# THE USE OF EAF STEEL SLAG IN BITUMINOUS MIXES FOR FLEXIBLE PAVEMENTS: A NUMERICAL AND EXPERIMENTAL ANALYSIS

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## ABSTRACT

The use of the metallurgical slags in substitution of the natural aggregates, is a consolidated reality in the field of the road constructions, by now from several years. Numerous international studies can document the positive performances of the mixtures realized with such marginal material, in particular for what concerns the Blastfurnace slag (BF) and the Basic Oxygen Steel slag (BOS), that are widely used in various European and extra-European countries, while is still subject of research the evaluation of the potential of the Electric Arc Furnace Steel slag (EAFS), that vice versa are finding a greater success in Italy.

Due to the increasing interest for such particular typology, the Authors presents a theoretical-experimental study on the composition, performance and mechanical characteristics, of both traditional and high performances bituminous mixtures (porous asphalt and stone mastic asphalt) made with EAFS slag, for road flexible pavements. The experimental trial has been articulated in a preliminary study of the physical-geotechnical properties of the EAF steel slag by itself, and in a mechanical characterization of the bituminous concretes, in terms of Marshall tests and Indirect Tensile Strength test, while the performance behaviour of the mixtures has been investigated with stiffness modulus tests (ITSM) at various temperatures and with permanent deformations tests (static Creep and Repeated Load Axial Test).

Focusing attention on rutting phenomena, and with the aim of evaluating the performance behaviour of mixes studied in the laboratory in service conditions, the work has been completed with FEM analysis of the deformations induced by traffic loads, using a specifically developed visco-elasto-plastic law as a constitutive model for the bituminous layers.

*Keywords: EAF slags, rutting, FEM analysis*

# 1. INTRODUCTION

The potential of marginal (or non-conventional) materials as components of road infrastructures has been studied for many years. In particular, their physical-mechanical characteristics have been ascertained, with the aim of identifying the best ways and means to use them in roads. Since 1989, PIARC has been classifying the various types of succedaneum materials, in order to contribute towards a more rigorous definition of their performance. In this way the following categories of materials have been identified, and their possible applications in the road-building sector:

a. non-traditional natural materials (rocks and soils);
b. industrial by-products (from metallurgical industry, thermal electric power stations, chemical industry);
c. wastes (mining and quarrying, municipal, industrial and demolition wastes; dredging sludges).

For the industrial by-products from metallurgical industry there have been frequent applications in road wearing courses, constituted of blast furnace (crystallized and vitrified) granulated slags (BFS) and basic oxygen steel slag (BOS), both widely used in European countries as England and France (Dunster (2002), Rockliff et al (2002)). Electric arc furnace (EAF) steel slags (Ellis & Widyatmoko (1999)), are instead more diffused in Italy.

Use of these materials is justifiable for technical, economic and ecological reasons; the sector and types of use are also accounted for by the same reasons.

The *technical* evaluations consist of the definition of the physical, chemical and mechanical properties which the material must possess to be suitable for use in road construction. These can be based on specifications, regulations and norms inherent in the choice of the materials, their characterisation and acceptance, for the identification of new design standards.

The *economic* evaluations take into account the global cost of the natural aggregate in relation to the cost of the alternative material, considering:

1. preparations necessary to render the succedaneum materials suitable for use;
2. necessity for stricter quality control of the aggregate used;
3. necessity for greater environmental protection;
4. increased maintenance of the road superstructure including marginal material;
5. consequent lower production of high-quality aggregates, with the increase of the relative market prices.

The *ecological* evaluations consider:

1. fewer areas required for storing the materials and consequent reduced environmental impact;
2. risk of groundwater pollution by elution;
3. possibility of exploiting the use of non-traditional natural materials to encourage quarrying activities, perhaps in small areas widespread throughout the territory (the increased number of points of environmental impact might not be compensated for by their smaller dimensions).

There are many possibilities for using metallurgical slag in the construction of road pavements. The electric arc furnace steel slags described in this paper are among the more interesting materials for application in the building sector.

## 2. MATERIALS USED

The performance was studied of three types of bituminous mixtures for road construction:
1. Stone Mastic Asphalt (SMA);
2. Wearing Course Asphalt Concrete (WCAC);
3. Porous Asphalt (PA).

The mixes were produced with natural crushed limestone aggregate, basalt, limestone filler and two types of Electric Arc Furnace Steel Slag (EAF: Type P and Type B, from different suppliers), using: “hard” modified bitumen for SMA and PA mixes; normal bitumen (50/70 dmm pen) for WCAC.

Table 1 reports the grading composition of the mixes and proportions of the components. The overall EAF slag content is equal to 59% for SMA, 30% for WCAC and 39% for PA.

**Table 1 Mix composition: aggregate type and particle size fraction**

| Mixes composition | Fraction | Quantity (%) | | |
|---|---|---|---|---|
| | | SMA | WCAC | PA |
| **Crushed Limestone** | 0/5 | - | 15 | - |
| | 5/10 | - | 45 | - |
| | 10/15 | 30 | - | - |
| **Basalt** | 0/5 | - | - | - |
| | 5/10 | - | - | 11 |
| | 10/15 | - | - | 45 |
| **EAF Type P** | 0/5 | - | 10 | - |
| | 5/10 | - | 5 | - |
| | 10/15 | - | - | 10 |
| **EAF Type B** | 0/5 | 12 | 5 | 13 |
| | 5/10 | 32 | 10 | 4 |
| | 10/15 | 15 | - | 12 |
| **Filler** | | 11 | 10 | 5 |

The limestone aggregate was characterised by an Equivalent in Sand of 70%, Los Angeles Coefficient of 23.5%, Accelerated Polishing Test Coefficient of 0.43. The basaltic aggregate was characterised by a Los Angeles Coefficient of 13-13.5%, Accelerated Polishing Test Coefficient of 0.41.

The slag was made available in 3 particle sizes: 0/5, 5/10, 10/15 mm. The EAF Type P Slag was characterised by an Equivalent in Sand of 96%, Los Angeles Coefficient of 24%, Accelerated Polishing Test Coefficient of 0.50. EAF Type B Slag had an

Equivalent in Sand of 66%, Los Angeles Coefficient of 15.5-21%, Accelerated Polishing Test Coefficient of 0.50.

By Italian Law, the above-mentioned slags are “non-hazardous, special non-toxic and non-noxious” refuse. They are solid material, greyish in colour and odour-free.

In terms of composition of both slags, the Italian CNR-IRSA test demonstrates major contents (evaluated in mg/kg) of chromium, zinc and copper.

## 3. MIX-DESIGN OF THE ASPHALT MIXTURES

The mixes were produced using, with appropriate bitumen, aggregates of various types, the overall grading curve of which was constructed starting from the individual particle sizes, optimised in accordance with the grading envelopes included in different Specifications (ANAS – Italian Road Agency, motorway companies, Italian Ministry of Transport and Infrastructures).

For each of the 3 mixes, different mixtures were analysed, in which, having defined the type of aggregate, grading composition and type of bitumen, the amounts of binder were varied at intervals of 0.5% on the weight of the aggregate (within specific ranges for each of the 3 mixes: 4.5 - 6% for WCAC and PA, 5.5 - 7% for SMA).

The classic Marshall procedure was used for determining the optimal binder content, along with the indirect tensile strength test (indirect traction). The mixes characterised by maximum Marshall Stability and maximum Indirect Tensile Strength at 25 °C were considered optimal.

Table 2 reports the results of the optimisation. All the mixes have satisfied the respective requisites according to the Italian standards, so are suitable for use in road-building. The result of the test of indirect tensile strength was particularly satisfactory, with strength values always above 1 N/mm$^2$.

**Table 2 Marshall test and indirect tensile test**

| Mix | Opt. Bitumen content [%] | Marshall Stability [daN] | Marshall Stiffness [daN/mm] | Ind. Tensile Strength [N/mm$^2$] |
|---|---|---|---|---|
| **SMA** | 6.0 | 1,024 | 351 | 1.36 |
| **WCAC** | 5.0 | 1,221 | 435 | 1.38 |
| **PA** | 5.0 | 626 | 238 | 1.15 |

## 4. DYNAMIC CHARACTERISATION OF THE MIXTURES

Dynamic tests were done to determine the Stiffness Modulus on the mixtures identified as optimal by the mix design, following the indications in the EN 12697 – 26 standard, in the indirect tensile strength configuration (IT-CY), with peak horizontal deformation set at 5 µm, load rise-time of 124 ms, corresponding to a frequency of approx. 2 Hz, and test temperatures of 0 °C, 10°C, 20 °C and 30 °C.

The results are presented in Table 3. The dense graded mixtures registered higher moduli than the porous one; in particular, SMA exceeded 18,800 MPa at 0 °C and 2,500 MPa at 30 °C.

The study has been completed by means of the Repeated Load Axial Test (RLAT) with confinement, following the specifications of EN 12697-25 standard (Method A).

For each optimised mixture, specimens of 150 mm in diameter and 60 mm in height, were tested with a cyclic axial pressure applied using an upper platen 100 mm in diameter. In this way, the specimen is divided into a “virtual” internal cylinder with a diameter of 100 mm, directly loaded by the overhead platen, and a “virtual” cylindrical ring of surrounding material with a radius of 25 mm, not axially loaded, which develops an effective confinement action that impedes the lateral expansion of the sample.

**Table 3 Stiffness modulus @ 124 ms**

| Mix | Stiffness Modulus (MPa) | | | |
|---|---|---|---|---|
| | **0°C** | **10°C** | **20°C** | **30°C** |
| **SMA** | 18,862 | 11,846 | 5,858 | 2,540 |
| **WCAC** | 15,040 | 9,261 | 4,782 | 1,991 |
| **PA** | 13,321 | 8,989 | 3,340 | 1,681 |

The concept is that a stress–strain condition is reproduced, similar to that in situ, where the material surrounding the area of pavement directly bearing the vehicle tyres exercises a confining action. The EN standard prescribes 3,600 pulses of a 100 kPa stress, with loading and unloading times fixed at 1 s, at a temperature of 40 °C.

Figure 1 reports the evolution of the creep curves during the test conducted; the temporal evolution of the axial strain, for all the mixes, is that typical of visco-elasto-plastic materials: a first phase with a decreasing creep rate, and a second with a constant creep rate can be clearly distinguished. The usual third phase, which is characterised by a sudden increase in the strain rate until the rupture of the specimen, cannot be evidenced because the test is carried on during 2 hours (according to the standards).

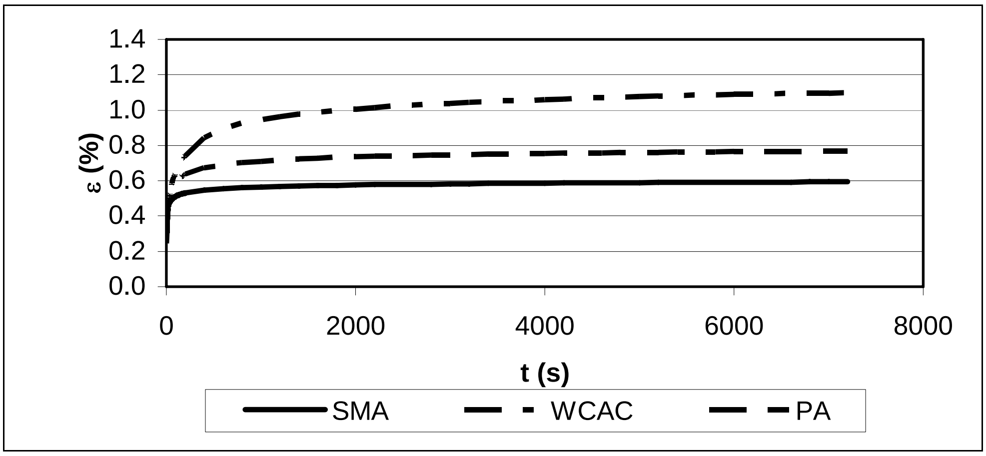

**Figure 1 RLAT @ 40°C. Longitudinal strain *vs* time**

Table 4 reports the RLAT results in terms of Creep Modulus and creep rate, determined following the indications of the EN standard. The aggregate with gap grading, higher EAF steel slag content and modified bituminous matrix, allowed the SMA and PA to display clearly better performances in terms of Creep Modulus than traditional asphalt for a wearing course, and to register final creeps of 46% and 30% lower than traditional asphalt, respectively. The creep rate of the SMA was indeed almost 5 times lower than that of the WCAC.

**Table 4 Creep modulus and creep rate**

| **Mix** | **Cumulative strain (με)** | **Creep Modulus (MPa)** | **Creep rate (με /s)** |
|---|---|---|---|
| **SMA** | 5,944 | 16.82 | 0.04 |
| **WCAC** | 10,974 | 9.11 | 0.19 |
| **PA** | 7,685 | 13.01 | 0.07 |

## 5. NUMERICAL ANALYSIS ON THE RUTTING BEHAVIOUR

To complete the investigation, the tendency of the mixes with EAF steel slag to develop permanent deformation of a plastic and visco-plastic type was further tested using a series of finite element numerical analyses aimed at quantifying the amount of rutting caused by the static application of traffic loads for different lengths of time.

Using a general purpose finite element code, a flexible pavement was modelled subject to the loading action transmitted by a pair of twinned wheels with a single axis of 120 kN.

Whereas a constitutive law of the elastic type was used for the base course, road base, sub-base and subgrade, a visco-elasto-plastic model developed ad hoc was used for the wearing course, and implemented in the FEM code by means of software of using constitutive laws defined by the user.

This is an energetic approach, of general validity for materials with visco-elasto-plastic behaviour and thermodynamically congruent. Taking the approach proposed by Simo & Hughes (1997), based on the Helmholtz free energy definition for a visco-elastic material, taking into account the thermodynamic constraints that the system must satisfy, it was also possible to consider the plastic and visco-plastic deformational contribution through the introduction of a suitable yield criterion.

The model is characterised by a parameter for the elastic response (Elastic Modulus $E^0$), a pair of parameters for each viscous process introduced (relative stiffness $\gamma_i$ and relaxation times $\tau_i$) and a further pair for the plastic component (yield strain $\varepsilon_y{}^0$ and hardening modulus $K$). Having introduced four viscous processes to reliably obtain the various relaxation phases of the material, a total of eleven constitutive parameters were thus associated to the model. The model calibration, on the basis of the real deformational response of the considered mixes, necessitated a preliminary experimental-numerical analysis, which was conducted following an innovative procedure.

The formulation of the constitutive visco-elasto-plastic law is fully described in Pasetto & Baldo (2007), while the salient elements of the model calibration and validation are reported below, with reference to asphalts produced with EAF steel slag. This if followed by details of the FEM analyses conducted on flexible pavements with the wearing course composed of SMA, WCAC, PA mixes.

## 5.1 Calibration of the Constitutive Model

For the determination of the constitutive parameters, the data obtained from static creep tests at free lateral expansion on Marshall specimens were elaborated, using a numerical technique, based on the least square curve fitting method and the Levenberg - Marqardt optimisation algorithm (Pasetto & Baldo, 2007).

For each mixtures, a set of four tension levels was selected (100 kPa, 200 kPa, 300 kPa, 400 kPa), so that the deformational response of the asphalt could be studied in a representative way, with a loading time of 500 seconds and unloading time for visco-elastic recovery set at 1500 seconds. The values of the constituent parameters of the mixtures studied are summarized in Table 5.

**Table 5 Constitutive parameters value @ 40°C**

| **Constitutive parameters** | **Mixtures** | | |
|---|---|---|---|
| | SMA | WCAC | PA |
| **$E^0$ (MPa)** | 1.23564E+02 | 1.16891E+02 | 1.34406E+02 |
| $\varepsilon_v^0$ | 9.62414E-04 | 9.04009E-04 | 7.58816E-04 |
| **K (Mpa)** | 1.36374E+01 | 1.03750E+01 | 1.57553E+01 |
| $\gamma_1$ | 6.85128E-02 | 1.00367E-01 | 9.43214E-02 |
| $\tau_1$ **(s)** | 3.71580E-01 | 2.68649E-01 | 1.00154E+00 |
| $\gamma_2$ | 5.32447E-02 | 5.82493E-02 | 1.01596E-01 |
| $\tau_2$ **(s)** | 9.09078E+00 | 7.57007E+00 | 1.28911E+01 |
| $\gamma_3$ | 1.00145E-03 | 1.00001E-03 | 2.22196E-02 |
| $\tau_3$ **(s)** | 3.00000E+01 | 3.00008E+01 | 3.76687E+01 |
| $\gamma_4$ | 1.85925E-01 | 1.78684E-01 | 2.05924E-01 |
| $\tau_4$ **(s)** | 6.07430E+02 | 6.11128E+02 | 5.26373E+02 |

The different composition of the mixtures, in terms of both aggregate and as regards the binding phase, translates into a more or less accentuated differentiation of the values of the constitutive parameters, depending on whether those elasto-plastic or those viscous are considered. A certain similarity is found in the relaxation times and relative stiffness of the medium and long-term viscous processes (processes 3 and 4) for the SMA and PA mixes, because of the identical type of binder used. Variable differences of between approximately 6% and 31%, as regards the elasto-plastic parameters, anyway identify the different behaviour of the two mixes in a precise way. The WCAC is instead very different from the other two asphalts, in the whole range of constitutive parameters.

## 5.2 Evaluation of the Constitutive Model

In order to verify the capacity of the model to represent the salient points of the deformational behaviour of the three mixtures studied (qualitative trend, maximum and permanent strains), the methodology developed by Pasetto & Baldo (2007) has been used; therefore, numerically static creep tests at 40 °C were simulated, with a stress of 100 kPa, characterized by load application and recovery times both set at 3600 s, with free lateral expansion, using traditional Marshall specimens.

Figure 2 presents the result of the validation, while Tables 6 summarize the results for all the mixtures, in terms of maximum and permanent strain; the differences between the visco-elasto-plastic model (VEP) and experimental data are also indicated.

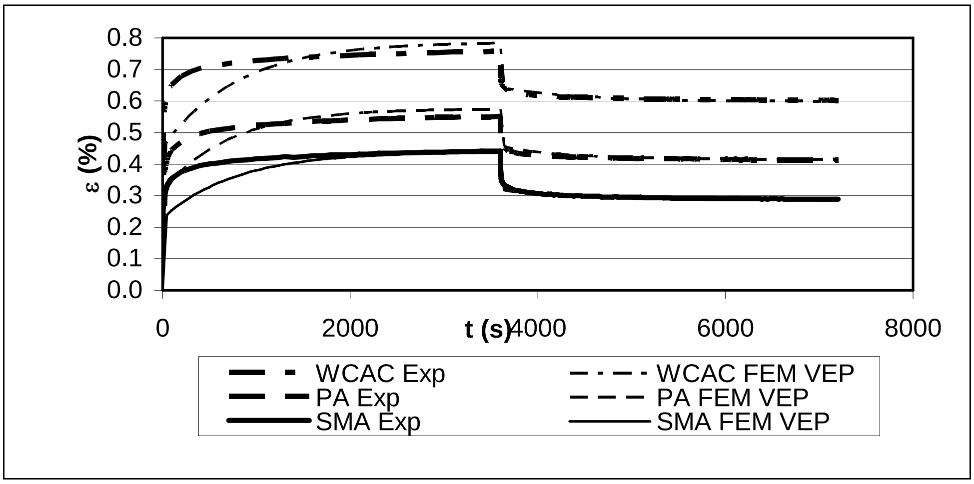

**Figure 2 Static creep @ 40°C. Longitudinal strain *vs* time**

**Table 6 Model validation: static creep @ 40°C**

| **Mix** | **Type of data** | $\varepsilon^{max}$ **(%)** | $\varepsilon^{p}$ **(%)** | $\Delta\varepsilon^{max}_{VEP-EXP}$ **(%)** | $\Delta\varepsilon^{p}_{VEP-EXP}$ **(%)** |
|---|---|---|---|---|---|
| **SMA** | VEP | 0.4341 | 0.2862 | -1.83 | -0.87 |
| | Exp | 0.4422 | 0.2887 | | |
| **WCAC** | VEP | 0.7834 | 0.5992 | +3.23 | -0.51 |
| | Exp | 0.7589 | 0.6023 | | |
| **PA** | VEP | 0.5737 | 0.4139 | +4.04 | +0.07 |
| | Exp | 0.5514 | 0.4136 | | |

The qualitative trend of the curves of the VEP model is similar in general to that of the experimental ones for all the mixes. The maximum difference is just over 4% for the maximum strain, and always under 1% in terms of permanent strain.

The experiments done to support the numerical analyses confirmed what emerged from the RLAT tests. Also in the case of static creep, the lower deformations are recorded for the SMA, the maximum ones for the traditional wearing course. The porous asphalt is again in an intermediate position between the two close textured mixes. Observation of the deformational behaviour of the asphalts also in the unloading phase of the experimental creep test allowed the visco-elastic recovery to be quantified as 25.87%, 33.32% and 53.19% for the WCAC, PA and SMA respectively.

## 5.3 FEM Analysis

The analysed superstructure is a flexible pavement, composed of a wearing course of 40 mm, base course of 60 mm, road base of 150 mm, and sub-base in granular unbound mixture of 250 mm; for the subgrade, a depth of 400 mm was considered sufficiently representative, having verified *a posteriori* with the FEM analysis, that the stress-strain state was indeed negligible. Given the double-symmetry of the problem, a quarter of the global structural system was studied. The model, with dimensions of 300x300 mm, was therefore discretised with 31,320 *wedge* elements, for a total of 17,342 nodes. The mesh was thicker around the loading area, as well as for the wearing course and base course, so as to reliably determine the stress-strain state and obtain the stress gradients applied by the load. The mesh thinned out progressively for the road base, sub-base and subgrade.

As regards constraints, at the nodes of the lower surface of the subgrade layer, an annulling of the vertical displacements was imposed. At the interface between the various layers a condition of perfect adhesion was hypothesised.

As already mentioned, the analysis was done with reference to a pair of twinned wheels with a single axis of 120 kN. Each wheel uniformly distributes the 30 kN load on a circular impression with a radius of 11 cm. The load application was static, in the form of a constant pressure of 800 kPa (the maximum value allowed by the Italian Highway Code), acting perpendicularly to the pavement surface.

Five different times of load application were considered: 120 s, 300 s, 600 s, 1800 s, and 3600 s. In each case the rut depth was evaluated after a relaxation time equivalent to the corresponding load application period. The time range considered is intended to cover a range of service conditions, varying from a brief stop at a red traffic light to a more or less prolonged stay in a parking area.

As regards the materials, a visco-elasto-plastic model was used for the wearing course, assuming, for the constitutive parameters, the values obtained in the calibration phase for the three mixes with EAF steel slag, and using a Poisson coefficient of 0.35 for all of them. A linear elastic model was used for the other layers, characterised by values of Elastic Modulus and Poisson coefficient equal to 400 MPa and 0.35 for the base course, 300 MPa and 0.35 for the road base, 200 MPa and 0.4 for the sub base, 90 MPa and 0.4 for the subgrade, respectively.

Figure 3 shows the temporal evolution of deformational phenomenon beneath the loading area, with reference to the case of 3,600 seconds. Similar trends were obtained for the other loading times. Tables 7, 8 and 9 report the maximum and residual values of the rut depths, not only as regards the visco-elasto-plastic model, but also with reference to a visco-elastic model (VEL), obtained as a specific case of the VEP one, imposing a very high yield tension, so as not to allow the material to enter the plastic field.

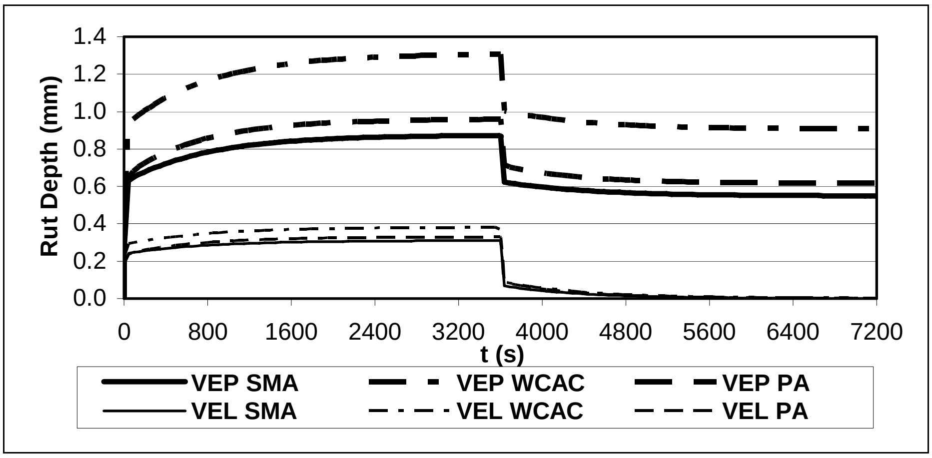

**Figure 3 FEM analysis @ 40°C. Ruth depth *vs* time**

**Table 7 FEM analysis: SMA wearing course**

| Time<br>(s) | Type of data | Rut depth$^{max}$<br>(mm) | Rut depth$^{p}$<br>(mm) |
|---|---|---|---|
| **3600** | VEP | 0.8672 | 0.5498 |
| | VEL | 0.3087 | 0.0007 |
| **1800** | VEP | 0.8445 | 0.5404 |
| | VEL | 0.3018 | 0.0062 |
| **600** | VEP | 0.7543 | 0.4940 |
| | VEL | 0.2744 | 0.0174 |
| **300** | VEP | 0.7008 | 0.4596 |
| | VEL | 0.2586 | 0.0152 |
| **120** | VEP | 0.6559 | 0.4223 |
| | VEL | 0.2456 | 0.0085 |

Again referring to the simulation of one hour, the permanent strains always show values of less than a millimetre. The strain rate, calculated in the final 600 seconds of loading, is also extremely limited for all the mixes: 3.34E-06 mm/s, 11.90E-06mm/s, 6.99E-06 mm/s, for the pavements with the wearing course in SMA, WCAC and PA, respectively. This can also be appreciated from a qualitative point of view: Figure 3 shows that, at the end of phase I, the creep curves have an asymptotic trend that is substantially horizontal, indicating little further development of permanent strains.

A comparison between the values calculated by the VEP model and those of the VEL, which underestimates the peak strain by up to three times, depending on the type of mix chosen for the wearing course, clearly demonstrates how inappropriate an analysis of the maximum strains is in visco-elastic ambits. For obvious reasons, the VEL model cannot reliably quantify permanent strains.

**Table 8 FEM analysis: WCAC wearing course**

| Time (s) | Type of data | Rut depth$^{max}$ (mm) | Rut depth$^{p}$ (mm) |
|---|---|---|---|
| **3600** | VEP | 1.3065 | 0.9062 |
| | VEL | 0.3702 | 0.0010 |
| **1800** | VEP | 1.2657 | 0.8851 |
| | VEL | 0.3589 | 0.0083 |
| **600** | VEP | 1.1317 | 0.8004 |
| | VEL | 0.3338 | 0.0232 |
| **300** | VEP | 1.0422 | 0.7443 |
| | VEL | 0.3129 | 0.0188 |
| **120** | VEP | 0.9317 | 0.6681 |
| | VEL | 0.2826 | 0.0112 |

**Table 9 FEM analysis: PA wearing course**

| Time (s) | Type of data | Rut depth$^{max}$ (mm) | Rut depth$^{p}$ (mm) |
|---|---|---|---|
| **3600** | VEP | 0.9579 | 0.6165 |
| | VEL | 0.3286 | 0.0006 |
| **1800** | VEP | 0.9342 | 0.6077 |
| | VEL | 0.3217 | 0.0068 |
| **600** | VEP | 0.8268 | 0.5509 |
| | VEL | 0.2898 | 0.0222 |
| **300** | VEP | 0.7577 | 0.5046 |
| | VEL | 0.2693 | 0.0204 |
| **120** | VEP | 0.6988 | 0.4566 |
| | VEL | 0.2519 | 0.0122 |

Lastly, for the road pavement with a wearing course in SMA, it can be seen that 77% of the permanent strain at one hour had already been reached after just 2 minutes, and 90% after 10 minutes. The deformational phenomenon therefore mostly develops very rapidly, remaining on values very slightly higher for the longer loading times. The other two mixes gave basically similar results.

## 6. CONCLUSIONS

The experiments have verified that the use of waste material from steel production in the lithic skeleton of asphalts is a technically satisfactory option that fulfils the spirit of the “Zero Waste” target that the iron and steel industry has been aiming for in the last decade.

The experimental results are decidedly satisfactory for all the mix designs with the slag, with good values of Marshall Stability and Indirect Tensile Strength.

The limited axial deformation developing during the RLAT, lead to the conclusion that the mix designs have little likelihood of developing excessive permanent deformations.

The dynamic analysis at low frequency, representative of conditions with slow channelled traffic, has further confirmed an extremely positive overall performance of the mixtures.

The results of the SMA stand out, which is also the one with the highest slag content, its lithic skeleton being composed of 59% of this material.

The FEM simulations conducted have demonstrated the good resistance to permanent strain of pavements with a wearing course in asphalt with EAF steel slag.

The numerical analysis done with the VEL model has lastly allowed the limitations in the study of rutting phenomenon to be displayed.

## REFERENCES

Dunster, A.M. (2002) - “The use of blastfurnace slag and steel slag as aggregates” - *Proc. 4th European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements,* Nottingham, (UK), pp. 257-260.

Rockliff, D., Moffett, A.., Thomas, N. (2002) - “Recent developments in the use of steel (BOS) slag aggregates in asphalt mixtures in the UK” - *Proc. 4th European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements*, Nottingham, (UK), pp.251-255.

Ellis, C., Widyatmoko, I. (1999) - “Performance and durability aspects of asphalts incorporating electric arc furnace steel slag aggregates designed for use in thin pavement surfacings” - *Proc. 3rd European Symposium on Performance and Durability of Bituminous Materials and Hydraulic Stabilised Composites,* Leeds, (UK), pp. 195-204.

Pasetto M. & Baldo N. (2007) – “A theoretical-experimental visco-elastic-plastic analysis of the Mastic Asphalt” - *Proceedings International Conference on Advanced Characterisation of Pavement and Soil Engineering Materials***,** Athens, Greece, [cd-rom].