



## Research Article / Araştırma Makalesi

## UTILIZATION OF ELECTRIC ARC FURNACE SLAG AS AN ARTIFICIAL AGGREGATE IN UNBOUND GRANULAR LAYERS OF HIGHWAYS

Fatih YONAR\*<sup>1</sup>, Murat ERGÜN<sup>2</sup>, Hüseyin Atilla DİKBAŞ<sup>3</sup><sup>1</sup>TechnoBee Ltd. Şti., İTÜ Ayazağa Kampüsü, Ari-2 Teknokent, Sarıyer-İSTANBUL<sup>2</sup>İstanbul Teknik Üniversitesi, İnşaat Fakültesi, İnşaat Mühendisliği Bölümü, Sarıyer-İSTANBUL<sup>3</sup>Medipol Üniversitesi, Güzel Sanatlar Tasarım ve Mimarlık Fakültesi, Kavacık-İSTANBUL

Received/Geliş: 18.03.2016 Accepted/Kabul: 27.06.2016

## ABSTRACT

As have been in many developed countries; to reduce the environmental impact of raw material 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 8<sup>th</sup> biggest steel producer in the world and 75% of annual steel production is obtained from electric arc furnaces (EAF). However just 1% of steel slag occurred from total steel production is used for manufacturing interlocking paving stones. Another high volume area of utilization should be specified in order to reduce the environmental impact. With the end of 2015 treated steel slag is accepted as by-product. Nevertheless only 24% of steel producers in Turkey have treatment facilities and all producers have treated and non-treated slag piles in stocking yards. Therefore in this paper; treated and non-treated EAF steel slag form three different regions in Turkey are examined. Treatment procedures, cooling and contamination conditions are specified. Chemical contents are investigated according to X-ray diffraction (XRD) test. Mechanical properties are examined according to ASTM standards and compared with the limits in Turkish Highway Specifications (THS) 2013. Unbound granular layers (UGL) specified in THS 2013 are compacted; maximum dry density values (MDD) and California bearing ratios (CBR) are determined. Potential expansion rates are observed. Environmental effects are researched. Lastly all results are evaluated within the scope of possible applications.

**Keywords:** Electric arc furnace, steel slag, artificial aggregate, unbound granular layers.

## ELEKTRİK ARK OCAĞI CÜRUFUNUN KARAYOLU GANÜLER TABAKALARINDA YAPAY AGREGA OLARAK DEĞERLENDİRİLMESİ

## ÖZ

Pek çok gelişmiş ülkede olduğu gibi Türkiye’de de çevresel etkinin ve doğal kaynak tüketiminin azaltılması için alternatiflerin dikkate alınması gerekmektedir. İnşaat, Türkiye’de en çok hammaddeye ihtiyaç duyan öncü sektördür. Bu kapsamda uluslararası araştırma ve uygulamalar ışığında üretici olarak çelik sektörü, tüketici olarak ise karayolu inşaatı sektörü öne çıkmaktadır. Türkiye, dünyanın en büyük 8. çelik üreticisi konumundadır ve yıllık üretimin %75’i elektrik ark ocakları (EAO) ile yapılmaktadır. Buna rağmen çelik üretiminde elde edilen cürufun sadece %1’i kilitli parke taşı imalatında kullanılmaktadır. Çevresel etkinin azaltılması açısından daha yoğun bir kullanım alanının tanımlanması gerekmektedir. 2015 yılı sonuna doğru işlenmiş çelikhane cürufu yan ürün olarak kabul edilmiştir. Fakat Türkiye’deki üreticilerin sadece %24’ünün cüruf işleme tesisleri mevcuttur ve hepsinin stok sahasında işlenmiş ve işlenmemiş cüruf mevcuttur. Bu amaçla bu çalışmada Türkiye’deki 3 farklı bölgeden işlenmiş ve işlenmemiş EAO cürufu temin edilmiştir. İşlenme usulleri, soğutma ve kontaminasyon durumları belirtilmiştir. XRD deneyi ile kimyasal içerikleri belirlenmiştir. Mekanik özellikleri ASTM standartları uyarınca test edilmiş, Karayolları Teknik Şartnamesi (KTŞ) 2013 limitleri ile karşılaştırılmıştır. KTŞ 2013’te tanımlanan granüler tabakalara göre maksimum kuru birim hacim ağırlık ve CBR (California Bearing Ratio) değerleri belirlenmiştir. Potansiyel genleşme oranları gözlemlenmiştir. Çevresel etkiler araştırılmıştır. Son olarak olası uygulamalar kapsamında sonuçlar değerlendirilmiştir.

**Anahtar Sözcükler:** Elektrik ark ocağı, çelikhane cürufu, yapay agrega, bağlayıcısız granüler tabakalar.

\* Corresponding Author/Sorumlu Yazar: e-mail/e-ileti: fyonar1981@gmail.com, tel: (212) 276 80 34

## **1. INTRODUCTION**

Turkey is the 8<sup>th</sup> biggest steel producer in the world with the capacity of 49.6 million tones. Two main processes produce this capacity: the integral cycle, which starts from mineral iron, and the electric cycle, which uses scrap metal [1]. EAF's produce 75.9% of this capacity. Currently twenty-nine facilities are operating in Turkey. These facilities are located in Mediterranean Region (10), Marmara Region (8), Aegean Region (6), Black Sea Region (3) and Central Anatolia Region (2). Three of these facilities are integrated; one is 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. Treated EAF slag newly accepted as by-product however there are just seven producers with treatment facility and all EAF steel producers have treated and non-treated slag piles in their stocking yards. In this context, mass utilization EAF slag as 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 also 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 [2].

Steel slags, including EAF, have mostly been used in surface layers of road pavements, in order to exploit their high resistance to polishing [1, 3], 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 [2].

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 [4, 5, 6, 7, 8, 9, 10, 11].

The study described here aimed to determine chemical, mechanical properties and possible UGL applications of three different EAF slag samples taken from three different dense production regions in Turkey with different treatment procedures.

Chemical contents of EAF slag samples are investigated with XRD test. Mechanical properties, structural abilities in unbound granular layers and potential expansion tests are performed according to ASTM standards and results compared with a natural aggregate sample. Environmental effects are researched from international literature. Lastly all results are evaluated and discussed.

## **2. MATERIALS AND METHODS**

This part is divided into five subparts. The first part is related to the chemical contents and observed properties of EAF slag samples and a natural aggregate as a reference. The second part is related to the mechanical characterization and comparison of EAF slag samples and the natural aggregate according to THS 2013. The third part is related to structural abilities of unbound granular layers defined in THS 2013. Fourth part is related to observed potential expansion rates of EAF slag samples according to ASTM standard. Fifth part is related to international literature review about environmental effect of EAF steel slag.

## 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 EAFS1 from Marmara Region, EAFS2 from Aegean Region and EAFS3 from Mediterranean Region. Natural aggregate sample (NAS) is taken from Omerli-Alyans quarry in Marmara region as reference.

Samples taken from 1<sup>st</sup> steel mill are fresh (no weathering procedures). No contamination is determined during sampling. The facility has a crushing, screening and magnetic separation unit in order to recover iron from slag. Samples have been cooled by water spray when poured from ladle at about 1300 °C. High porosity observed.

Samples taken from 2<sup>nd</sup> steel mill are fresh. No contamination is determined during sampling. The facility does not have a crushing, screening and magnetic separation unit in order to recover iron from slag. Samples have been cooled by water spray when poured from ladle at about 1300 °C. High porosity observed.

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

The chemical composition of the natural aggregate and EAF slag samples are analyzed with XRD test. XRD is used in order to determine the chemical and mineralogical composition of a rock, soil or slag aggregate [12]. XRD is the most widely used method for the determination of fine-grained soil minerals and the study of their crystalline structure. As the X-rays penetrate the crystal, small portions of them are absorbed by the atoms, which cause them to oscillate. This results in some waves that are in phase, which can then be detected as waves that have resulted from a reflection of the incident beam. The direction of the parallel planes of the crystal structure, which are relative to the direction of the incident beam, at which the radiations are in phase depends on the wavelength of the X-rays and the spacing between atomic planes [13]. Obtained results are given in Table 1.

**Table 1.** Chemical compositions.

Parameter	Samples			
	EAFS1	EAFS2	EAFS3	NAS
Metallic Fe, %	0.48	6.68	0.56	0.24
Total Fe, %	20.02	26.92	23.14	0.78
FeO, %	19.54	20.24	22.58	0.54
SiO <sub>2</sub> , %	12.86	19.73	18.62	0.92
Al <sub>2</sub> O <sub>3</sub> , %	7.84	6.52	7.77	0.42
Total CaO, %	19.78	16.20	18.91	32.50
Free CaO, %	5.80	0.27	0.21	0.17
MgO, %	9.36	4.79	3.43	22.05
MnO, %	4.58	4.92	3.06	0.05

While all parameters are close in each steel slag sample, metallic iron value of EAFS2 is higher than other samples because of no recovery. Also EAFS3's metallic iron value was

expected to be close to EAFS2. However long weathering period has oxide nearly all metallic iron. That can be also observed from FeO values.

In order to remove the unwanted chemical elements of the melt, the furnace is charged with fluxing agents, such as lime (CaO) or dolomite (MgCa(CO<sub>3</sub>)<sub>2</sub>), during the oxygen blowing cycles. The impurities combine with the burnt lime or dolomite forming slag and reducing the amount of undesirable substances in the melt [14]. Both agents remain in steel slag as free CaO (lime) and MgO (periclase). In the presence of water these two components hydrate. Hydration results in volume increase [15]. In order to prevent expansion, steel slag must be weathered. As seen in Table 1, highest free CaO and MgO values are obtained from fresh EAFS1. For this reason highest expansion values are expected from EAFS1. Lowest CaO and MgO values are obtained from EAFS3 with more than 6 months of weathering period.

## 2.2. Mechanical Properties

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 2.

As seen on Table 2, water absorption values of EAF steel 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 steel slag shows that the porosity of coarse particles is higher.

Water absorption limits in THS 2013 are given in Table 3. According to Table 2 and 3, water absorption values of EAF steel slag samples 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 THS 2013 [16].

**Table 2.** Bulk density and water absorption values.

Sample	Size	Bulk Density,	Water Absorption,
		gr/cm <sup>3</sup>	%
EAFS1	Fine	3.72	3.75
	Coarse	3.70	3.69
EAFS2	Fine	3.72	3.59
	Coarse	3.72	5.86
EAFS3	Fine	3.64	2.82
	Coarse	3.58	3.73
NAS	Fine	2.84	0.44
	Coarse	2.85	0.28

**Table 3.** Water absorption limits in THS 2013.

Layer	Size	
	Fine	Coarse
Subbase (SB)	≤ 3.5	≤ 3.5
Base <sup>#</sup>	-	≤ 3.0

<sup>#</sup> THS 2013 Base Layer limits is specified for both Granular Base (GB) and Plent-Mix Base (PMB).

No limit is given for bulk density values in THS 2013. However high bulk density values would shorten the hauling distance. This factor must be reconsidered according to application densities in construction sites.

**Table 4.** Flakiness index, friable particles, resistance to degradation and soundness of aggregate values.

Tests	Samples			
	EAFS1	EAFS2	EAFS3	NAS
Flaky Particles, %	8.00	4.59	5.93	17.68
Friable Particles, %	0.20	0.33	0.41	0.58
Resistance to Degradation, Degradad Particles, %	25.20	23.94	18.85	18.75
Soundness of Aggregate, Degradad Particles %	1.88	1.87	3.00	1.50

**Table 5.** THS 2013 limits.

Tests	Layers	
	SB	Base <sup>#</sup>
Flaky Particles, %	≤ 35	≤ 30
Friable Particles, %	≤ 2	≤ 1
Resistance to Degradation, Degradad Particles, %	≤ 45	≤ 35
Soundness of Aggregate, Degradad Particles %	≤ 25	≤ 20

<sup>#</sup> THS 2013 Base Layer limits is specified for both Granular Base (GB) and Plent-Mix Base (PMB).

Flakiness index test is performed according to ASTM D4791 standard. As seen on Table 4 and 5, flakiness index of each sample is within the limits of specifications. Moreover flakiness index values of EAF steel slag samples 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 tests are performed according to ASTM D4318. 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. Clay like materials only allowed in SB layers according to THS 2013. Non-plastic materials are demanded for all other UGLs.

Clay lumps and friable particles test performed according to ASTM C142. No clay lumps are expected in EAF steel slag samples according to observation and plasticity index test. This test is performed to determine the percentage of friable particles like anhydrite CaO and MgO in slag. Results are given in Table 4 and THS 2013 limits are given in Table 5. No clay or clay-like materials are determined in EAF steel slag samples. Therefore all lost materials in the test are accepted as friable particles. Friable particles could be decreased by longer weathering period.

Besides all, higher percentage of friable particles is obtained from natural aggregate. This is a result of filler cling on the surface of coarse aggregate.

### 2.3. Unbound Granular Layers

Three UGL types are defined in THS 2013, as subbase (SB), granular base (GB) and plant-mix base (PMB). Also these UGL types are subdivided into different types according to applications in construction site. SB layer is defined with two different particle distributions as Type-A and Type-B. GB layer is defined with three different particle distributions as Type-A, Type-B and Type-C. PMB layer is defined with two different particle distributions as Type-I, and Type-II.

Proctor tests according to ASTM D1157, are performed for all types of UGLs. Ideal particle distribution is taken into consideration. Maximum dry density and optimum water content values are determined and given in Table 6 and 7.

Each layer is compacted with optimum water content according to ASTM D1883 standard. Thereafter force ring displacement and specimen displacement values obtained and CBR values calculated. Calculated CBR values and THS 2013 limits are given in Table 8.

**Table 6.** Optimum water contents (%).

Layer	Type	Samples			
		EAFS1	EAFS2	EAFS3	NAS
SB	Type-A	4.69	4.67	5.19	4.38
	Type-B	4.80	3.82	6.08	3.93
GB	Type-A	4.52	4.32	6.66	3.55
	Type-B	5.05	4.43	5.54	3.77
	Type-C	4.46	5.12	5.64	3.18
PMB	Type-I	4.48	4.94	6.04	3.76
	Type-II	4.64	5.16	5.46	4.04

**Table 7.** MDD values (kN/m<sup>3</sup>).

Layer	Type	Samples			
		EAFS1	EAFS2	EAFS3	NAS
SB	Type-A	27,82	25,53	26,59	23,33
	Type-B	28,23	25,58	26,33	23,26
GB	Type-A	28,32	25,30	25,95	23,14
	Type-B	28,16	24,79	26,93	23,29
	Type-C	26,99	24,96	26,52	23,31
PMB	Type-I	27,19	25,17	26,82	23,10
	Type-II	27,25	25,06	27,24	23,32

**Table 8.** CBR values and THS 2013 limits (%).

Layer	Type	Samples				THS 2013 Limits
		EAFS1	EAFS2	EAFS3	NAS	
SB	Type-A	126	145	169	92	≥ 50
	Type-B	142	119	179	93	≥ 70
GB	Type-A	147	113	127	130	≥ 100
	Type-B	117	136	184	89	≥ 100
PMB	Type-C	140	154	140	107	≥ 100
	Type-I	135	146	155	121	≥ 120
	Type-II	127	143	183	90	≥ 120

As seen in Table 8, all UGL specimens consist of EAF steel slag compensated all limits given by THS 2013 while natural aggregate specimens could not compensate all. It is considered that this situation is a result of higher internal friction angle of porous EAF steel slag particles. Besides, highest values are obtained from EAFS3. EAFS3 is the only specimen with longer than 6 months of weathering period. Low amount of CaO and MgO is considered to increase internal friction angle especially when compacting layers with water.

#### 2.4. Potential Expansion Rate

Utilization of steel slag depends on its physical and mechanical properties as well as its volume stability. The amount of CaO and MgO components are very important that need to be examined, since they are the main components that are responsible for volume instability [12]. When the free CaO and MgO in the slag are exposed to water, they hydrate and this hydration causes the expansion of the slag. Free lime can be present in the slag in two forms, as precipitated CaO and as residual free CaO. The precipitated CaO does not have any major impact on the volume stability of the slag, but the residual free CaO does [4, 17].

The residual free lime can be separated into two categories, granular free lime that has a particle size of 3 to 10  $\mu\text{m}$ , and spongy free lime that has a particle size of 6 to 50  $\mu\text{m}$ . The spongy free lime is the most important factor in the volume stability of the slag [17].

The presence of free MgO is also a factor in the long-term stability of the steel slag. The free MgO in the slag originates from undissolved slag or is due to the saturation of the slag with MgO [17]. Steel slags that have a high content of MgO will generally have higher contents of free MgO [12].

Potential expansion tests are performed according to ASTM D4792 to determine expansion characteristics of EAF steel slag samples. Layers with highest MDD values are taken into consideration to simulate the worst scenario. Highest MDD values are obtained from EAFS1 GB layer Type-A, EAFS2 SB layer Type-B and EAFS3 PMB Type-II compactions. These layers are re-compacted according to calculated optimum water contents. Compacted granular layer samples are immersed in water at 70°C for 7 days with a surcharge load of 4.54 kgs. Graphics are drawn with daily displacement values of samples (Figure 1, 2, 3). Also PennDOT Form 408 limit is drawn in each graphic. According to PennDOT Form 408; if total expansion is less than %0.5 steel slag might be used in highway construction [18].

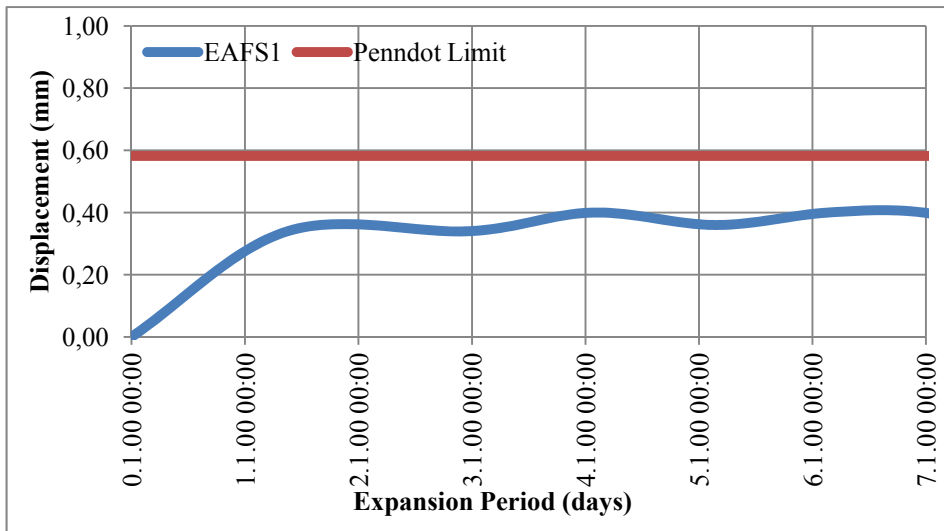


Figure 1. EAFS1 expansion graphic.

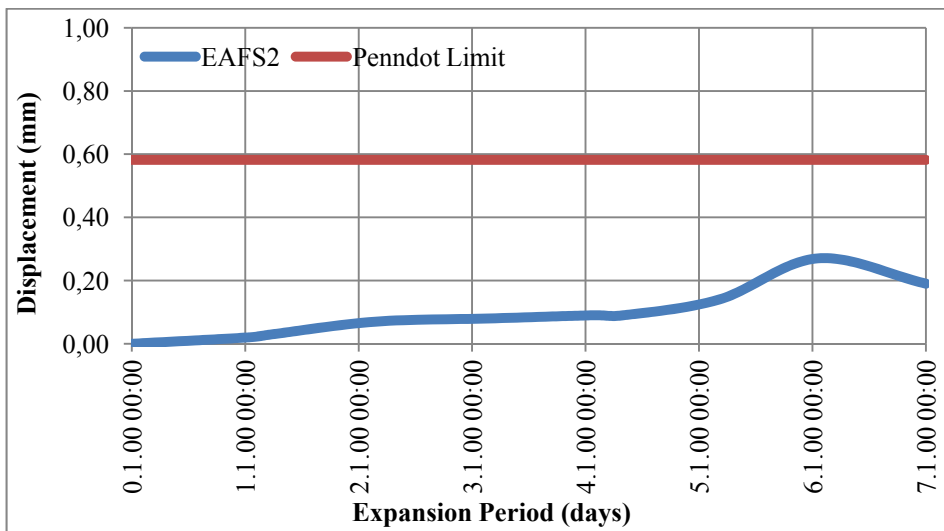


Figure 2. EAFS2 expansion graphic.

As seen in Figure 1, 2 and 3 maximum expansion is obtained from EAFS1 and the lowest expansion is obtained from EAFS3. This situation was also expected from free CaO, MgO values given in Table 1 and also weathering conditions given in Part 2.1.



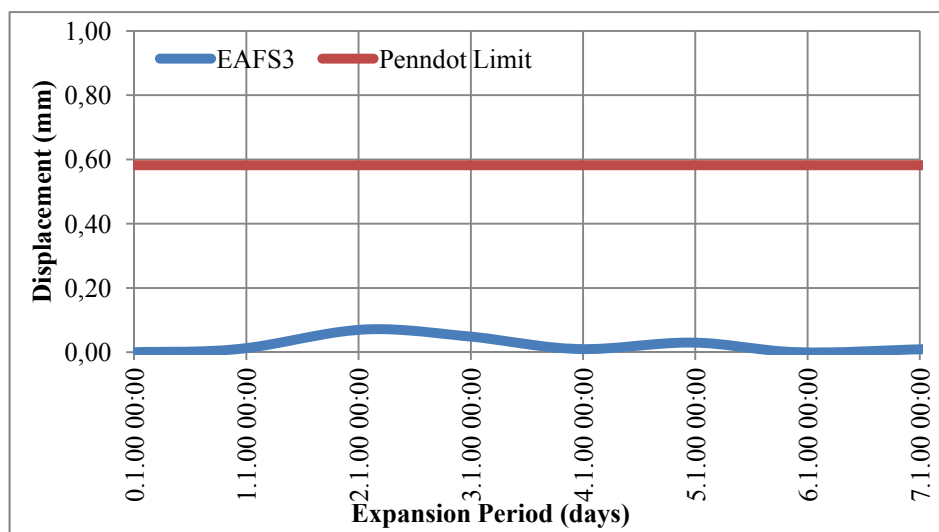


Figure 3. EAFS3 expansion graphic.

## 2.5. Environmental Effect

A concern with the use of steel slag in unbound applications is its potential to leach chemicals and metals into the environment. These chemicals and metals can possibly pose a risk to the health of both people and animals. The leaching of metals from the slag can become harmful when the amount of metal leached is greater than the amount found naturally in the soil or water [12]. Some metals within the slag may be in higher concentrations than those found naturally in soil. These are: antimony, beryllium, cadmium, chromium, copper, manganese, molybdenum, nickel, selenium, silver, thallium, tin, vanadium, and zinc [6]. Chromium as a mineral component may be found in higher concentrations in steel slag, but its concentration in the leachate is low since its ions are bound within the crystalline phases of the slag [19]. Moreover steel slag's highly alkaline structure limits the amount of metals leached from the slag [9]. However elevated pH values were observed in slag leachates and also in groundwater affected by steel slag disposal sites. pH levels are elevated in steel slag affected waters, mainly due to the leaching of alkaline substances from steel slag into the water. Therefore the effect of changes in pH on the ecosystem in the vicinity of slag disposal sites should be evaluated with caution [20, 21, 22].

In a risk assessment study conducted in 1998, the use of slag in environmental applications was found to not pose a hazard in most situations to the health of people or the ecology [9]. According to this study; the "reasonable maximum exposure" (RME) and "most likely exposure" (MLE) were assessed in accordance to the Environmental Pollution Agency (EPA) guidelines. This exposure assessment calculated average daily doses for exposures from all pathways and scenarios [9]. Beryllium, cadmium, and certain forms of nickel were the only constituent of interest (COI) to be considered potentially carcinogenic. The exposure and toxicity assessments are combined to form the risk characterization, which describes the potential health effects from the different uses of the slag. The theoretical excess cancer risk was calculated to be in a range of 2 in-ten-billion to 8 in-ten-billion for the RME, which is below the range of 1 in-a-million to 1 in-ten-thousand which the EPA considers to be negligible [12].

The hazard index (HI) is calculated based on the potential hazard associated with a cumulative exposure from all pathways. When a total HI is calculated to be larger than one, there is potential for a hazard and more studying of the COI is needed. The HI's ranged from 0.07 to 1

for the RME scenarios, with the maximum being calculated for a child onsite residential scenario and for the construction worker for an EAF slag. HI's ranged from 0.01 to 0.5 for the MLE scenarios with the maximum being calculated for the child onsite residential exposure for both EAF and BOF slag [9]. Since all of the calculated HI values are equal to or less than 1, this indicates that the use of slag does not pose a hazard to human health [12].

The risk to the environment and animals in the environment is another important aspect of the leaching of chemicals and metals from steel slag. The ecological risk associated with aquatic invertebrates in freshwater and saltwater as well as terrestrial organisms that might come in contact with the soil or ingest the soil was assessed. The ASTM water leachate data was used for comparison with the freshwater and salt water screening levels [9].

The findings of the ecological risk assessment by Exponent Inc. state: "The results of the initial screening-level evaluations indicate that, when plausible environmental conditions and application scenarios are considered, in which slag particles or leachate are naturally diluted by ambient water, sediment, or soil particles, no significant hazard to ecological receptors is anticipated. The only potential caveat involves the need for sufficient dilution in scenarios where the slag is applied next to freshwater bodies due to the potential aluminum concentrations." It is recommended that site specific investigations should be conducted when the slag-to-water ratio is low and the dilution of the leachate is questionable or when the possibility of aluminum concentration could affect the ambient water [9].

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. According to these studies:

- The leachate from steel slag was investigated using the tank leaching test and it was determined that the leachate from steel slag into the environment contained insignificant elements and did not pose an impact on the environment. This includes chromium due to the fact that the ions are bound within the stable crystalline form [4].
- Leaching test was conducted on an EAF steel slag aggregate in order to establish the leaching of toxic compounds from EAF steel slag. These values were then compared to limits of the Italian standards. The slag was found to have leaching values below the limits and is acceptable for utilization [10].
- Leachate from concrete containing EAF slag showed results that all values for sulphate, fluoride and Cr were below limits set by Spanish legislations [8].

### **3. CONCLUSIONS**

Treated steel slag is newly accepted as a by-product in Turkey. Annually 1% of steel slag is utilized by special processing plants as artificial aggregate for interlocking paving stones. In this study; basic mechanical properties and structural abilities of unbound granular layers consisting of EAF steel slag are studied in order to provide its dense usage in highway construction as artificial aggregate. Obtained results and suggestions are presented below.

Nearly all metallic iron could be recovered from steel slag by magnetic separation. In addition to this, long weathering period could oxidize nearly all metallic iron. Weathering could decrease CaO and MgO components that are responsible for volume instability. By this means expansion could be reduced to necessary limits. Therefore weathering process is obligatory for utilization of EAF steel slag in UGLs.

High application density of EAF steel slag might increase hauling costs. However low processing cost of EAF steel slag might equalize this situation.

Steel slags' water absorption values are higher than natural aggregate because of their porous structure. This situation has not substantially affected optimum water contents of granular layers. Besides porous structure increases internal friction angle and so CBR values.

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.

Friable particle rates of EAF steel slag samples are under THS 2013 UGL limits. If needed these rates could be decreased by longer weathering periods. However friable particle rates would draw a bell-shaped curve because of precipitated CaO as seen in Table 4, EAFS3 value.

Resistance to degradation value of EAF slag samples is lower than natural aggregate. Despite the fact that steel slag particles are tougher, their porous structure makes them more brittle.

Soundness value of EAF slag samples is slightly higher than natural aggregate. Porous structure of steel slag would not substantially affect degradation of particles during chemical freezing-thawing action.

CBR values of UGLs' consist of EAF steel slag are higher than natural aggregate values because of higher internal friction angle. Moreover the highest CBR values are obtained from weathered sample. Low amount of free residual CaO and MgO is considered to increase internal friction angle especially when compacting layers with water.

Samples used in this study have recessive expansion characteristics. In the worst scenario; all layers' expansion rates were below the limits. However lowest expansion rate is obtained from weathered sample. Therefore and according to literature, weathering and determination of expansion characteristics are obligatory processes for utilization of steel slag.

According to literature no significant hazard to ecological receptors has been anticipated in case of utilization of steel slag as artificial aggregate. However investigations should be conducted for aluminum and pH when slag to water ratio is low.

#### **Acknowledgement / Teşekkür**

This study is a part of "Elektrik Ark Ocağı ile Çelik Üretiminde Elde Edilen Cürufun Yol Yapımında Kullanımı ve Performansı" Ph.D. thesis which is based on Turkish Highway Administration's "Çelikhane Cürufunun Karayolu İnşaatında Kullanımı, Performansı ve Mevzuat Önerisinin Oluşturulması" R&D project.

#### **REFERENCES / KAYNAKLAR**

- [1] Fontini K. (2009). Skid resistance performance of asphalt wearing courses with electric arc furnace slag aggregates, *Waste Manag. Res.* 27, 288-294
- [2] 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
- [3] 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
- [4] Geiseler J., (1996). "Use of steel works slag in Europe." *Waste Management*, 16, 1-3, 59-63.
- [5] NSA, (1998). *Steelmaking Slag: A Safe and Valuable Product*. Washington: The Steel Slag Coalition-National Slag Association.
- [6] Proctor D., Fehling K., Shay E., Wittenborn J., Green J., Avent C., Bigham R., Connolly M., Lee B., Shepker T., and Zak M., (2000). Physical and chemical characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace steel industry slags. *Environ. Sci. Technol.* 34: 1576-1582.
- [7] Proctor D., Shay E., Fehling K., and Finley B., (2002). Assessment of human health and ecological risks posed by the uses of steel industry slags in the environment. *Human and Ecological Risk Assessment* 8: 681-711.

- [8] Manso J.M., Polanco J.A., Losanez M., and Gonzales J.J., (2006). Durability of concrete made with EAF slag as aggregate. *Cement and Concrete Composites*, 28, 6, 528-534.
- [9] 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 August 2007.
- [10] Pellegrino C, Gaddo V., (2009). Mechanical and durability characteristics of concrete with EAF slag as aggregate. *Cement Concr Compos* 31, 663-671.
- [11] Sofilic T., Cosic M., Mladenovic A., Sofilic U., (2010). Utilization of EAF Steel Slag as Alternative Aggregate in Road Construction, Proceedings Book of "Utilization of steelmaking slags with by-product recovery", Krakow, Poland, 105-120.
- [12] Fronck B. A., (2011) Feasibility of Expanding the Use of Steel Slag as a Concrete Pavement Aggregate, MSci Thesis, Department of Civil and Environmental Engineering, Cleveland State University, USA
- [13] Mitchell J. K., Soga K., (2005). *Fundamentals of Soil Behavior, Third Edition*. New Jersey: John Wiley & Sons, Inc.
- [14] Yildirim I. Z., Prezzi M., (2011). Chemical, Mineralogical, and Morphological Properties of Steel Slag. *Advances in Civil Engineering* Volume 2011, Article ID 463638
- [15] Ramachandran V. S., Sereda P.J., Feldman R. F., (1964). "Mechanism of hydration of calcium oxide," *Nature*, vol. 201, no. 4916, pp. 288-299.
- [16] Karayolları Teknik Şartnamesi, 2013.
- [17] Makikyro M., (2004). *Converting Raw Materials into the Products - Road Base Materials Stabilized with Slag-based Binders*. University of Oulu, Department of Process and Environmental Engineering. Oulu: University of Oulu.
- [18] PennDOT, (2000). Form 408, COARSE AGGREGATE, 703.2 (a) 4. Steel Slag, Pennsylvania Department of Transportation.
- [19] Motz H., Geiseler J., (2001). Products of Steel Slags an Opportunity to Save Natural Resources. *Waste Management*, 21, 285-293.
- [20] Yan J., Baverman C., Moreno L., and Neretnieks I. (1998). "Evaluation of time-dependent neutralizing behaviors of MSWI bottom ash and steel slag." *The Science of the Total Environment*, Volume 216, Issues 1-2, pp. 41-54.
- [21] Bayless E.R., Schulz M.S., (2003). "Mineral precipitation and dissolution at two slag-disposal sites in northwestern Indiana, USA." *Environmental Geology*, Vol. 45, No.2, pp. 252-261.
- [22] Roadcap, G.S., Kelly, W.R., and Bethke, C.M., (2005). "Geochemistry of extremely alkaline (pH.>12) ground water in slag-fill aquifers." *Ground Water*, Vol. 43, No. 6, pp. 806-816.

Copyright of Sigma: Journal of Engineering & Natural Sciences / Mühendislik ve Fen Bilimleri Dergisi is the property of Sigma: Journal of Engineering & Natural Sciences / Mühendislik ve Fen Bilimleri Dergisi and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.