EAF slag aggregate behavior in antiskid course in road construction industry

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ABSTRACT: One of the major by-products of the steel industry is the Electric Arc Furnace (EAF) slag. AEIFOROS S.A. was established in 2001 and since then has been producing EAF Slag aggregates for antiskid course for highways, rural and urban motorways. Through a joint research program with the Aristotle University of Thessaloniki a continuous investigation of slag aggregate behavior in skid resistant course has been closely studied. The findings were compared to in-situ data taken from anti-skid courses with natural hard aggregates on the same highways. The results have shown greater durability of skid resistant courses by EAF slag compared to natural hard aggregates, fully satisfying greek specifications.

1. PRODUCTION OF EAF SLAG

1.1. *Electric Arc Furnace Slag (EAF)*

The Electric Arc Furnace (EAF) Slag is an industrially-produced artificial aggregate which, after suitable treatment, constitutes an excellent material for the manufacture of wearing course in the road construction industry. This practice although internationally recognized and applied in most European countries for many years has only in recent years begun to establish itself in Greece. The production and its use are friendly to the environment, while contributing in the manufacture of safer highways. Coarse aggregates for bituminous mixtures from EAF slag are being produced for the Greek market since 2001. The practice is fully and successfully applied (Prapidis, 2005).

The skid resistant aggregates are produced with methods friendly to the environment and according to the European Directive of I.P.P.C. (Integrated Pollution Prevention and Control). Furthermore, the use of EAF slag for road construction is a Best Available Technique (BAT) and under this prism it has been implemented by the Company. The use of an artificial aggregate from recycling offers a serious alternative solution to the excavation of natural aggregates, thus contributing to sustainable development.

The European Community originally published the European Directive of I.P.P.C. on Best Available Techniques (BAT) in 1996. Since May 2004 all member states including new members are obliged to comply with the directive, both existing as well as new industrial installations, which amongst others compels the steel manufacturing companies to minimise the waste resulting from the production process.

Due to the need for adaptation to European regulations and environmental developments, SIDENOR S.A., main steel manufacturer in Greece, sought solutions for complete compliance for its steel manufacturing plants. Part of the improvement decisions was the establishment of, AEIFOROS S.A., aiming at the recycling of all by-products of steel plants and the development and production of new products., In that way, based on international knowledge and practices, the whole quantity of EAF slag production in VIOHALCO group is being processed, fulfilling the purpose of establishment.

1.2. *EAF slag aggregate production*

The main advantage of EAF slag aggregates is the excellent mechanical properties that satisfy both international and domestic specifications for incorporation into bituminous mixtures for skid resistant layers and surface treatments. The use of such aggregates for highway construction offer the advantage that newly constructed roads are of equivalent quality and safety with those of other European countries and contributes in the manufacturing of a safer road network (Motz, 2001).

Furthermore, when compared to natural aggregates, EAF slag aggregates present the advantage of quality stability and constant chemical composition since the raw material is produced during the controlled industrial process of steel manufacturing.

The production of coarse aggregates for road construction from EAF slag is financially viable for the producer and economically attractive to the customer since part of competitive products available on the Greek market is imported (Vamvakoglou, 2004, Anastasiou, 2005).

Scrap metal is the raw material for all steel production industry in Greece. Initially metal parts are segregated through a shredder. Only the ferrous material is transferred to the furnace for melting, together with lime and other additives. The lime combines with the silicates, aluminum, magnesium oxides and ferrites to form the steel furnace slag. Slag is poured from the furnace through a hatch in a molten state at a temperature of approximately 1500 ^{0}C, collected and stockpiled where it is cooled. The rapid cooling of slag gives the crystalline form necessary for the excellent mechanical properties. After cooling, the slag is transported for further mechanical treatment (Paparrigas, 2005, Papayianni, 2005). At this point, slag ceases to be a steel industry by-product and becomes raw material for the production company.

For the production of the final products, a procedure comprising of several mechanical processes follows, primary sorting, scrap recovery, primary and secondary crushing and sieving. The aggregates produced are separated into various categories and are stockpiled in storing areas. Since 02/2006, the production of the main producer is certified with CE marking according to ΕΛΟΤ ΕΝ 13043 and the entire control system is also certified according to ΕΛΟΤ ΕΝ ISO 9001:2000 since 04/2006.

1.3. *Project description*

Through the aforementioned joint research program focusing on skid resistance characteristics, the performance of in situ antiskid courses has been studied through a period of three years (2002-2005).

The aim of the study was the recording of the mechanical properties and the determination of the fields of application of EAF slag aggregates. The data collected included measurements taken from skid resistant courses from both natural and EAF slag aggregates in order to evaluate through comparison, the benefits or possible drawbacks of the use of EAF slag aggregates to a) Greek standards for bituminous mixtures and b) climate and traffic impact on the deterioration of antiskid courses through the set period of time of approximately 4 to 14 months after construction. All measurements were taken for courses of the same specification of the department of Public Works, the open graded TYPE II with aggregate nominal size 12,5mm of Technical Specifications (T.O.EK2/8.11.85) as well as the later version adopted specifically for P.A.TH.E. Highway, TYPE II with aggregate nominal size 12,5mm of article ST4 of TSY (Hellenic Ministry for the Environment, Physical Planning & Public Works). The data were recorded on roadways as shown in Table 1.

Table 1. List of road and specifications

Road	Specification
P.A.TH.E. highway Ag. Theodoroi – Almyros	(article ST4 of TSY)
P.A.TH.E. highway Yliki – Ag. Konstantinos	(article ST4 of TSY)
P.A.TH.E. highway Skotina – Katerini	(article ST4 of TSY)
Rural road Volos – N. Agchialos	(T.O.EK2/8.11.85)
Highway Lamia – Karpenisi	(T.O.EK2/8.11.85)

2. IN-SITU MEASUREMENTS OF SURFACE COURSES WITH EAF SLAG

For the purposes of the study two main mechanical properties were measured, Skid Resistance value (SRV) and macrotexture depth (HS). It must be mentioned that there is no standard procedure for SRV in-situ testing described in Greek or international bibliography. The test was conducted using the traditional British pendulum. Tables 2, 3 and 4 show the results for P.A.TH.E. Highway between Ag. Theodoroi and Almyros, Yliki and Ag. Konstantinos and Skotina – Katerini respectively.

Table 2. Results for P.A.TH.E highway Ag. Theodoroi – Almyros

a/a	Road	Position (number)	Time* (months)	SRV (%)	HS (mm)
1	P.A.TH.E. Ag. Theodoroi – Almyros	1	0	79-81	1.15-1.20
2	P.A.TH.E. Ag. Theodoroi – Almyros	1	4	53-60	1.00
3	P.A.TH.E. Ag. Theodoroi – Almyros	2	0	80-81	n/a
4	P.A.TH.E. Ag. Theodoroi – Almyros	2	4	59-61	1.00-1.15

* Months after opening to traffic

Table 3. Results for P.A.TH.E highway Yliki – Ag. Konstantinos

a/a	Road	Position (number)	Time* (months)	SRV (%)	HS (mm)
1	P.A.TH.E. Yliki – Ag. Konstantinos	1	4	55-60	0.90-1.00
2	P.A.TH.E. Yliki – Ag. Konstantinos	1	14	61-65	0.64
3	P.A.TH.E. Yliki – Ag. Konstantinos	2	4	58-60	1.10
4	P.A.TH.E. Yliki – Ag. Konstantinos	2	14	61-66	0.64-0.68
5	P.A.TH.E. Yliki – Ag. Konstantinos	3	4	58-60	n/a
6	P.A.TH.E. Yliki – Ag. Konstantinos	3	14	65-66	0.64

* Months after opening to traffic

Table 4. Results for P.A.TH.E. highway Skotina – Katerini

a/a	Road	Position (number)	Time* (months)	SRV (%)	HS (mm)
1	P.A.TH.E. Skotina – Katerini	1	4	60-66	1.32-1.38
2	P.A.TH.E. Skotina – Katerini	1	14	56-62	1.15-1.24
3	P.A.TH.E. Skotina – Katerini	2	4	63-64	1.20-1.35
4	P.A.TH.E. Skotina – Katerini	2	14	62-67	0.96-1.21
5	P.A.TH.E. Skotina – Katerini	3	4	62-70	1.35
6	P.A.TH.E. Skotina – Katerini	3	14	61-64	1.06-1.40

* Months after opening to traffic

For all of the above cases, specifications set SRV value to 50 % and HS to 1,00mm as minimum requirement. The characteristics of the open graded mixture studies where slag was used for the coarse aggregates are shown in table 5. Coarse aggregates from EAF slag are produced into two particle size distributions, 5-12mm and 12-16mm. The sand 0-3mm used in all cases is limestone. The open graded form of the course is achieved through the absence of 2,5 to 5mm size particles, smaller percentage of sand and bituminous binder in the mixture. It must be mentioned that in the case of P.A.T.H.E. highway between Yliki and Ag. Konstantinos there was an increase in SRV value of approximately 5%. Regardless of the statistical error the increase can be traced to the thin asphalt layer developed during construction and effectively covering the micro texture when the four-month examination was carried. After 14 months of traffic the thin asphalt layer was removed due to normal weathering, leaving the surface of the aggregates exposed and thus resulting in higher SRV values than the original four-month test (Tsochos, 2006).

Table 5. Characteristics of mixture studies

Highway (a/a)	LA (%)	PSV (%)	AAV (%)	% EAF*	% sand*	% Binder	% of air voids
Ag. Theodoroi – Almyros	15.00	62	3.00	74.9	25.1	4.68	9.49
Yliki – Ag. Konstantinos	21.68	65	2.92	67	33	4.65	9.10
Skotina – Katerini	18.06	64	2.57	63	37	4.85	10.30

* Percentage per weight of aggregates in the mixture

where LA standard Los Angeles abrasion test according to ASTM C131/89

PSV Polished Stone Value according to ΕΛΟΤ EN 1997.80

AAV Aggregate Abrasion Value according to BS 812.113-1991

The SRV values are summarised against the designed PSV value of each mixture study in table 6. In all cases, even after 14 months, the SRV values satisfy the limit set by the specifications. Due to weathering through climate conditions and traffic volume the decrease varies between 0-6 percent.

Table 6. Summary of results

Highway (a/a)	PSV (%)	mean SRV after 4 months (%)	mean SRV after 14 months (%)
Ag. Theodoroi – Almyros	62	58	-
Yliki – Ag. Konstantinos	65	59	64
Skotina – Katerini	64	64	62

In all above cases short term data confirm the efficiency of EAF slag aggregates for skid resistant courses after a 14-month period after construction under heavy load traffic conditions.

Natural crushed aggregates were also used to construct parts of the highways mentioned previously. Data were not collected as any comparison between results would be inappropriate due to a) the original designed PSV value was much lower than EAF slag surface courses, b) parts with natural aggregate courses were rehabilitated using EAF slag aggregates and c) the surface courses with natural aggregates were constructed two years before EAF slag courses. In order to compare natural and EAF slag mechanical properties, tests were conducted in rural road Volos – N. Agchialos and Highway Lamia – Karpenisi.

3. COMPARISON BETWEEN EAF SLAG AND NATURAL AGGREGATES

For the purposes of the analysis, measurements were taken on Volos – N. Agchialos roadway and the Lamia – Karpenisi highway in a time period of eight months to one year after construction. The same mechanical properties were examined (SRV and HS) as previously (Kechagia, 2004). Measurements were taken on bituminous mixtures of the continuously graded TYPE II with aggregate nominal size 12,5mm of Technical Specifications (T.O.EK2/8.11.85), 4.00cm thick course. Data for both natural hardstone and EAF slag aggregates were collected and summarized in table 7.

Table 7. EAF slag and hardstone wearing course

a/a	Road	Position (number)	Material for coarse aggregates	SRV (%)	HS (mm)
1	Volos – N. Agchialos	1	EAF slag	52	0.85
2	Volos – N. Agchialos	1	hardstone	51	0.65
3	Lamia – Karpenisi	1	EAF slag	52	0.7
4	Lamia – Karpenisi	1	hardstone	41	0.4

In all cases EAF slag wearing course presents higher SRV and HS values than courses with natural hardstone. Even though that in Volos – N. Agchialos case the variation in the mean SRV value is not statistically significant between EAF slag and natural hardstone courses, the constant higher values of the individual measurements for the courses with EAF slag throughout the time period of examination leads to the same conclusion. The superiority of EAF slag mixtures is more obvious in Yliki – Ag. Konstantinos case presented in table 8. Previous studies on steel slag aggregates used in wearing course in Rotherham during the 1980s led to the conclusion that "steel slag road surfaces have at least as good long-term skidding resistance properties as those of comparable natural aggregate road surface" (Stock, 1996).

Table 8. EAF slag and hardstone wearing course in P.A.TH.E. Yliki – Ag. Konstantinos

a/a	Road	Natural hardstone		EAF slag aggregate	
		SRV(%)	HS (mm)	SRV(%)	HS (mm)
1	P.A.TH.E. Yliki – Ag. Konstantinos	52	0.25	65	0.79
2	P.A.TH.E. Yliki – Ag. Konstantinos	52	0.24	66	0.64
3	P.A.TH.E. Yliki – Ag. Konstantinos	50	0.28	66	0.79
4	P.A.TH.E. Yliki – Ag. Konstantinos	50	0.24	62	0.64
5	P.A.TH.E. Yliki – Ag. Konstantinos	52	0.38	61	0.68
6	P.A.TH.E. Yliki – Ag. Konstantinos	52	0.31	66	0.64

For this later case all tests were conducted within a time period of 14 months after construction.

The results coincide with similar measurements held in UK comparing bituminous mixtures with EAF slag and high PSV gritstome (Jones, 2000). In this later case, instead of SRV measurements, the sideway force coefficient was determined which is an alternative method of examining the skid resistance.

4. COMPARISON BETWEEN HOMOGENEOUS BITUMINOUS MIXTURES

Since 2001, more than 30 mixture studies have been prepared for over 35 construction companies for all major highway projects for both construction and rehabilitation. Specifically, for the predominant open graded type of asphalt concrete, TYPE II with aggregate nominal size 12,5mm of article ST4 of TSY, this company acquired significant experience as aggregate producer. Through this experience, which is not limited to the experimental data but also through the observations during and after construction, some important conclusions can be drawn.

4.1. *EAF slag and natural aggregate mixtures*

The aggregates of the skid resistant course are constituted by two or three particle size distribution, depending on the type of specification the mixture must comply with i.e. being closed or open graded and the percentage of voids required in the mixture. Usually there are one or two particle size distributions used for coarse aggregates and one for fine. In all types of the specification apart from ST6 of TSY, coarse aggregates can be of different origin to fines, while ST6 necessitates both aggregates being from the same source. Table 9 includes most of the mixture studies carried according to TYPE II of article ST4. The results are derived from Marshall Test according to AASHTO T-166.

Table 9. Mixture studies according to Type II of article ST4

Mixture No.	Year	% EAF*	% sand*	% Binder	% of air voids
14	2005	67	33	4.75	10.04
13	2005	67	33	4.75	9.64
7	2004	67	33	4.65	9.10
6	2004	63	37	4.85	10.00
2	2003	75	25	4.68	10.30
1	2002	73	27	4.70	9.10

* Percentage per weight of aggregates in the mixture

As far as TYPE II is concerned, mixtures with EAF slag coarse aggregates and limestone fines require smaller percentage of bituminous binder per weight of the aggregates compared to mixtures where natural hardstone and limestone sand is used. The percentage of binder in the former ranges between 4.4-4.6 percent while maintaining high stability levels (2200 lb) according to Marshall tests (A.S.T.M. D1559). On the other hand natural hardstone mixtures of normal practice require slightly higher percentage of binder 4.9-5.1 percent resulting in lower stability (1960 lb). In both cases and for the purposes of the experiment the same percentage of voids in the final compacted mixture was accomplished (approximately 11%) and the best percentage of binder determined. This is mainly due to the greater specific weight of EAF slag and, due to the presence of smaller percentage of fines, greater degree of compaction.

4.2. *Coarse and fine aggregates by EAF slag compared to natural aggregate mixtures*

Table 10 shows the mixture studies carried according to article ST6 using modified asphalt. Similarly to table 9, all results are deriving from Marshall Test according to AASHTO specifications. It must be mentioned that article ST6 limits percentage of air voids between 6-15 percent and percentage of asphalt to 5.5-6.2 for normal and 5.7-6.4 percent for modified asphalt per weight of aggregates (Nikolaidis, 2002). These two ranges apply to aggregates with usual specific weight 2.65-2.70 g/cm^3 and modification is required for aggregates, like EAF slag, with considerable difference in specific weight.

Table 10. Mixture studies according to ST6

Mixture No.	Year	% EAF*	% EAF sand*	% Binder	% of air voids
21	2006	74	26	5.80	12.00
20	2006	73	27	5.20	10.80

* Percentage per weight of aggregates in the mixture

Considering mixtures with coarse and fine aggregates from natural hardstone requiring 6.00-6.20 percent of modified asphalt while the corresponding percentage for EAF slag aggregates varies between 5.20-5.80, the reduction of asphalt content in the mixture is considerable. Again, all results refer to mixtures with modified asphalt and air voids 10-12 percent. The main reason again is the greater specific weight of EAF slag aggregates. Due to the fact that these specifications have been adopted very recently as well as put in use solely for Egnatia Odos highway, the experience is limited and data only indicative.

4.3. *Limestone sand the preferred solution in mixtures*

Yet another aspect of bituminous mixture studies and which also pointed out by construction companies is the preference towards EAF slag coarse aggregates combined with natural limestone sand instead of EAF slag sand. In addition to financial reasons, mixtures with EAF slag aggregates and limestone sand exhibit lower asphalt percentage for the same specification with the same percentage of air voids.

Data from mixture studies show that limestone sand from different quarries require different percentages of binder depending on the particle size distribution, constantly smaller percentage of bituminous binder than mixtures with EAF slag sand. Initial indications show that the percentage of filler (particles passing No200 sieve, 0.075mm) in the sand affects, to a great extend, the percentage of binder required. The finer the sand the less binder is required to achieve the specified air void percentage while maintaining the specified stability of the specimen ensuring compliance to the mix specification.

Finer sand can be translated to smaller particles. Thus the specific surface increases and it would be expected that the binder percentage would normally increase. In practice, smaller aggregate particles fill the air voids improving macrotexture of the specimen, resulting in much smaller percentage of binder required. Due to this reason the overall binder requirements are decreased. As the sand particle distribution is limited by the specifications, a particle size distribution closer to the upper limit curve (more fines) would be suggested in order to reduce the overall binder content maintaining compliance to the specifications.

Contrary to limestone, EAF slag, being a much harder material, is more resistant to abrasion. Normal quarrying methods cannot apply, especially for production of fine sand. For this purpose, the producer company proceeded in 2006 towards a 250 thousand Euro investment for a) produce sand with greater percentage of fines and b) satisfy the requirements set by article ST6 of Egnatia Odos for particle size distribution of fine aggregates. The result was the production of a fine sand, similar to limestone in terms of particle size distribution, which fully satisfied road construction specifications and construction companies requirements by being economically competitive.

The comparison of very fine EAF slag and limestone sand in bituminous mixtures is yet to be examined.

5. CONCLUSIONS

Aeiforos SA is the main producer of hard aggregates from EAF slag in Greece. The production started in 2001 and since then hundreds of kilometers of national highways, rural and urban motorways have been constructed.

Since experience in the use of EAF slag in the skid resistant course is limited in Greece, Aristotle University of Thessaloniki, through a joint research program with the main producer, studied the performance of EAF slag aggregates in comparison to natural hardstone. Results show the superiority in terms of durability and mechanical properties of EAF slag aggregates in the on-going short term studies and up to a period of 14 months after construction, always above the limits set by national specifications.

Through the cooperation with major construction companies and their experience in the use of slag combined with mixture studies the conclusions drawn are

- mixtures with EAF slag coarse aggregates require smaller percentage of bituminous binder per weight of aggregates
- similar are the results in mixtures where both coarse and fine aggregates originate from EAF slag compared to mixtures with natural hardstone
- mixtures with EAF slag aggregates and limestone sand can be regarded as the optimum solution by ensuring compliance to the specifications while reducing the percentage of binder and thus being cost effective.

REFERENCES

Anastasiou, E. & Papayianni, I. 2005. Production of concrete of high environmental standards with the use of industrial by-products. *EVIPAR 1st Panhellenic Conference*, Thessaloniki: EVIPAR

Hellenic Ministry for the Environment, Physical Planning & Public Works. ΣΤ-4. Αντιολισθηρή ασφαλτική στρώση από ασφαλτικό σκυρόδεμα, *Τεχνική Συγγραφή Υποχρεώσεων (Τ.Σ.Υ.) Έργων Οδοποιίας*: 4-8

Jones N. 2000. The Successful Use of Electric Arc Furnace Slag in asphalt, *2nd European Slag Conference*, Düsseldorf, 2000

Kechagia, F. 2004. Χρήση σκωριών χαλυβουργίας σε κατασκευές οδοστρωμάτων. *Χρήση βιομηχανικών παραπροϊόντων στην οδοποιία Πρακτικά Ημερίδας*, Thessaloniki: Aristotle University of Thessaloniki

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

Nikolaidis, A., 2002, *Οδοστρώματα – Υλικά Έλεγχος Ποιότητας*, Thessaloniki: M.Triantafylloy

Papayianni et al. 2005. Use of steel slag aggregates in the production of concrete paving blocks. *EVIPAR 1st Panhellenic Conference*, Thessaloniki: EVIPAR

Paparrigas, D., 2005. Use of steel slag in structural industry and in road constructions. *EVIPAR 1st Panhellenic Conference*, Thessaloniki: EVIPAR

Prapidis et al., 2005. Use of slag in skid resistant asphalt mixes based on mechanical and environmental criteria, Athens: HELLECO 2005

Stock et al. 1996. Skidding Characteristics of Pavement Surfaces Incorporating Steel Slag Aggregates. *Transportation Research Record 1545, Asphalt Pavement Surfaces and Asphalt Mixtures*: 35-40

Tsochos, G. & Mouratidis, A. 2006. *Χρήση σκωριών χαλυβουργίας σε αντιολισθηρούς τάπητες*. Thessaloniki: Aristotle University of Thessaloniki

Vamvakoglou, K. 2004. Χρήση σκωριών χαλυβουργίας στη δομική βιομηχανία. *Χρήση βιομηχανικών παραπροϊόντων στην οδοποιία Πρακτικά Ημερίδας*, Thessaloniki: Aristotle University of Thessaloniki