Steel Slag Concrete for Pavement Construction

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ABSTRACT

Steel Slags are by-products of Steel Industry using the Electric Arc Furnace method for steelmaking. This methodology is widely used in South Europe where the research on steel slag applications in concrete has been developed. In this paper, the properties in fresh and hardened state of concrete for pavements are described as well as a pilot application of steel slag concrete in road pavement. Based on the results it is obvious that the use of steel slags in pavement application is very advantageous from technical point of view. Basic desirable characteristics are enhanced or significantly increased, such as the compressive strength, ductility and resistance to abrasion. Furthermore, the anti slipping properties of the pavements are considerably enhanced. A comparison of conventional concrete pavement with steel slag concrete is made based on the cost and environmental footprint considerations, taking into account the maintenance cost during the service life of the pavement.

Keywords: *Steel Slag, concrete, road pavement, compressive strength, ductility, abrasion*

INTRODUCTION

Slags are the industrial by-products of the steel production process. Depending on the production method, slag accounts for 7.5-15% of the total steel produced [1], and the total annual world production is estimated at 115-280 million tons for 2006 [2]. Annual slag production in Greece is about 250,000 tons and consists only of electric arc furnace steel slag. The melting of scrap for the production of steel in an electric arc furnace is common practice in many countries [3]. Electric Arc Furnace Slag (EAF) is produced in granulated form during the first stage of steel production is a granular form and can find uses as aggregate in concrete applications [4]. The chemical compositions of both steel slag and LFS vary depending on the batch synthesis, due to the fact that in scrap melting the production is carried out in batches, as opposed to the continuous process of blast furnace steel making. Furthermore, local conditions, different manufacturing practices, and scrap metal variations could also affect significantly the chemical composition of the produced slag [5].

The primary uses of EAFS are in cement clinker production, as aggregate in roadbeds and asphalt concrete or in hydraulic structures. These uses have been common practice for a long time, even from the beginning of the 20th century [6]. However, only recently, during the past decade, a relative regulative frame has been established in Europe and Japan for EAFS use in concrete applications, such as concrete pavements [7]. The use of steel slag in concrete is part of the main research activities of the AUTH Laboratory of Building Materials, which has contributed greatly to the utilization of industrial by-products and the general social and economic framework through which industrial by-products could be incorporated by the construction sector.

Among the technical advantages of using EAFS aggregates that could be mentioned are high resistance to abrasion, increased apparent specific density and surface roughness of the EAFS granules that enhances the bond of cement matrix to the aggregate [8]. Experience showed that failures associated to volume stability due to EAFS free lime or magnesia content could be avoided by its “natural ageing” or “steam ageing” before use [9]. By this process, the conversion of the above mentioned oxides into more stable chemical compounds is achieved.

In this paper, EAF steel slags were used as aggregates for the development of concrete for pavement construction. The properties in fresh and hardened state of slag based concretes were tested and compared with reference mixtures with limestone aggregates. Additionally, a pilot pavement application of the two types of concrete mixtures was implemented. The slag based concrete was compared to the reference one regarding strength and abrasion resistance, while economical and environmental assessment of the pilot application was also conducted using the Life Cycle Assessment methodology. This research work was developed in the frame of the TEFRODOS Project 2011-2014, funded by the General Secretary of Research and Technology in Greece. The partners were TITAN Cement Industry, the National Technical University of Athens and the Aristotle University of Thessaloniki as coordinator.

LABORATORY MIXTURES

The composition of the Roller Compacted Concrete (RCC) was based on literature recommendations, as well as on previous experience of the Laboratory of Building Materials of the Aristotle University of Thessaloniki, from the use of calcareous fly ash in RCC dams and pavements [10]. The required strength was fck C25/30 and the design of the RCC mixtures was based on the determination of Vebe density according to ACI 325.10R-95 and relevant standards. A mixed type binding system based on fly ash was used instead of Portland cement for environmental and cost reasons. Mixed type binding system is usually called the combination of powdered materials in a system which develops cementing properties with water under environmental conditions and strength after setting and hardening. Fly ash in Greece is a by-product of lignite-fired power plants and despite the abundant quantities produced annually, only a small percentage is utilized and the rest is landfilled, causing serious environmental problems. The use of fly ash or slags in RCC road pavement has a history in many countries such as USA, Austria, Australia and many relevant technical guidelines exist [11-13]. The characteristics of the constituents of the hydraulic binder are given in Table 1, while the final composition of the mixed type binder, which comprised of 50% calcareous fly ash, 25% clinker, 12.5% natural pozzolan and 12.% limestone filler and its characteristics are given in Table 2. The grinding to a high Blaine value was considered necessary for the development of 28-day laboratory compressive strength of 40 MPa, so as to have on-site compressive strength of at least 30 MPa. Consequently, the water demand for normal consistency paste of this fly ash-based hydraulic binder was 41.5% which is considered high, but its volume stability was normal, without any problems. The quantity of the new hydraulic binder called "tefrocement" was 280 kg/m^3. The water to cementitious ratio was selected to be ~0.50 when possible and a superplasticizer was also added at different rates.

Table 1 Chemical analysis and characteristics of the constituents of the hydraulic binder

Content/ Property	Cement clinker	Calcareous fly ash	Limestone filler	Natural pozzolan
SiO_2 (%)	21.35	34.40	0.20	63.80
Al_2O_3 (%)	5.40	13.60	0.20	18.10
Fe_2O_3 (%)	3.40	6.10	0.05	4.10
CaO (%)	65.75	32.80	55.00	2.80
MgO (%)	1.60	3.80	0.60	1.00
CaO_{free} (%)	1.30	6.40	n/a	n/a
$SiO_{2\text{-reactive}}$ (%)	n/a*	n/a	n/a	35.00
SO_3 (%)	1.20	6.78	0.00	0.00
L.O.I. (%)	0.00	3.26	44.10	3.20
Insoluble residue (%)	0.00	23.80	0.00	82.80

*not measured

Table 2 Properties of the produced mixed type hydraulic binder

Physical properties	
Blaine (cm^2/g)	9550
Fineness (retained at 45 μm)	0.4
Water requirement (%)	41.5
Initial setting time (min)	210
Le Chatelier dilation (mm)	0.0
2-day compressive strength (MPa)	15.9
7-day compressive strength (MPa)	26.3
28-day compressive strength (MPa)	40.1
Chemical properties	
L.O.I. (%)	8.40
SO_3 (%)	3.20
Insoluble residue (%)	26.40
CaO_{free} (%)	4.80
Chemical analysis	
SiO_2 (%)	29.90
Al_2O_3 (%)	12.65
Fe_2O_3 (%)	3.80
CaO (%)	42.90
MgO (%)	2.20

Regarding the aggregates, coarse EAFS was compared to ordinary limestone aggregate for the following:

- Physical properties, such as density, water absorption and resistance to fragmentation.
- Geometrical properties, such as grading and flakiness index and obtaining a suitable gradation curve for concrete mixtures.
- Chemical properties, such as chemical analysis and volume stability.
- Resistance to freeze-thaw cycles and magnesium sulfate soundness.

The results are summed up in Table 3.

Table 3 Physical properties of different coarse aggregates used

Property	Test method	EAF slag	Crushed Limestone
App. specific density (kg/m^3)	EN 1097-6	3330	2680
Loose bulk density (kg/m^3)	EN 1097-3	1482	1385
Percentage of voids (%)	EN 1097-3	55.5	48.3
Water absorption (%)	EN 1097-6	2.50	0.75
Resistance to fragmentation (%)	AASHTO T96	13.9	24.1
Flakiness index (%)	EN 933-3	8.0	38.4
Freeze-thaw resistance (1% NaCl) (%)	EN 1367-6	0.81	0.87
Magnesium sulphate soundness (%)	EN 1367-2	23.6	21.4
Steel slag expansion (%)	EN 1744-1	0.14	-
Aggregate abrasion value AAV (%)	EN 1097-8	3	-
Polished stone value PSV (%)	EN 1097-8	64	-

Steel slag aggregates show excellent resistance to fragmentation and fulfilled the requirements for abrasion resistant concrete. They exhibited increased water absorption, a factor that has to be taken into account in the concrete mixture design. Despite the higher absorption, the freeze-thaw resistance and magnesium sulfate soundness results were good, equal to those of the limestone aggregate.

The final proportions of the laboratory concrete mixtures are presented in Table 4. Consistency of fresh concrete was measured with the Vebe test at t = 0’ and at t = 30’ after water addition in order to account some time for concrete transportation, while the Vebe density was compared to that obtained from compaction with an electrical hammer (Table 4). As it can be seen from the results, the values obtained from the two different methods of measuring density were similar.

Table 4 New series of laboratory test mixtures series A and B, accounting for transport time

Mixture	EAF1	EAF2	LIM1	LIM2
Hydraulic Road Binder (kg/m^3)	280	280	280	280
Water (kg/m3)	148	148	159	148
Fine aggregate (kg/m^3)	1096	1096	1096	1096
Coarse aggregate (kg/m^3)	913	913	630	630
Maximum aggregate size (mm)	16	16	31.5	31.5
superplasticizer (%wt. of binder)	0.0%	0.5%	1.0%	0.0%
water/binder	0.53	0.53	0.57	0.53
Vebe time (s), t=0'	60	40	12	50
Vebe time (s), t=30'	100	80	30	80
Vebe density (kg/m^3), t=0'	2485	2413	2430	2447
Vebe density (kg/m^3), t=30'	2450	2410	2415	2400
Electrical hammer density (kg/m^3), t=0'	2474	2505	2466	2490
7-d compressive strength (MPa)	31.4	30.7	25.5	33.7
28-d compressive strength (MPa)	45.6	43.4	37.9	39.3

Compressive strength of EAF mixtures was significantly higher compared to the reference ones with limestone aggregates, reaching 45 MPa after 28 days of curing. However, workability of fresh slag concrete is reduced, since the needed time for compaction is higher.

PILOT CONSTRUCTION OF RCC ROAD PAVEMENT

The pilot construction of the RCC road pavement was implemented in a rural road next to the National Road Thessaloniki-Serres (E65), near Liti. The total length of the pavement that constructed was 1000 m, 500 m with slag based concrete and 500 m with limestone concrete. The average width was 6.25 m and the desired thickness 20 cm. The two concrete mixture proportions that were based on the laboratory work presented above are given in Table 5. Water/binder ratio of the EAF slag mixture was increased (0.58 instead of 0.53) in comparison to the laboratory mixtures in order to increase workability.

Table 5 Concrete mixtures of the pilot application

Limestone mixture (1st part of the road, 500m)	Comments	Kg/m³
Binder	tefrocement	280
Water	-	148.4
Active water/binder ratio	-	0.53
Limestone fine aggregate	(50%)	985
Coarse limestone aggregate 8-16mm	(30%)	591
Coarse limestone aggregate 16-31.5mm	(20%)	394
Superplasticizer	(%wt. of binder)	0.60%
EAF mixture (2nd part of the road, 500m)		
Binder	tefrocement	280
Water	-	162.2
Active water/binder ratio	-	0.58
Limestone fine aggregate	(50%)	1111
Coarse EAF aggregate 5-16mm	(50%)	1090
Superplasticizer	(%wt. of binder)	0.60%

The base was wetted 15-20 min before the application. Ordinary equipment of asphalt concrete pavement construction was used (truck for concrete transportation and delivery, finisher with a vibrating table shown in Figure 1, 4t and 10 t roller). The compaction achieved by the paver and rollers was measured on site with a Humboldt nuclear gauge (Figure 2) and the results are presented in Table 6. The rolling comfort of the final surface was considered moderate. This observation was more intense at the first part of the road where the working staff was unfamiliarity with the material. The use of EAF slag in the second part of the road did not changed the colour of the final surface, while concrete with slag aggregates showed a more closed structure compared to the initial section with 100% limestone aggregates (Figure 3).

Figure 1 Left: Truck unloading onto paver and RCC laying
Figure 2 Right: Fresh concrete density measured with nuclear gauge

Figure 3 Concrete with limestone on the left and EAF on the right

Table 6 Nuclear gauge density measurements on freshly bedded RCC (expressed as % of the measured Vebe density)

depth	directly after the paver	after compaction
5 cm	81.8%	90.4%
10 cm	81.2%	91.3%
15 cm	81.0%	90.6%
20 cm	79.7%	89.3%
average total pavement thickness (cm)	-	20.5

It was found that an effective compaction scenario was to have 2 non-vibrating passes with a 4 ton roller, followed by 1 vibrating pass with a 10 ton roller (Figure 4). With the available paver, the achieved compaction did not exceed the 80% of the maximum concrete density. Furthermore, the maximum single layer thickness after compaction could not exceed 20 cm. The shrinkage joints were cut every 5.5-6.0 m after the hardening of the pavement to a depth corresponding to 1/4-1/3 of the road thickness (Figure 5). Curing membranes were not used; water spraying was applied in order to keep the road surface dry.

Figure 4 Roller compaction of pavement

Figure 5 Joint cutting

Two months after the construction of 1 km of RCC road pavement, a survey was carried out and cores were obtained by drilling for concrete density and strength estimation and the results are shown in Table 7. Frost resistance was also measured by following freeze-thaw cycle testing from -25°C to 20°C on the drilled cores. After 50 cycles the drilled cores showed an average 8% loss of material, while ordinary C20/25 concrete which was used as reference showed an average 5% loss of material. The compressive strength of the initial part of the pavement with limestone was low (25 MPa) but improved at the last part reaching 32 MPa (because of unfamiliarity of staff with the material and methods during construction). The part with EAF aggregates also showed a compressive strength of 31.8 MPa. Resistance to abrasion was measured in situ according to ASTM C779 [15]. After the completion of the test, the part of the road with EAF aggregates showed a lower depth (4.49 mm) compared to one with limestone (6.77mm), which means stronger resistance to abrasion.

Table 11. Mechanical properties of cores drilled from different areas of the test road (average of 6 cores per area)

Construction area	Limestone (start)	Limestone (end)	EAF
pulse velocity u (m/sec)	4625	5022	4713
density ρ (kg/m³)	2295	2394	2345
Compressive strength f_c (MPa)	25.0	32.0	31.8

LIFE CYCLE ASSESSMENT

The Life Cycle Assessment methodology [15] is used to evaluate and compare the environmental impact of the different cases ("Case 1" refers to pavement with concrete mixtures containing limestone aggregates and "Case 2" refers to pavements utilizing steel slag aggregates). The evaluation is based on certain impact factors that summarize all the different outputs (air/water/soil emissions, land use etc) and express them into one single measurement unit. For this paper the "IPCC 2007 GWP 100a" impact factor was used, which derives from the Intergovernmental Panel on Climate Change, and the unit in which this factor presents the results is kilograms of CO_2 equivalent (kg CO_2 eq). The boundaries regarding the life cycle of the assessed cases are characterized as "Cradle to Grave" meaning that the whole life cycle of the pavement is considered, from the raw materials acquisition, to the construction, to the use of the pavement (along with maintenance works when they were needed) and finally to its decommission (part of it was suitable for recycling in order to produce materials that can be used for other purposes or reconstruction of the pavement). The data for the assessment are taken mainly from industries in Greece, as well as the libraries of LCA software SimaPro.

Based on the mechanical and durability properties of the two different cases, the pavement that utilizes slag aggregates shows an improved durability to abrasion (which is the main type of wear for road pavements) by a rate of 34%, compared to the one that utilizes limestone aggregates. Translating this into service life years, we assume that if Case 1 pavement has a service life of 40 years before it needs reconstruction, then Case 2 pavement would have roughly a 54 year service life. Therefore, the tie frame of the assessment was chosen to be 54 years. A "Case 3" pavement was also introduced, that refers to a common Asphalt pavement, in order to have a better comparison of the suggested cases with the existing practices. The data for the Case 3 pavement are taken from an existing pavement that is constructed from Egnatia Odos company, in the area of Northern Greece. The service life of such a common asphalt pavement is considered to be roughly 20 years (with maintenance works taking place every 10 years throughout the 54 years of the assessment) [16-18].

In Figure 5 the results are shown, for the 3 different cases. The results are presented in kg CO_2 eq, per km of constructed pavement, for presentation reasons.

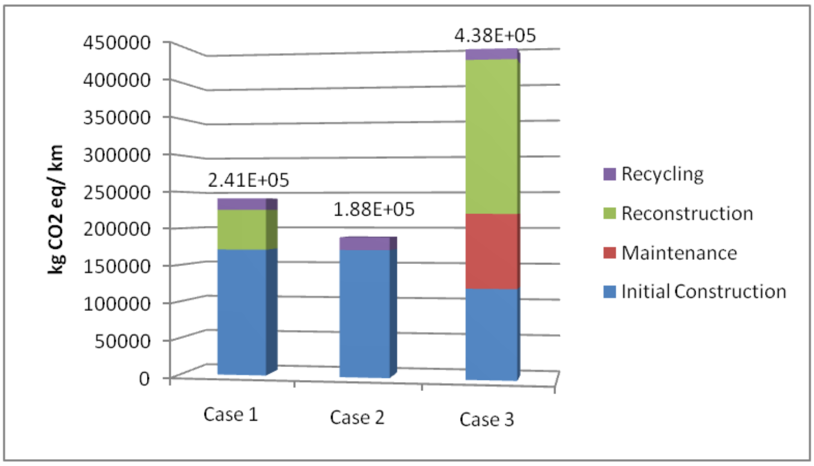

Figure 5 LCA Results

The different stages of the life cycle of the 3 case pavements are presented, for better evaluation. We can see that comparing the Initial Construction, the asphalt pavement (Case 3) has less environmental impact than the other two. However, considering the needed maintenance and reconstruction of the pavement in order to reach the time frame of 54 years, the environmental benefit of the RCC pavement cases is clear (it should be noted that the environmental impact of any minor maintenance works for the RCC pavements are not included as they are insignificant). The same principle applies when comparing the two RCC cases. Only when we consider the needed reconstruction of Case 1 pavement after 40 years in order to reach the time frame of 54 years, the environmental benefits from choosing Case 2 pavement are clear.

ECONOMICAL COST ASSESSMENT

For evaluating the economic impact of the compared cases, this paper uses the methodology of the Net Present Value (NPV), with which all future expenses and incomes that derive from the life cycle of the constructed pavements are expressed in economic terms of the time of the assessment, in our case the present time (time point = 0). The assessment period was chosen as 40 years, mainly because the methodology states that after that time frame the financial rates are not accurately predictable and this may lead to inaccuracies in our assessment. All data are taken from the updated costing charts for public works, from the Greek Ministry of Infrastructure, Transport and Networks [20]. The expenses refer to Initial Construction cost (IC), Maintenance cost (MC) and Reconstruction cost (RC). As an income we consider any residual value (RV) that the pavements will have once the 40 years of the assessment have passed. All the fore-mentioned expenses and incomes are multiplied with the following Discount Factor:

$$DF = \frac{1}{(1+i)^t} \tag{1}$$

where ‘i’ is the interest rate, taken 5% as a mean value for European Countries and ‘t’ is the year that the regarded cost takes place. Finally the Present Values that occur for every expense or income, are summarized in order to find the Net Present Value:

$$NPV = DF * \Sigma(IC) + DF * \Sigma(MC) + DF * \Sigma(RC) - DF * RV \tag{2}$$

The results can be seen in Figure 6. All results for the 3 cases are presented in Euro per m^2 of constructed pavement.

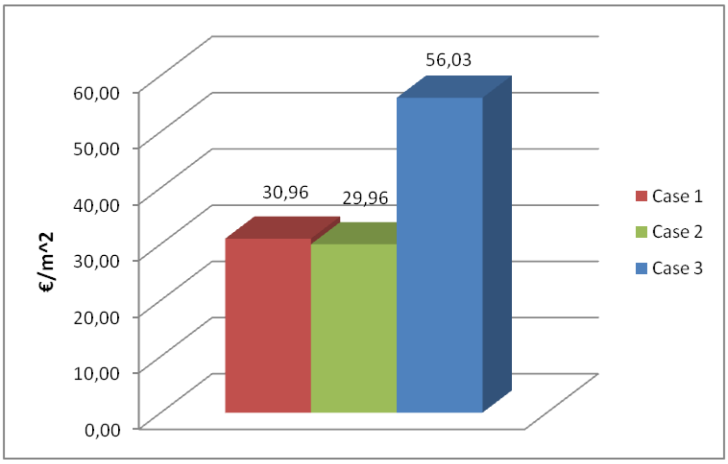

Figure 6 Economical Cost Results

The small difference between Case 1 and Case 2 can be explained due to the methodology's nature, where at the end of the 40th year the residual value of Case 2 (14 more years of service life) is not as defining as it would be e.g. in the 10th or 20th year, because of financial depreciation, which is expressed through the Discount Factor.

CONCLUSION

The utilization of steel-industry byproducts into pavement construction, in the form of partially replacing limestone aggregates with steel slag aggregates in concrete mixtures for rigid road pavements, is an efficient choice, in terms of mechanical and durability performance, along with environmental and economical benefits. Although tests from the pilot construction showed similar compressive strengths for Cases 1 and 2 (limestone and slag/limestone aggregates' mixtures respectively), the pavement with steel slag aggregates showed a high abrasion resistance, approximately at a rate of 34% higher than Case 1. This is also the main reason for the environmental (by a rate of 22%) and economical (by a rate of 3%) advantage of Case 2 compared to Case 1, due to longer service life of the construction. Moreover, regardless of the advantages of one RCC Case-pavement relative to the other, when comparing the rigid pavement generally to an asphalt one, the environmental-economical benefits of the former are much obvious.

REFERENCES

[1] National Slag Association, Steel slag – a premier construction aggregate. Accessed February 12th, 2010 at http://www.nationalslag.org (2001).

[2] U.S. Geological Survey, Mineral Commodity Summaries, USGS (2007).

[3] H. van Oss, Slag – Iron and Steel, In U.S. Geological Survey Minerals Yearbook V.1., USGS, Reston, VA, USA (2003).

[4] J. Geiseler, Use of steelworks slag in Europe, Waste Management & Research, 16, Nos.1-3 (1999) 59-63.

[5] M. Tossavainen, F. Engström, Q. Yang, N. Menad, M. Lidstrom Larsson, B. Bjorkman, Characteristics of steel slag under different cooling conditions, Waste Management, 27 (2007) 1335-1344.

[6] H. Motz, J. Geiseler, Products of steel slags an opportunity to save natural resources, Waste Management, 21 (2001) 285-293.

[7] E. Anastasiou, I. Papayianni, Criteria for the use of steel slag aggregates in concrete. In: Konsta-Gdoutos MS, editor. Measuring, Monitoring and Modelling Concrete Properties. Dordrecht, The Netherlands: Springer, (2006) 419-426.

[8] I. Papayianni, E. Anastasiou, Production of high-strength concrete using high volume of industrial by-products, Construction and Building Materials (2010) article in press.

[9] N.O. da Silveira, M.V.A.M. Silva, E.J. Agrizzi, M.F. de Lana MF, ACERITA – Steel slag with reduced expansion potential. In: Motz H, editor. Proceedings of the 4th European Slag Conference: Slag Products-Providing Solutions for Global Construction and other Markets. Oulu, Finland: Euroslag Publication No. 3 (2005) 145-157.

[10] Papayianni I. (2010). "Use of calcareous ash in civil engineering". Proceedings of the International Conference Eurocoalash 2010, Copenhagen, Denmark, May 27-28, 2010

[11] National Concrete Pavement Technology Center (2010). "Guide for Roller-Compacted Concrete Pavements". Iowa State University and Portland Cement Association, USA.

[12] ACI 325.10R-95 (2001). "State-of-the-art report on roller-compacted concrete pavements". ACI Manual of Concrete Practice, ACI, USA

[13] PCA (2004). "Guide Specification for Construction of Roller-Compacted Concrete Pavements". Portland Cement Association, Illinois, USA

[14] ASTM C779-12. Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces

[15] ISO 14040/14044, 2006. International Standard. Environmental Management-Life Cycle Assessment.

[16] Anastasiou E.K., Liapis A., Papayianni I., (2015) Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials, Resources, Conservation & Recycling, 101, Pages 1–8

[17] Papayianni I, (2013), Use of Calcareous Fly ash in Sustainable Concrete Applications with emphasis on RCC dam and road pavement, Presentation from Sustainability Seminars, 18-25 May 2013, China

[18] Liapis A., Anastasiou E., Papayianni I., (2015), Environmental and economical benefits from the use of a new type of binder with fly ash, in road pavement applications, 4th Int. Conference for the utilization of industrial byproducts in building, EVIPAR, Thessaloniki, Greece

[19] Descriptive costing charts for public works, Greek Ministry of Infrastructure, Transport and Networks, (2013), Official Government Gazette, paper 363