfully used in swampy and water logged areas as filling materials because of its low water absorption and free draining ability. When it is compacted it remains stable and can be placed easily in wet environments. Besides, it is not susceptible to frost action; high percentage of coarse aggregates and its special chemical composition make it suitable for road foundations in cold areas like North America [38].

Besides, high resistance to crushing, angular shape, dense, inert, durable and polishing under the action of all kinds of traffic qualifies it for good road construction. It also provides better skid resistance surface than natural aggregates.

3.5 Miscellaneous

Aside from the enumerated applications, it is also useful as railway ballast, filter media, chippings etc. The products must conform to relevant specifications before use. A Vibro-flotation and stone column application is the latest application of steel slag [38]. Steel slag with high content of quicklime, CaO can be used as sinter ore fluxing agent. It has been proved that addition of slag can reduce the cost of sinter, decrease fuel consumption as a result of Fe liberation and oxidation reaction of FeO. In the advanced nations like USA and Germany, steel slag that have been used as sinter material exceeded 56% and 24% respectively [46]. Some steel rolling mills in China like Baoshan Iron and Steel Group and Lianyuan Iron and Steel Company have been using steel slag for sintering purposes since 1996. Due to its physical, mechanical and chemical properties of steel slag, it has many environmental applications as showed in Table 4.

■4.0 PROBLEM AND CHALLENGES OF USING STEEL SLAG

Volume instability has been considered as the major threat to its utilization as aggregates in highway engineering. The rate of cooling of steel slag is highly dependent on its mineral constituents. Both free lime (CaO) and free periclase (MgO) which are not totally consumed react with water in a humid environment and subsequently hydrated to form portlandite $Ca(OH)_2$ and brucite $Mg(OH)_2$ respectively. These hydrates are majorly accounted for massive expansion. This reaction leads to volume increase in slag and thus results in loss of strength and disintegration. This development renders steel slag unsuitable for use in Portland cement concrete or as compacted fill material. Similarly Verhasselt and and Choquet [40] had extensively discussed the use of steel slag as unbound aggregate in highway construction in detail. They also have the similar opinion that the free lime present in steel slag constitutes a major factor of instability by its transformation into portandite where its volume is almost increased by 100%.

The formation as a result of exposure of steel slag aggregates to both atmospheric condition and water, called Tufa-like formation is another challenge when using steel slag in road and highway construction. Tufa is a form of white powdery precipitate that consists mainly of calcium carbonate. When calcium hydroxide solution that is formed when free lime in steel slag reacts with water is exposed to atmospheric condition, calcium carbonate is precipitated in the form of tufa and powdery sediment on surface water. According to Hamilton and Socotch [41], Tufa precipitates may result in clogging of highway drain systems.

Another problem that arises from the use of steel slag in road is that there is no standard or specification with respect to the usage of steel slag in road construction in most part of the globe. In view of this, steel slag should be used with caution and standard and specification should be developed for its use in highway construction.

Some nations have developed different techniques of curbing the problem of steel slag expansion. In the USA and Japan, the immersion expansion ratio was developed to evaluate the volume stability of slags while in China steel slag stability test method was adopted. A maximum of 2% is allowed for immersion expansion test. In Germany, the measure adopted is steam test and boiling test for road construction and hydraulic construction respectively [21].

Weathering is another method that can be adopted. Though, both the British standards and European standards did not specify any duration for weathering process, most researchers believe that between 3-18 months will be adequate. It is strongly advisable that steel slag is weathered or undergoes any other suitable method before utilization in road works.

■5.0 CONCLUSIONS

This paper has reviewed the utilization of steel slag and its characterization. Also, the problems associated with its use were also examined. The assessment of this review work results in the following recommendations:

Microstructure analysis should be conducted for steel slag to identify any harmful components present in it. Slag should be stored in an open space for a period at least 3 months before use. The volumetric stability of steel slag should be ascertained before use by conducting volumetric swelling test. There is a need of standard methods to assess its suitability as highway construction material. Field performance data should be made available to assess its performance on surface treatment.

Table 4 Typical uses of iron and steel slag [47]

Iron and steel slag uses	Environmental applications					
	Applied to land surface	**Applied to land subsurface**	**Placed in water**	**Encapsulated uses**	**Agricultural uses**	**Landfill uses**
Aggregate in bitumen mixes				x		
Concrete aggregate and as a cement ingredient				x		
Antiskid aggregate (snow and ice control)	x					
Surfacing stabilized shoulders, banks and other select material	x		x	x		
Bank stabilization (erosion control aggregate)	x		x			
Gabions and riprap	x		x			
Aggregate base courses and sub-bases	x	X		x		
Unpaved driveways, surface roads and walkways	x					
Railroad ballast	x					
Neutralization of mine grainage and industrial discharge	x	X	x			
Agricultural uses	x				x	
Controlled, grannular fills, such as those required for unpaved parking areas and storage areas	x	X				
Fluxing agents	x	X	x	x		
Landfills						x
Landscape aggregate	x	X				
Trench aggregate/drain fields	x	X				
Sand blast grit	x					
Roofing granules				x		
Bulk fillers e.g paints, adhesives				x		
Mineral wool (home and appliance insulation)				x		
Fill	x	X	x			x

References

[1] Godfrey, E and M. Nie, 2004. A Germanic Ultrahigh Carbon Steel Punch of the Late Roman–Iron Age. *Journal of Archaeological Science*. 31: 1117–1125.

[2] Kalyoncu, R. S. 2001. Slag–Iron Geological Survey. Mineral Yearbook.

[3] Meng, H. D., and L. Liu, 2009. Stability Processing Technology and Application Prospect of Steel Slag. Steelmaking. 26: 74–78.

[4] Rossini-Lake, L., J. Jiang, and C. Curtis. 1995. Reclaimed Steel Slag Pavements for Use as Aggregates-Highway 10 Test Sections. Interim Report. Ontario Ministry of Transportation, Toronto, Ont.

[5] Kandhal, P. S., F. Parker, and R. B. Mallick. 1997. Aggregate Tests for Hot-Mix Asphalt: State of the Practice (Transportation Research Board, National Research Council).

[6] Norton, J. 1979. Use of Steel Furnace Slag in Bituminous Mixtures. Research Report. 78.

[7] Noureldin, A. S., and R. S. McDaniel. 1990. Evaluation of Steel Slag Asphalt Surface Mixtures. Transportation Research Board 69th Annual Meeting, Washington, DC. 152.

[8] Schoenberger, H. 2001. Final Draft: Best Available Techniques Reference Document on the Production of Iron and Steel. Publication of EC: European Commission, Joint Research Centre, IPTS, European IPPC Bureau.

[9] Yildirim, I. Z., and M. Prezzi. 2009. Use of Steel Slag in Subgrade Applications. Joint Transportation Research Program (JTRP) Technical Reports.

[10] Qian, G., D. D. Sun, J. H. Tay, Z. Lai, and G. Xu, 2002. Autoclave Properties of Kirschsteinite-based Steel Slag. *Cement and Concrete Research*. 32(9): 1377–1382.

[11] Teoh, C. Y. 2008. Performance Evaluation of Steel Slag as Natural Aggregates Replacement in Asphaltic Concrete. USM.

[12] Hainin, M. R., N. I. M.Yusoff, M. Sabri, M. A. A. Fahmi, M. H. Azizi, S. A. M. Hameed, and W. Wasid. 2012. Steel Slag as an Aggregate Replacement in Malaysian Hot Mix Asphalt, ISRN Civil Engineering.

[13] Yi, H., G. Xu, H. Cheng, J. Wang, Y. Wan, and H. Chen. 2012. An Overview of Utilization of Steel Slag. *Procedia Environmental Sciences*. 16: 791–801.

[14] Belhadj, E., C. Diliberto, and A. Lecomte, 2012. Characterization and activation of Basic Oxygen Furnace Slag. *Cement and Concrete Composites*. 34: 34–40.

[15] Ameri, M., H. Shahabishahmiri, and S. Kazemzadehazad. 2012. Evaluation of the Use of Steel Slag in Concrete. 25th ARRB Conference. 1–9.

[16] Zhu, X., H. Hou, X. Huang, M. Zhou, and W. Wang, 2012. Enhance Hydration Properties of Steel Slag Using Grinding Aids by Mechanochemical Effect. *Construction and Building Materials*. 29: 476–481.

[17] Li, J., Q. Yu, J. Wei, and T. Zhang, 2011. Structural Characteristics and Hydration Kinetics of Modified Steel Slag. *Cement and Concrete Research.* 41: 324–329.

[18] Wang, G. 2010. Determination of the Expansion Force of Coarse Steel Slag Aggregate. *Construction and Building Materials*. 24: 1961–1966.

[19] Wang, G., Y. Wang, and Z. Gao. 2010. Use of Steel Slag as a Granular Material: Volume Expansion Prediction and Usability Criteria. Journal of Hazardous Materials. 184(1): 555–560.

[20] Mahieux, P. Y., J. E. Aubert, and G. Escadeillas 2009. Utilization of Weathered Basic Oxygen Furnace Slag in the Production of Hydraulic Road Binders. *Construction and Building Materials*. 23(2): 742–747.

[21] Shen, D. H., C. M. Wu, and J. C. Du, 2009. Laboratory Investigation of Basic Oxygen Furnace Slag for Substitution of Aggregate in Porous Asphalt Mixture. *Construction and Building Materials*. 23: 453–461.

[22] Shen, W., M. Zhou, W. Ma, J. Hu, and Z. Cai, 2009. Investigation on the Application of Steel Slag-fly Ash-Phosphogypsum Solidified Material as Road Base Material. *Journal of Hazardous Materials.* 164(1): 99–104.

[23] NSA. 2008. Slag and Its Relation to the Corrosion Characteristics of Ferrous Metals. National Slag Association Publications, Alexandra, V.A.

[24] Nicolae, M., I. Vilciu, and F. Zaman. 2007. X-Ray Diffraction Analysis of Steel Slag and Blast Furnace Slag Viewing Thier Use for Road Construction. U.P.B. Sci. Bull. 69(2): 99–108.

[25] Das, B., S. Prakash, P.S.R. Reddy, and V.N. Misra. 2007. An Overview of Utilization of Slag and Sludge from Steel Industries. Resources, Conservation and Recycling. 50(1): 40–57.

[26] Chaurand, P., J. Rose, V. Briois, L. Olivi, J-L. Hazemann, O. Proux, J. Domas, and J-Y Bottero. 2007. Environmental Impacts of Steel Slag Reused in Road Construction: A Crystallographic and Molecular (XANES) Approach. *Journal of Hazardous Materials.* 139(3): 537–542.

[27] Xue, Y., S. Wu, H. Hou, and J. Zha. 2006. Experimental Investigation of Basic Oxygen Furnace Slag Used as Aggregate in Asphalt Mixture. *Journal of Hazardous Materials.* 138(2): 261–268.

[28] Reddy, A. S., R. K. Pradhan, and S. Chandra. 2006. Utilization of Basic Oxygen Furnace (BOF) Slag in the Production of a Hydraulic Cement Binder. *International Journal of Mineral Processing*. 79(2): 98–105.

[29] Tossavainen, M., F. Engstrom, Q. Yang, N. Menad, M. Lidstrom Larsson, and B. Bjorkman. 2007. Characteristics of Steel Slag Under Different Cooling Conditions. *Waste Management.* 27(10): 1335–1344.

[30] Poh, H.Y., G. S. Ghataora, and N. Ghazireh, 2006. Soil Stabilization Using Basic Oxygen Steel Slag Fines. *Journal of Materials in Civil Engineering*. 18(2): 229–240.

[31] Pasetto, M., and N. Baldo, 2012. Performance Comparative Analysis of Stone Mastic Asphalts with Electric Arc Furnace Steel Slag: A Laboratory Evaluation. *Materials and Structures.* 45(3): 411–424.

[32] Lekakh, S. N., C. H. Rawlins, D. G. C. Robertson, V. L. Richards, and K. D. Peaslee. 2008. Kinetics of Aqueous Leaching And Carbonization of steelmaking slag. *Metallurgical and Materials Transactions B*. 39(1); 125–134.

[33] Tsakiridis, P.E., G. D.Papadimitriou, S. Tsivilis, and C. Koroneos, 2008. Utilization of Steel Slag for Portland Cement Clinker Production. *Journal of Hazardous Materials*. 152(2): 805–811

[34] Manso, J. M., J. A. Polanco, M. Losañez, and J. J. González, 2006. Durability of Concrete Made with EAF Slag as Aggregate. *Cement and Concrete Composites*. 28(6): 528–534.

[35] Manso, J. M., J. J. Gonzalez, and J. A. Polanco, 2004. Electric Arc Furnace Slag in Concrete. *Journal of Materials in Civil Engineering*. 16(6): 639–645.

[36] Shi, C. 2004. Steel Slag-its Production, Processing, Characteristics, and Cementitious Properties. *Journal of Materials in Civil Engineering.* 16(3): 230–236.

[37] Gahan, C. S., M. L. Cunha, and A. Sandstrom, 2009. Comparative Study on Different Steel Slag as Neutralising Agent in Bioleaching. *Hydrometallurgy.* 95: 190–197.

[38] Holiday, K. A, 1997. Steel Slag-The High Performance Industrial Aggregate. In *Proceedings of the XIIth World Meeting of the International Road Federation, Toronto*.

[39] Ahmedzade, P., and B. Sengoz, 2009. Evaluation of Steel Slag Coarse Aggregate in Hot Mix Asphalt Concrete. *Journal of Hazardous Materials*. 165(1): 300–305.

[40] Verhasselt, A., and F. Choquet. 1989. Steel Slags as Unbound Aggregate in Road Construction: Problems snd Recommendations. *Proceeding of the 3rd International Symposium, University of Nottingham.*

[41] Hamilton, J., J. Gue, and C. Socotch. 2007. The Use of Steel Slag in Passive Treatment Design for AMD Discharge in the Huff Run Watershed Restoration. *Proc. Amer. Soc. Of Minning and Reclamation*. Gillette, WT, 272–282.

[42] Tüfekçi, M., A. Demirbaş, and H. Genc, 1997. Evaluation of Steel Furnace Slags as Cement Additives. *Cement and Concrete Research.* 27(11): 1713–1717.

[43] Arabani, M. and A. R. Azarhoosh. 2012. The Effect of Recycled Aggregate and Steel Slag on the Dynamic Properties of Asphalt Mixtures. *Construction and Building Materials.* 35: 1–7.ss.

[44] Altum, I. A., and I. Yimax, 2002. Study on Steel Furnace Slags with Mgo as Additive in Portland Cement. *Cement Concrete Res*. 32: 1247–1249.

[45] Pasetto, M., and N. Baldo, 2010. Experimental Evaluation of High Performance Base Course and Road Base Asphalt Concrete with Electric Arc Furnace Steel Slags. *Journal Of Hazardous Materials*. 181(1): 938–948.

[46] Jiang, C. S., Q. J. Ding, F. Z. Wang, and C. Li, 2002. Chemical and Physical Characteristics of Steel Slag and Its Utilization Progress. *Overseas Bulid Master Sci Technol (in china)*. 23(3): 3–5.

[47] Sofilić, T., U. Sofilić, and I. Brnardić. 2012. The Significance of Iron and Steel Slag as By-product for Utilization in Road Construction. *12th International Foundrymen conference Sustainable Development in Foundry Materials and Technologies*.