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Use of electric arc furnace slag in thin skid-resistant surfacing

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Abstract

One of the major by-products of the steel production industry is Electric Arc Furnace (EAF) slag. In the field of research and development and in cooperation with the laboratory of EGNATIA ODOS SA, the current study focuses on the mechanical properties of electric arc furnace slag, as used in the thin, porous surfacing of Egnatia Odos highway. The in-situ measurements refer to two highway segments constructed in July 2007 and August 2008. The data collected is compared to the initial results of the mixture studies and the behaviour of the wearing course is examined in the time span of 30 and 41 months, subject to normal traffic and environmental weathering. The data obtained refers to three types of measurements, skid resistance, macro texture depth and permeability. The results show minor differences in between initial and later measurement. The data is also compared to skid-resistant layers with natural hard aggregates which were constructed at the same time period and were subject to identical environmental and traffic conditions on the Egnatia Odos highway. Comparison is made to a study on the P.A.TH.E. highway with similar skid resistant wearing courses of asphaltic concrete. Both results show the suitability of EAF slag aggregates to fully satisfy the technical specifications. The comparison to wearing courses made with natural hard aggregates highlights the superiority of artificial aggregates, primarily due to their enhanced mechanical properties.

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1. Introduction

1.1. Electric arc furnace slag

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. 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 have been produced for the Greek market since 2001. The use of EAF has been found to be successful (Prapidis, 2005).

The skid resistant EAF slag 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 an ideal 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. This compels the steel manufacturing companies to minimise waste resulting from the production process.

Due to the need for adaptation to European regulations and environmental developments, Sidenor S.A., the main steel manufacturer in Greece, sought solutions for complete compliance for its steel manufacturing plants. Part of the improvement decision was the establishment of AEIFOROS S.A. aiming at the recycling of all steel plant by-products and the development and production of new products. EAF slag production by the SIDENOR group is such an example.

1.2. Slag aggregate production

Aggregate for bituminous mixtures with EAF slag have been produced for the Greek market since 2001. The practice is fully applied and internationally accepted in most European countries for many years, but has only recently begun to establish itself in Greece. Certified according to EN 13043, the skid resistant aggregates have been found to be excellent substitutes to natural hard aggregates. The main advantage of EAF slag aggregate is its excellent mechanical properties that satisfy both international and domestic specifications for incorporation into bituminous mixtures for skid resistant layers and surface treatments (Stock et al, 1996, Jones, 2000). The use of such aggregates for highway construction offers the advantage that newly constructed roads are of equivalent quality and safety with those of other European countries and contribute towards a safer road network (Motz, 2001).

Furthermore, when compared to natural aggregates, EAF slag aggregate 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 aggregate for road construction from EAF slag is financially viable for the producer and economically attractive to the customer (Pasetto, 2010) since comparable products available to the Greek market are imported (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 1630 ^{o}C, collected and stockpiled where it is cooled. The rapid cooling of slag gives the specific amorphous phases necessary for the acquiring of excellent mechanical properties. After cooling, the slag is transported for further mechanical treatment. At this point, slag ceases to be a steel industry by-product and becomes raw material for the production company.

1.3. Research description

EGNATIA ODOS SA is the company responsible for the supervision of construction, operation and maintenance of the Egnatia highway. They have adopted a thin surfacing of asphaltic concrete, 2,5cm in thickness, according to article ST6 of Technical Specifications (Hellenic Ministry for the Environment). The thin surfacing main characteristic is the open graded design resulting in 8 to 12% air voids in the compacted mix. The specification states that both gravel and sand must be from the same hard aggregate. In this case the aggregate is Electric Arc furnace (EAF) slag processed by the recycling company AEIFOROS SA. The final surfacing course is required to provide skid resistance, reduce aquaplaning and spray during heavy rain conditions and so improve visibility and safety.

The drawbacks of this specification are a) greater oxidization of asphalt, b) risk of decreasing binder efficiency in cases of improper mix, c) decreased life span in comparison to close-graded mixes, d) fines and dust filling air voids reducing beneficiary effects of increased macro-texture, e) necessity of close-graded underlying layer with sufficient traverse gradient, f) reduction of load bearing capacity in comparison to thicker 4,5cm skid-resistant surfacing of normal practice.

This paper is the result of close co-operation between the managing company of the highway, Egnatia Odos SA, and the main producer of EAF hard aggregate in Greece, Aeiforos SA. It describes the findings from two separate time periods. The first period is June - July 2008 and refers to the time period prior to the initiation of construction works, the mix design, the in situ measurements during laying and generally all the initial tests held during construction. The tests included aggregate and asphalt property testing, asphalt mix Marshall testing, penetration and softening as well as multiple in situ measurements. During the second time period i.e. between January and February 2011, field measurements were obtained to identify the environmental and traffic weathering of the thin surfacing constructed entirely with electric arc furnace slag aggregate. The second series of field measurements were obtained with the aim of measuring

a) the skid resistance of the surfacing,
b) surface texture after normal weathering and
c) water permeability to identify the porosity of the surface course.

This paper presents the technical data of the surfacing for Section 10.1 -11.2 of the Egnatia highway and specifically for the part between the Nymfopetra and Rentina Junctions. The part of the highway examined is shown in figure 1.

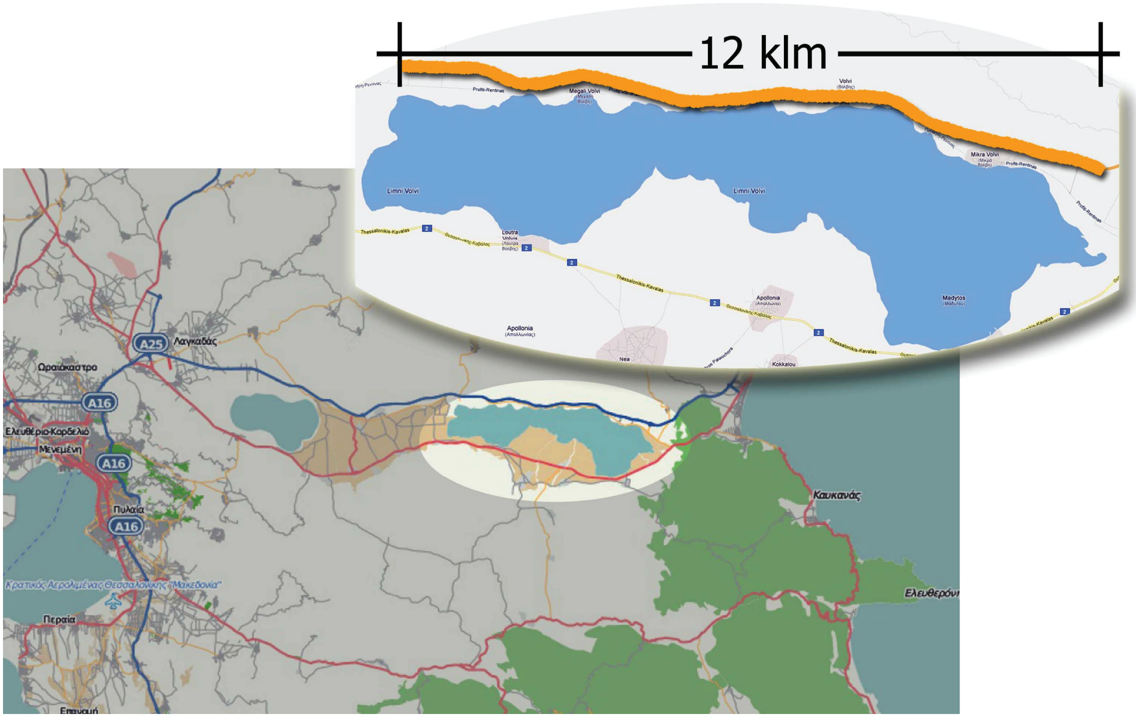

Fig. 1. Position of field testing

A total length of 15 kilometers of highway was studied. The first 12 km were constructed with EAF slag aggregates while the last 3 km were constructed with natural hard aggregates of igneous origin. The later part was constructed between May and June 2007, 11 months earlier than the respective part with EAF slag aggregates. As Egnatia is a closed highway, the traffic volume is the same between adjacent junctions i.e. at Nymfopetra and Rentina. The same environmental, traffic and weathering conditions has allowed comparison of the two surfacings.

The uniqueness of the research lies primarily in the examination of water cooled slag aggregates incorporated in the bituminous mixture in local environmental and traffic conditions. Similar performance characteristics for slags in Greece are non existent. Moreover, mechanical, physical and chemical properties of slags differ significantly at every steel plant mainly due to variability of raw material (quality of scrap metal) as well as quality of additives such as lime, carbon and other metallurgical fluxes in the steel plant. Apart from raw materials in the production process of steel which affect chemical composition, hot stage processing of slag or, in contrast, the absence of it, can alter all properties of engineering importance. Untreated slags can even present adverse behavior such as C_2S driven disintegration, extensive volume expansion or chromium/heavy metal leaching. Specific chemical composition accompanied by appropriate cooling paths can tailor slag to a certain application (Durinck, 2008). For the above reasons performance characteristics of slags must be examined, especially in cases where new specifications for highway surfacings are employed and projects of high significance are constructed. Comparison between common practice i.e. comparison between surfacing with slag and surfacing with natural hard aggregates is deemed as the appropriate method for the examination.

2. Initial Lab tests

Prior to production of the thin surfacing, EAF aggregate samples were taken by the managing body to establish conformation to the mix design. Grain size distributions for both coarse aggregate and sand is shown in Table 1. The distribution is compared to specification limits for each size. Figure 2 presents the grain size distribution for the aggregate mix with 72% coarse aggregate, 23% sand and 5% filler.

Table 1. Grain size distribution

6,3/10mm EAF Coarse Aggregate			0/2mm EAF Sand		
Sieve size (mm)	% Passing	Spec limits	Sieve size (mm)	% Passing.	Spec limits
14	100	100	14	100	–
10	92,71	99 – 85	10	100,00	–
8	57,24	37 – 62	8	100,00	–
6,3	11,35	1 – 15	6,3	100,00	–
4	1,89	0 – 5	4	99,96	100
2	1,89	–	2	96,43	99 – 85
0,5	1,06	0 – 2	0,5	37,36	40 – 60
0,063	0,00	–	0,063	10,87	11 – 16

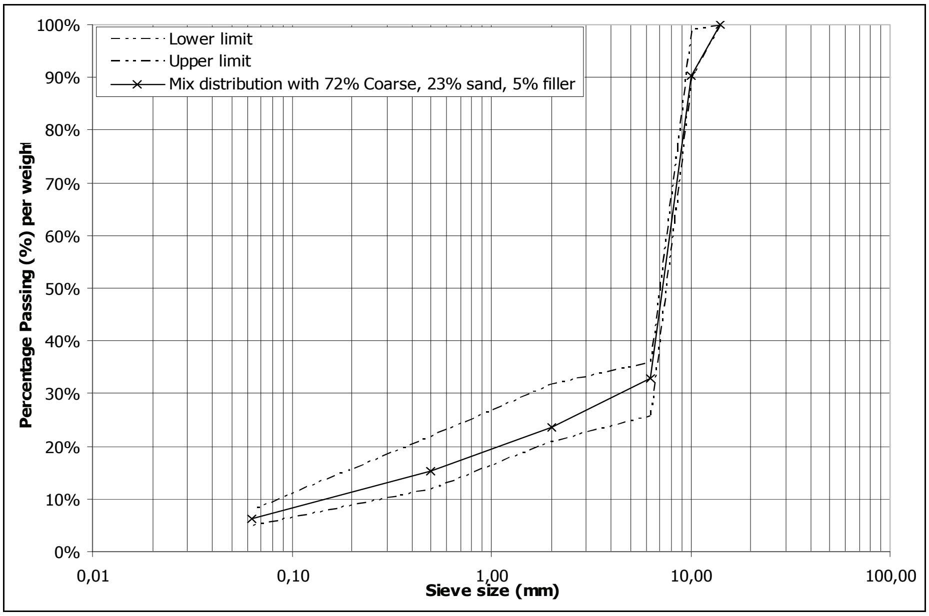

Fig. 2. Grain size distribution for mix

The managing body performed aggregate tests to identify compliance to the specification. These tests included determination of resistance to fragmentation and crushing (Los Angeles coefficient, aggregate abrasion value), fines quality for sand (methylene blue test), resistance to polishing (polished stone value), water absorption and apparent specific gravity. The results and specification limits are listed in Table 2.

Table 2. Aggregate mechanical properties

Description	Specification	Result	Specification limit
Apparent specific gravity	AASHTO T85	3,549	-
Water absorption (coarse)	AASHTO T85	1,919 %	-
Water absorption (sand)	AASHTO T85	2,190 %	-
Los Angeles	EN 1097-2	15,88%	< 22 %
Methylene Blue (MB)	ISSA TB 145	0,25	< 1
Methylene Blue (MBf)	EN 933-9	0,67	< 1
Polished stone value	BS 812 Part 114	64	> 62
Aggregate abrasion value	BS 812 Part 113	1,80	< 6
Sand equivalent	AASHTO T-176	77,0 %	> 60 %

The modified binder was tested for penetration index and softening point temperature and the results are shown in Table 3.

Table 3. Binder testing

Sample	Date	Penetration	Softening
1532	11/6/2008	51	72,8
1535	5/6/2008	51	75,2
1536	11/6/2008	54	77,4
1537	17/6/2008	54	70,6

Mix production of the mix was carried in a conventional hot mix plant. The production process with the use of modified binder did not differ from that followed in conventional mixes. The only difference was the heating temperature for the asphalt and the mix with the aggregates. These temperatures were 165-175 °C for the asphalt and 170 °C roughly for mixing.

The produced mix was transported 5 km to site where it was placed with a conventional asphalt paver. The laying temperature did not fall below 140 °C throughout the construction work.

During construction, several field tests were held by the managing company for quality assurance. For the surfacing with slag aggregates the average values for macrotexture depth were 1,80 mm and 26 seconds for permeability

3. In-situ measurements

In-situ measurements determined surface frictional properties, texture depth and permeability 30 months after construction. All data was collected in the right lane of the twin-lane highway 0,50 m from the side line i.e. which receives the highest traffic load. The measurements were taken at a distance of 1000 to 1500 m apart in both directions of the highway, eastbound and westbound.

3.1. Skid resistance value

The British Pendulum Skid Resistance Tester was used to measure skid resistance 0,50m from the side line of the highway. After leveling and zero adjustment, the slide length was calibrated in order to achieve 125mm of contact length (ASTM E 303 - 98). After proper calibration three test samples were taken on dry surface and three on wetted surface. At the same time the temperature of the test surface was recorded to adjust the readings of the pendulum (see figure 2).

Fig. 2. Positioning and calibration of Skid resistance tester

The Skid Resistance Value (SRV) for the different positions on the Egnatia highway, for both types of thin surfacing (with EAF slag and natural hard aggregates) is shown in figure 3. Measurements stated as “1st pair” and “2nd pair” refer to the measurements obtained heading towards east and west respectively.

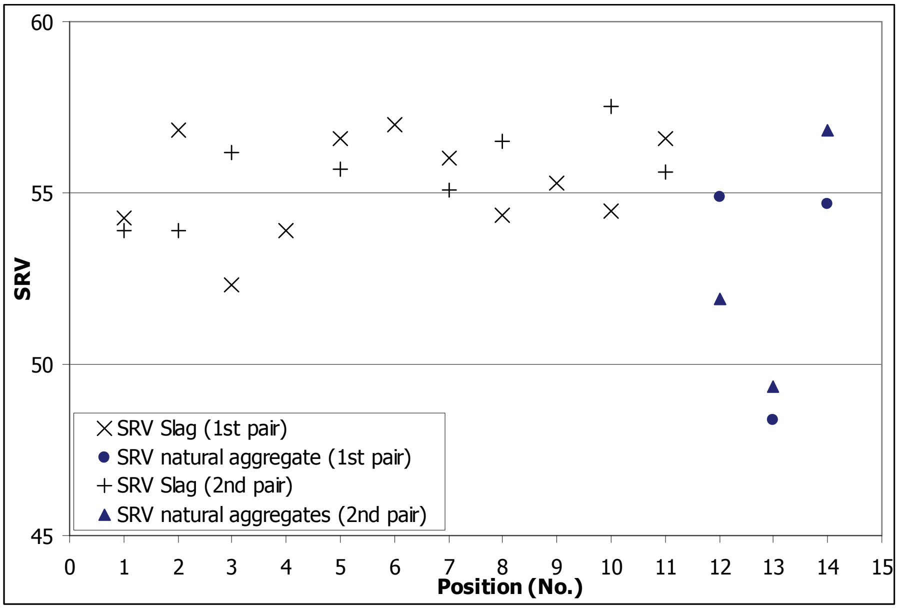

Fig. 3. SRV values for thin surfacing made with EAF and andesitic aggregate in wet conditions.

Regardless of the statistical error, the results for both types of thin surface course can be considered marginally non equal i.e. the average SRV for the EAF slag surfacing was 55,3 and for the natural hard aggregate 52,6. Both thin surfacings are above the specification limit. Even though the original PSV for the aggregates differed i.e. 64 for the EAF slag and 56 for the andesite, the found average SRV values are comparatively similar taking into account that the natural aggregate surfacing was laid 11 months prior to the EAF slag surface.

The reason behind this discrepancy may be due to the greater affinity of bituminous binder to the slag aggregate. As illustrated in figure 4, after 30 months of normal trafficking the EAF slag aggregates are still covered with a thin asphalt layer. The natural aggregate for the other surfacing had become completely exposed after 41 months. Due to this fact micro-texture is fully exposed in the later case and, despite lower PSV of the andesitic aggregate, SRVs do not differ significantly.

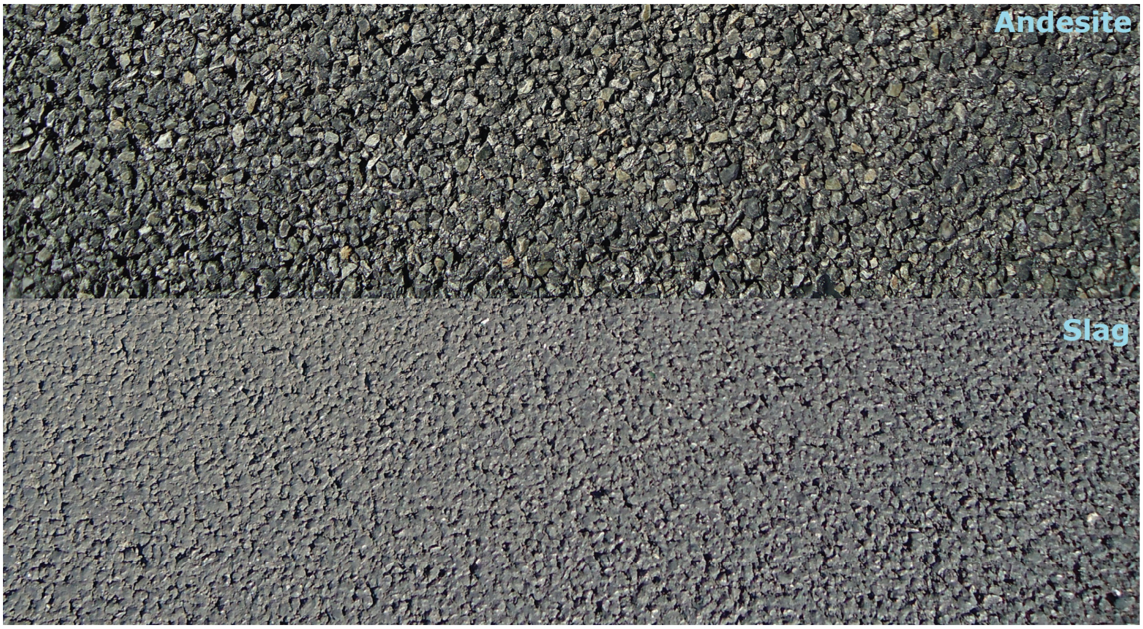

Fig. 4. Surfacings with natural aggregate of andesitic origin (top) and slag (bottom)

It is expected that once the thin bituminous film covering the slag aggregate is removed due to traffic and thus micro texture of the aggregate revealed, skid resistance values are bound to increase as observed in similar cases on the P.A.TH.E highway (Liapis, 2007). In the case of P.A.T.H.E. highway between Yliki and Ag. Konstantinos were similar measurements took place in 2004 and 2005, on a 4cm thick surfacing with slag, there was an increase in SRV of approximately 5% (Table 4). To identify the difference between the two types of aggregates the affinity of bituminous binder was determined according to EN 12697-11:2000.

Table 4. Increase in SRV in P.A.TH.E highway

a/a	Highway	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

3.2. Permeability of porous asphalt

The porosity of the thin surfacings was measured using the permeameter as described in the Belgian norms. Again the testing positions were 0,50 m from the highway sideline. The results are shown in Table 5. The permeability of the two types of surfacing layers differed significantly as the average value for permeability was 56 sec for slag and 103 sec for natural hard aggregate.

Table 5. Permeability of thin surfacings

1st pair	
Position	Permeability (in sec)
For EAF slag surfacing	
6+500	37
7+500	45
8+500	25
9+500	48
10+500	40
11+700	97
13+100	131
14+500	68
15+700	137
16+700	28
18+000	26
For natural hard aggregate	
18+500	84
19+700	83
21+000	48

2nd pair	
Position	Permeability (in sec)
For EAF slag surfacing	
8+700	26
10+000	57
12+500	45
15+000	30
17+600	60
19+700	41
20+700	53
21+800	62
For natural hard aggregate	
20+500	120
18+800	150
17+500	133

The above measurements for slag are in agreement with previous work comparing slags with basaltic aggregates (Shaopeng, 2007).

Unlike permeability, surface texture is limited by technical specifications to a minimum of 1,00 mm. Measurements for both slag and andesitic aggregate thin surfacings indicated excellent properties, fully complying with the limits set by specifications even 30 and 41 months after construction respectively (Table 6). Again the average HS values for slag layer (HS_{slag}=2,20 mm) are higher than the one with natural aggregates ($HS_{andesite}$=1,72 mm). The measurements were held according to ASTM E965-96 for measuring macrotexture depth using volumetric technique. Despite the fact that both surfacings were designed based on the same specifications which would normally result in similar characteristics, the macrotexture depth differs significantly. The difference rests in

- The mechanical and physical properties of electric arc furnace slag aggregates can be altered significantly by modifying the cooling process right after the extraction of slag from the furnace at 1630 ^oC. Water cooled EAF slag aggregates present higher microtexture. The volumetric estimation of the macrotexture depth used in the aforementioned in-situ measurements incorporate inevitably part of the higher microtexture presented by slag aggregates.
- Slag aggregates have higher water absorption. As such effective binder content is lower and, as a result, the percentage of air voids in the mix is increased. According to original Marshall tests 9,6% air voids is achieved in the mix with slag compared to 10,1% for the mix with natural hard aggregates.
- Normal traffic and environmental weathering of the two surfacings result in decrease of the macrotexture depth. High values for macrotexture depth are interpreted in smaller contact areas between tires and surfacing. These concentrated higher stresses tend to decrease by increasing the contact area and, as such, decreasing the macrotexture depth. The rate of decrease of macrotexture depth is related to PSV. As PSV is significantly higher for slag, macrotexture depth is expected to be higher for similar surfacings in the same weathering conditions compared to surfacings with aggregates of lower PSVs.
- To some extend, lower macrotexture depths for the andesitic mix is expected due to longer period of weathering which was 41 months, compared to 30 months of the slag surfacing.

Table 6. Surface texture measurements

1st pair		2nd pair	
Position	Texture depth (in mm)	Position	Texture depth (in mm)
For EAF slag surfacing		For EAF slag surfacing	
6+500	2,0	8+700	3,3
7+500	2,0	10+000	3,9
8+500	2,1	12+500	2,0
9+500	1,7	15+000	2,4
10+500	1,8	17+600	2,0
11+700	1,9	19+700	1,7
13+100	1,5	20+700	2,3
14+500	1,9	21+800	1,7
15+700	1,6		
16+700	2,9		
18+000	2,2		
For natural hard aggregate		For natural hard aggregate	
18+500	1,7	20+500	2,0
19+700	1,4	18+800	1,6
21+000	1,8	17+500	1,8

Further in-situ measurements are scheduled for March till May 2012 where indirect tensile modulus and creep modulus will be investigated. The high mechanical properties of slag in addition to low values of volume stability (0,35%) according to EN 1744-1:1998 are expected to give higher performance characteristics than similar measurements found in literature (Kok, 2008, Ahmedzade, 2009, Suer et al., 2009).

4. Conclusions

Thin surfacing asphalt made with EAF slag was compared with a similar asphalt mix made with natural hard aggregate. After 30 and 41 months trafficking respectively, the following conclusions are made:

- Initial testing and use of the EAF slag as 100% of the aggregate component was found to result in surfacing material that exhibits all of the required properties.
- Skid resistance values for both types of surfacing after 30 and 41 months trafficking meet Greek specifications.
- The SRV for the EAF slag layer is expected to increase once the thin film of binder is removed from its mirco-texture. Measurements to verify this have been scheduled.
- The permeability of the EAF slag thin surfacing was found to be significantly higher compared to the surfacing material made with the natural hard aggregate. Less aquaplaning and spraying during heavy rain conditions is expected.
- Greater macrotexture depth was found for the EAF slag thin surfacing, significantly higher to the respective one with andesitic aggregates.

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