Proceedings of the World Congress on New Technologies (NewTech 2015)
Barcelona, Spain – July 15 - 17, 2015
Paper No. 228

Environmental Effects and Possible Highway Applications of Electric Arc Furnace Slag in Turkey

Fatih Yonar
TechnoBee Limited Company
ITU Ayazaga Campus, Ari-2 Technocity B-Block, Istanbul, Turkey
fyonar1981@gmail.com

Emine Ubay Cokgor
Istanbul Technical University, Department of Environmental Engineering
ITU Ayazaga Campus, Maslak, Sariyer, Istanbul, Turkey
ubay@itu.edu.tr

H. Attila Dikbas
TechnoBee Limited Company
ITU Ayazaga Campus, Ari-2 Technocity B-Block, Istanbul, Turkey
dikbas@technobee.com

Birol Demir
General Directorate of Highways
Vecdi Diker Eğitim ve Araştırma Merkezi C2 Blok, Ankara, Turkey
bdemir@kgm.gov.tr

Murat Ergun
Istanbul Technical University, Department of Civil Engineering
ITU Ayazaga Campus, Maslak, Sariyer, Istanbul, Turkey
muratergun1963@gmail.com

Abstract **–**As have been in many developed countries; to reduce the environmental impact of production and consumption of natural resources in Turkey, alternatives should be taken in to consideration. Construction is a leading sector in Turkey and requires the highest amount of raw materials. In this respect, steel sector as the producer and highway construction sector as the consumer stand out, in scope of international researches and applications. Turkey is the 8th biggest steel producer in the world however steel slag still accepted as solid waste and no environmental and mechanical utilization procedures or processes defined. In this paper; three electric arc furnace slag samples are introduced according to cooling, contamination and weathering conditions. Firstly environmental effects are investigated according to "Solid Waste Landfill Criterions" in Turkish Solid Waste Landfill Regulations Appendix II. Parameters in "Solid Waste Landfill Criterions" are compared with international regulation variables. Deficient potential hazardous parameters are included to the research. Secondly mechanical properties are examined according to ASTM standards and compared with the limits in Turkish Highway Specifications 2013. Lastly environmental and mechanical properties are evaluated within the scope of possible applications.

Keywords**:** Electric Arc Furnace, Steel Slag, By-product, Highway Construction

1. Introduction

Turkey is the 8th biggest steel producer in the world with the capacity of 49.6 million tones. This capacity is produced by two main processes: the integral cycle, which starts from mineral iron, and the electric cycle, which uses scrap metal (Fotini, 2009). Electric arc furnaces (EAF) produce 75.9% of this capacity. Currently thirty facilities are operating in Turkey. These facilities are located in Mediterranean Region (10), Marmara Region (8), Aegean Region (7), Black Sea Region (3) and Central Anatolia Region (2). Three of these facilities are integrated, one of induction furnace and the rest twenty-six facilities are EAFs.

120 to 150 kg of slag obtained from each tone of steel produced in EAFs. According to the capacity of EAFs, 4.8 million tones of slag may be obtained in full production per year in Turkey. Even though EAF slag is accepted as a by-product in international literature, no utilization procedures or processes defined in Turkey and nearly all EAF slag is disposed of in rubbish dumps. In this context, utilization of EAF slag as an artificial aggregate in highway construction has a great importance in aspects of environment, economy and sustainability.

Because the requirement for mineral aggregates for civil infrastructure especially for highway construction in Turkey has progressively increased in recent years, with the consequent serious environmental problems (exploitation of finite natural resources, quarrying activity and the consequent landscape deterioration), the use of EAF steel slags in highway and airport construction can provide a very interesting alternative (Pasetto, Baldo, 2010). The use of these materials would allow the production of natural high-quality aggregate to be reduced, savings to be made and the environmental impact of waste disposal avoided (Pasetto, Baldo, 2010).

Steel slags, including EAF, have mostly been used in surface layers of road pavements, in order to exploit their high resistance to polishing (Fotini, 2009)(Huang et al., 2007), a property that allows the necessary roughness characteristics of the road surface to be maintained for longer and therefore guarantee the skid resistance that is indispensable for road safety (Pasetto, Baldo, 2010).

The leachate from steel slag has been investigated in a number of studies and compared to the standards of the country in which the slag was tested. The use of slag in environmental applications were found to not pose a hazard in most situations to the health of people or the ecology according to reviewed studies (Greisler, J. 1996; NSA, 1998; Proctor et al., 2000 and 2002; Manso et al., 2006; Exponent Inc., 2007; Pellegrino and Gaddo, 2009; Sofilic et al., 2010).

The study described here aimed to determine environmental and mechanical properties of three different EAF slags taken from three different production regions in Turkey. Environmental effects are investigated according to "Solid Waste Landfill Criterions" in Turkish Solid Waste Landfill Regulations Appendix II. Parameters in "Solid Waste Landfill Criterions" are compared with international regulation variables. Deficient potential hazardous parameters are included to the research. Mechanical properties are examined according to ASTM standards and compared with the limits in Turkish Highway Specifications 2013.

2. Materials and Methods

The study is divided into two main parts. The first part is related to the chemical and toxicological characterization of the EAF slags and a natural aggregate as a reference. The second part is related to the mechanical characterization and comparison of the EAF slags and the natural aggregate according to Turkish Highway Specifications 2013.

2. 1. Materials Used

The EAF slags used in this study are obtained from three different steel mills in Turkey. From each steel mill, a total amount of 360 kg sample is taken from three different locations of stockpiles. The samples are named as EAF_S1 from Marmara Region, EAF_S2 from Aegean Region and EAF_3 from Mediterranean Region and natural aggregate sample is taken from Omerli-Alyans quarry in Marmara region as reference.

Samples taken from 1^{st} steel mill are weathered for at least 6 months. No contamination is determined during sampling. The facility does not have a magnetic separation unit in order to recover iron from slag. Samples have been cooled by water spray when poured from ladle at about 1300^{o}C. High porosity observed.

Samples taken from 2nd steel mill are fresh. No contamination is determined during sampling. The facility does not have a magnetic separation unit in order to recover iron from slag. Samples have been cooled by water spray when poured from ladle at about 1300 ^oC. High porosity observed.

Samples taken from 3rd steel mill are weathered for at least 6 months. No contamination is determined during sampling. The facility does not have a magnetic separation unit in order to recover iron from slag. Samples have been cooled by water spray when poured from ladle at about 1300 ^oC. High porosity observed.

The chemical composition of the natural aggregate and EAF slags are analysed with XRF (X-ray fluorescence). Results are given in Table 1.

While all parameters are close in each sample, free CaO value of EAF_S3 sample is higher. However apart from CaO value, lowest MgO value is obtained from EAF_S3 sample. Free CaO and MgO values are critical for expansion possibility.

Table. 1. Chemical composition of EAF slag and natural aggregate.

Sample Name:	Metallic Fe (%)	Total Fe (%)	FeO (%)	SiO_2 (%)	Al_2O_3 (%)	Total CaO (%)	Free CaO (%)	MgO (%)	MnO (%)
EAF_S1	6.02	26.54	20.52	17.09	8.17	28.90	0.62	2.91	4.23
EAF_S2	2.94	34.43	31.49	13.34	4.55	30.07	0.49	4.75	5.64
EAF_S3	5.90	36.22	30.32	14.68	6.78	34.03	2.35	2.14	5.10
Natural Aggregate	0.24	0.78	0.54	0.92	0.42	32.50	0.17	22.05	0.05

2. 2. Leaching Test Result for Eco-toxicological Characteristics

New waste disposal regulations adopted EU in Turkey which are promulgated in 2008 (WMR 2008, LWR 2010, EU 2002) are rather stringent to prevent the possible leaching of organic chemicals and toxic metals into surface and groundwater. The regulation divides wastes into three groups according to the chemical characteristics in the eluent of the wastes and the wastes itself; namely: Inert. Non-hazardous and hazardous wastes. In order to evaluate the leaching behaviour of the three Electric Arc Furnace (EAF) steelmaking slag samples taken in different regions of Turkey and therefore the potential impact on the environment, the leaching test EN-12457-4 (2002) was carried out as follows: samples of EAFs were taken separately and reduced when necessary to a particle size below 10 mm and brought into contact with ten times the weight of water under continuous stirring for 24 hours. The corresponding eluents were passed through 45 µm membrane filters for subsequent analysis. All the leaching tests were done in duplicate and the results are presented as a mean value. The leachates were analysed by the accredited laboratory CEVRE Industrial Analyse Laboratory in Istanbul. Trace metal concentrations were determined by inductive coupled argon plasma mass spectrometry (ICP-MS). The results are shown in Table 2. As can be seen, both eluent and original samples for three EAFs are an inert wastes that can be disposed of in landfills without any previous treatment.

The definition of inert waste in the Landfill Directive is: "inert waste" means waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health. The total leachate potential and pollutant content of the waste and the eco-toxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwater. The risk to the environment and animals in the environment is important aspect of the leaching of chemicals and metals from steel slag. According to this definition the application of three slags for highway construction in Turkey will not pose any hazards in environment in agreement with the literature.

Table. 2. Regulation regarding the landfilling of wastes, Turkey.
26.03.2010/27533-Slag analysis results according to annex II.

Parameter	Unit	EAF_S2	EAF_S3	EAF_S1	Natural Aggregate	Inert Wastes Limits [LWR, 2010]
Eluent						
Fluoride	mg/L	0.7	0.5	0.8	0.3	1
Sulphate	mg/L	6	10	8	<5	100
Total Dissolved Matter (180 ^{o}C)	mg/L	162	228	280	<10	400
Dissolved Organic Carbon	mg/L	2.7	4.2	7.2	6.1	50
Chloride	mg/L	63	10	9	10	80
Copper	mg/L	<0.01	<0.01	<0.01	<0.01	0.2
Barium	mg/L	0.19	0.09	0.12	0.03	2
Mercury	mg/L	<0.0002	<0.0002	<0.0002	<0.0002	0.001
Nickel	mg/L	<0.001	<0.001	<0.001	0.002	0.04
Antimony	mg/L	<0.005	<0.005	<0.005	<0.005	0.006
Arsenic	mg/L	0.0012	0.0011	0.0019	0.001	0.05
Cadmium	mg/L	<0.0005	<0.0005	<0.0005	<0.0005	0.004
Total Chromium	mg/L	0.037	<0.001	0.002	0.002	0.05
Lead	mg/L	<0.0005	<0.0005	<0.0005	<0.0005	0.05
Selenium	mg/L	<0.001	<0.001	<0.001	<0.001	0.01
Molybdenum	mg/L	0.002	0.007	0.014	<0.001	0.05
Zinc	mg/L	<0.015	<0.015	<0.015	<0.015	0.4
Phenol Index	mg/L	<0.03	<0.03	<0.03	<0.03	0.1
pH (25 ^{o}C)	-	9.88	10.21	10.01	10.02	-
Original Sample						
Total Organic Carbon	%	0.1	<0.1	1.4	0.21	5

2. 3. Mechanical Characteristics

Firstly water absorption and bulk density tests are performed according to ASTM C127-12 and C128-12 standards. Three tests performed for each sample and average results are given in Table 3.

As seen on Table 3, water absorption values of EAF slags are extremely high in accordance to natural aggregate. These values are the result of high porosity. High porosity occurs because of high temperature difference between liquid slag and cooling water. This difference restrains the gases in slag and prevents them to depart. Moreover water absorption values of fine and coarse EAF slag shows that the porosity of coarse particles is higher.

Water absorption results are compared by Turkish Highway Specifications 2013 in Table 4. The values are beyond the limits for all layers. Besides “in special cases, aggregates with higher water absorption may be used on condition that other limits have been satisfied” statement is indicated in Turkish Highway Specifications 2013.

Another aspect that should be taken into consideration is the high bulk density of EAF slag. This would affect the hauling distance of EAF slag unless the slag satisfies other mechanical properties. As seen in Table 3 and 4 bulk density is not affected by metallic iron content but only by total iron percentage.

Table. 3. Bulk density and water absorption values of coarse aggregate.

Sample Name:	Size	Bulk Density (gr/cm^3)	Water Absorption (%)
EAF_S1	Fine	3.50	4.19
	Coarse	3.53	4.79
EAF_S2	Fine	3.75	2.30
	Coarse	3.85	3.04
EAF_S3	Fine	3.84	5.05
	Coarse	3.89	5.51
Natural Aggregate	Fine	2.84	0.44
	Coarse	2.85	0.28

Table. 4. Bulk density and water absorption values and specification limits.

Layer	Size	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Subbase	Fine	≤ 3.5	4.19	2.30	5.05	0.44
	Coarse	≤ 3.5	4.79	3.04	5.51	0.28
Base	Coarse	≤ 3.0	4.79	3.04	5.51	0.28
Surface Dressing	Coarse	≤ 2.5	4.79	3.04	5.51	0.28
Seal Coat	Coarse	≤ 2.5	4.79	3.04	5.51	0.28
Bituminous Base	Fine	≤ 2.5	4.19	2.30	5.05	0.44
	Coarse	≤ 2.5	4.79	3.04	5.51	0.28
Binder	Fine	≤ 2.5	4.19	2.30	5.05	0.44
	Coarse	≤ 2.5	4.79	3.04	5.51	0.28
Wearing Course	Fine	≤ 2	4.19	2.30	5.05	0.44
	Coarse	≤ 2	4.79	3.04	5.51	0.28
Stone Matrix Asphalt	Fine	≤ 2	4.19	2.30	5.05	0.44
	Coarse	≤ 2	4.79	3.04	5.51	0.28

Flakiness index test is performed according to ASTM D4791 C127-12 standard. Three tests performed for each sample and average results are given in Table 4 with Turkish Highway Specifications 2013 limits.

As seen on Table 5, flakiness index of each sample is within the limits of specifications. Moreover flakiness index values of EAF slag are lower than natural aggregate. It is considered that this situation is a result of rapid cooling. With rapid cooling slag starts to rupture with a more spherical shape.

Liquid limit and plasticity index test performed according to ASTM D4318. Three tests performed for each sample and all samples are determined as non-plastic. As mentioned before no contamination observed during sampling of EAF slag and this test is performed to check the observation. Only materials with liquid limit fewer than 25% and plasticity index fewer than 6% are only allowed to in subbase layer. Non-plastic materials are demanded for all other layers.

Table. 5. Flakiness index values and specification limits.

Layer	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Subbase	≤ 35	7.76	5.45	10.28	17.68
Base	≤ 30	7.76	5.45	10.28	17.68
Surface Dressing	≤ 25	7.76	5.45	10.28	17.68
Seal Coat	≤ 25	7.76	5.45	10.28	17.68
Bituminous Base	≤ 30	7.76	5.45	10.28	17.68
Binder	≤ 30	7.76	5.45	10.28	17.68
Wearing Course	≤ 25	7.76	5.45	10.28	17.68
Stone Matrix Asphalt	≤ 25	7.76	5.45	10.28	17.68

Clay lumps and friable particles test performed according to ASTM C142. Three tests performed for each sample and average results are given in Table 6 with Turkish Highway Specifications 2013 limits.

No clay lumps are expected in EAF slag samples according to observation and plasticity index test. This test is performed to determine the percentage of friable particles as anhydrite CaO and MgO in slag. Besides higher percentage of friable particles are obtained from natural aggregate. This is a result of filler on the surface of coarse aggregate.

Table. 6. Friable particle values and specification limits.

Layer	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Subbase	≤ 2	0.43	0.13	0.27	0.58
Base	≤ 1	0.43	0.13	0.27	0.58
Surface Dressing	≤ 0.3	0.43	0.13	0.27	0.58
Seal Coat	≤ 0.3	0.43	0.13	0.27	0.58
Bituminous Base	≤ 0.3	0.43	0.13	0.27	0.58
Binder	≤ 0.3	0.43	0.13	0.27	0.58
Wearing Course	≤ 0.3	0.43	0.13	0.27	0.58
Stone Matrix Asphalt	-	0.43	0.13	0.27	0.58

Resistance to degradation test performed according to ASTM C131. Three tests performed for each sample and average results are given in Table 7 with Turkish Highway Specifications 2013 limits.

As seen on Table 7, only EAF_S1 EAF slag sample is beyond the specification limits for stone matrix asphalt material. Despite the high bulk density values of EAF slags, degradation values are lower than the natural aggregate.

Soundness of aggregate by use of magnesium sulphate test performed according to ASTM C88. Three tests performed for each sample and average results are given in Table 8 with Turkish Highway Specifications 2013 limits.

All EAF slag results are within the limits of specifications as seen in Table 8. Though the porosity of EAF slag samples does not directly effect the soundness values.

Stripping resistance test performed according to Nicholson Method. Six tests performed for each sample, three with standard bitumen and three with %0.2 SCG-XL stripping resistance adjuvant. Average results are given in Table 9 and 10 with Turkish Highway Specifications 2013 limits.

Stripping resistance of all EAF slag samples are under the limits of specifications. With the addition of adjuvant, EAF_S1 and EAF_S2 sample values have come within the limits. It is assumed that the high metallic iron content would decrease the stripping resistance.

Table. 7. Resistance to degradation values and specification limits.

Layer	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Subbase	≤ 45	26.71	20.63	24.10	18.75
Base	≤ 35	26.71	20.63	24.10	18.75
Surface Dressing	≤ 30	26.71	20.63	24.10	18.75
Seal Coat	≤ 30	26.71	20.63	24.10	18.75
Bituminous Base	≤ 30	26.71	20.63	24.10	18.75
Binder	≤ 30	26.71	20.63	24.10	18.75
Wearing Course	≤ 27	26.71	20.63	24.10	18.75
Stone Matrix Asphalt	≤ 25	26.71	20.63	24.10	18.75

Accelerated polishing test performed according to ASTM D3319 standard. Three tests performed for each sample and average results are given in Table 11 with Turkish Highway Specifications 2013 limits.

As seen on Table 11 higher polishing resistance obtained from EAF slag samples. These results make EAF slags a good alternative for rough aggregates such as basalt.

3. Conclusions

Despite the steel slag is accepted as a by-product in international literature, no applications carried out in Turkey. In this study eco-toxicological and basic mechanical properties researched in order to provide its usage in highway construction as an artificial aggregate. Obtained results and suggestions are presented below.

EAF slags have higher water absorption values than natural aggregate. Therefore to determine economical aspect, granular base and bituminous layer mix designs should be performed for further information.

Flakiness index values of EAF slags are better than reference aggregate. This case is originated to rapid cooling process.

Clay lumps and friable particles test may be taken into consideration depending the anhydrite CaO and MgO content.

Porosity of EAF slag does not densely affect the soundness value.

Metallic iron should be recovered from EAF slag in order to obtain stripping resistance limits.

EAF slag could be used as an artificial aggregate in highway construction in unbound granular layers in the scope of this study. With high polishing values, applications in bituminous layers should be supported especially in regions without rough aggregate resources.

EAF slags studied in this paper are inert wastes according to the EU and Turkey regulations. The application of three EAF slags for highway construction in Turkey will not pose any hazards in environment in agreement with the literature.

Table. 8. Soundness of aggregate values and specification limits.

Layer	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Subbase	≤ 25	5.58	2.04	2.10	1.50
Base	≤ 20	5.58	2.04	2.10	1.50
Surface Dressing	≤ 18	5.58	2.04	2.10	1.50
Seal Coat	≤ 18	5.58	2.04	2.10	1.50
Bituminous Base	≤ 18	5.58	2.04	2.10	1.50
Binder	≤ 18	5.58	2.04	2.10	1.50
Wearing Course	≤ 16	5.58	2.04	2.10	1.50
Stone Matrix Asphalt	≤ 14	5.58	2.04	2.10	1.50

Table. 9. Stripping resistance values and specification limits.

Layer	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Surface Dressing	≥ 60	35	35	15	65
Seal Coat	≥ 60	35	35	15	65
Bituminous Base	≥ 60	35	35	15	65
Binder	≥ 60	35	35	15	65
Wearing Course	≥ 60	35	35	15	65
Stone Matrix Asphalt	≥ 60	35	35	15	65

Acknowledgements

This work is prepared partly using the material developed during the project titled “Performance, Feasibility and Applications of Steel Slag in Highway Construction (KGM AR-GE 2012/7)” supported by Turkish General Directorate of Highways.

Table. 10. Stripping resistance values with adjuvant and specification limits.

Layer	Turkish Highway Specifications 2013 Limits (%)	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Surface Dressing	≥ 60	75	75	55	95
Seal Coat	≥ 60	75	75	55	65
Bituminous Base	≥ 60	75	75	55	65
Binder	≥ 60	75	75	55	65
Wearing Course	≥ 60	75	75	55	65
Stone Matrix Asphalt	≥ 60	75	75	55	65

Table. 11. Stripping resistance values with adjuvant and specification limits.

Layer	Turkish Highway Specifications 2013 Limits	EAF_S1	EAF_S2	EAF_S3	Natural Aggregate
Surface Dressing	≥ 40	54.13	62.00	56.50	51.10
Seal Coat	≥ 40	54.13	62.00	56.50	51.10
Binder	≥ 35	54.13	62.00	56.50	51.10
Wearing Course	≥ 50	54.13	62.00	56.50	51.10
Stone Matrix Asphalt	≥ 50	54.13	62.00	56.50	51.10

References

EC (2002). Council Decision Of 19 December 2002 Establishing Criteria And Procedures For The Acceptance Of Waste At Landfills Pursuant To Article 16 Of And Annex II To Directive 1999/31/EC. 2003/33/EC. OJ L, 11, 27.

EN 12457-4 (2002). Characterisation Of Waste. Leaching. Compliance Test For Leaching Of Granular Waste Materials And Sludges. One Stage Batch Test At A Liquid To Solid Ratio Of 10 L/Kg For Materials With Particle Size Below 10 Mm (Without Or With Size Reduction).

Exponent (2007). Human Health and Ecological Risk Assessment for the Environmental Applications of Steel-Making Slag: An Update. Prepared for Steel Slag Coalition Kelley Drye Collier Shannon 1050 K Street, NW Suite 400 Washington, DC 20007-5108. Prepared by Exponent 320 Goddard, Suite 200 Irvine, California 92618.

Fontini, K. (2009). Skid Resistance Performance Of Asphalt Wearing Courses With Electric Arc Furnace Slag Aggregates. *Waste Manag. Res.*, 27, 288-294.

Geiseler, J. (1996). Use Of Steel Works Slag In Europe. *Waste Management*, 16(1-3), 59-63.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A Review Of The Use Of Recycled Solid Waste Materials In Asphalt Pavements. *Resour. Conserv. Recycl.*, 52, 58-73.

LWR (2010). Regulation Regarding the Landfilling of Wastes, Turkey. 26.03.2010/27533.

Manso, J.M., Polanco, J.A., Losanez, M., & Gonzales, JJ. (2006). Durability Of Concrete Made With EAF Slag As Aggregate. *Cement and Concrete Composites*, 28(6), 528-534.

NSA (1998). Steelmaking Slag: A Safe and Valuable Product. *Washington: The Steel Slag Coalition-National Slag Association.*

Pasetto, M., & Baldo, N. (2010). Experimental Evaluation Of High Performance Base Course And Road Base Asphalt Concrete With Electric Arc Furnace Slags. *Journal of Hazardous Materials*, 181, 938-948.

Pellegrino, C., & Gaddo, V. (2009). Mechanical And Durability Characteristics Of Concrete With EAF Slag As Aggregate. *Cement Concr Compos*, 31, 663-671.