Use of Marginal Materials in Road Constructions: Electric-Arc Furnace Slag

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Synopsis

Electric-arc furnaces are one of the most common ways followed by steelworks for the steel production. In Italy, they generate some two tons of waste materials per year; from an international point of view, only a minor part of these wastes is reused as marginal materials. In road construction the recycling of electric-arc furnace slag is very interesting because of the significant environmental considerations connected with this matter.

The Authors propose the use of EAF slag for the stabilization of soils, giving at the same time a complete survey of the percentages of use and of the deriving benefits.

Therefore, chosen a study soil, three different binary mixes soil-EAF slag are analyzed with slag percentages equal to 10%, 15% and 20%, and finally the 20% percentage is considered the best.

Subsequently, the study considers two additional ternary mixtures, soil-EAF slag-hydrated lime, with optimal percentage of slag equal to 20% and hydrated lime equal to 2% and 4%. The analysis of the five admixtures prepared, from the point of view of constipation tests, CBR tests in optimal conditions and after water imbibitions and compression test with free lateral expansion, allowed an investigation on the performances of each of them and the conclusion on useful design indications for the use of such slag in road constructions.

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Most of the steel produced in Italy and in Europe every year comes from electric-arc furnaces (EAF) - (Fig.1a) which, together with blast furnaces (Fig.1b) represent the main production systems used by Italian steelworks. Electric-arc furnaces produce in our country about 2 million tons of waste per year. Apart from discharging the material into dumps, a certain percentage of this sub-product is manipulated, with respect to the environmental standards in force, so that it could assume environmental features for a road infrastructures use. The products of the slag manufacturing are generally divided into three different particle sizes: 0-4mm, 4-8mm and 8-12mm, amongst which the last two are generally used for bituminous binders.
This investigation aims at the technical verification of the possible use of the EAF slag with the size 0-4mm for the cohesive and not cohesive soils stabilization with silt and/or clay matrix.

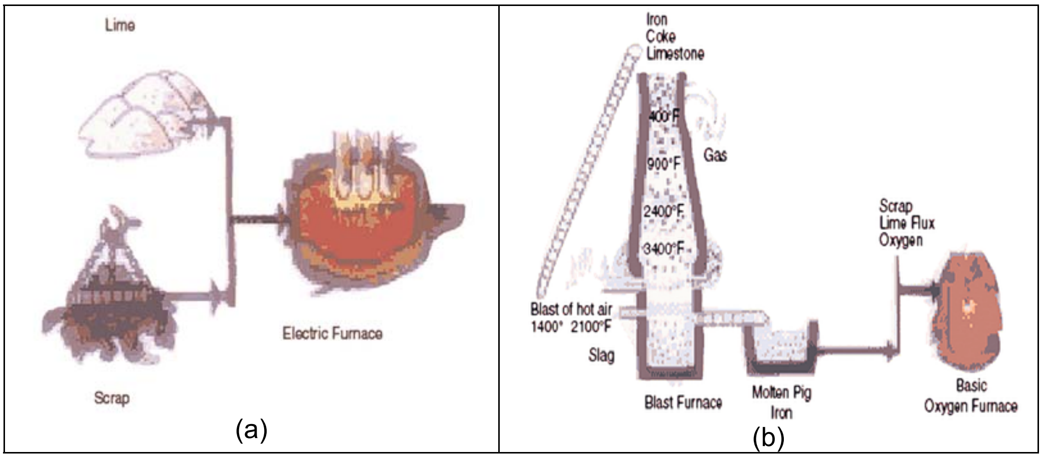

Figure 1: (a) Electric furnace and (b) blast furnace

ELECTRIC ARC FURNACE SLAG (EAF)

Nowadays in the EU 60% of the EAF slag is addressed to dumps (60 millions tons), with strong environmental effects. The direct exploitation of this sub-product for the obtainment of second quality raw materials reaches the goal of reducing the exploitation of natural sources and of managing potential waste materials.
The environmental norms in civil engineering say that a material has a limited impact on environment if its use technique reduces the exploitation of natural resources, it is an alternative to the dump discharge and does not cause negative alterations of the environment where it is included.
In the following paragraphs the production and transformation processes of the EAF slag are analysed along with the aspects connected with the chemical composition of them, referring also to the indications found in literature on the subject.

Production and transformation

The EAF slag is produced as a consequence of the quick cooling of the superficial ad oxidized liquid phase present in the electric-arc furnaces, during the passage from 1300°C to room temperature.
The solidification in blocks occurs in the air, and this process, sometimes, in accelerated by water sprinkles.
In this way a certain amount of free lime can be entrapped into the blocks, potentially subjected to hydration and carbonation. These inclusions can cause inhomogeneous expansions of the material and a consequent segregation.
The process of transformation of steelworks slag in a product which can be used in road constructions, starts with its stabilization. For this reason the EAF slag is subjected to an adequate seasoning, which varies also with the production size, during which the stabilization of the unbound calcium oxide and magnesium oxide fraction is naturally realized.
In order to avoid the swelling of slag, the free lime percentage present should be smaller than 2-3%.
At the end of the seasoning process, the material can still include a steel-iron part which can be easily extracted by means of a magnetic device and pre-crushing phases.

The production process of the EAF slag considers, after seasoning, a double crushing phase performed firstly with a jaw crusher, then completed with a cone one. Finally, with the following sieve analysis phases the different particle sizes are produced.
The final product is generally divided in 3 different sizes: sand and grit (0-4mm), grit (4-8mm) and grit and gravel (8-12mm), whose mean particle size is reported in Fig.2.

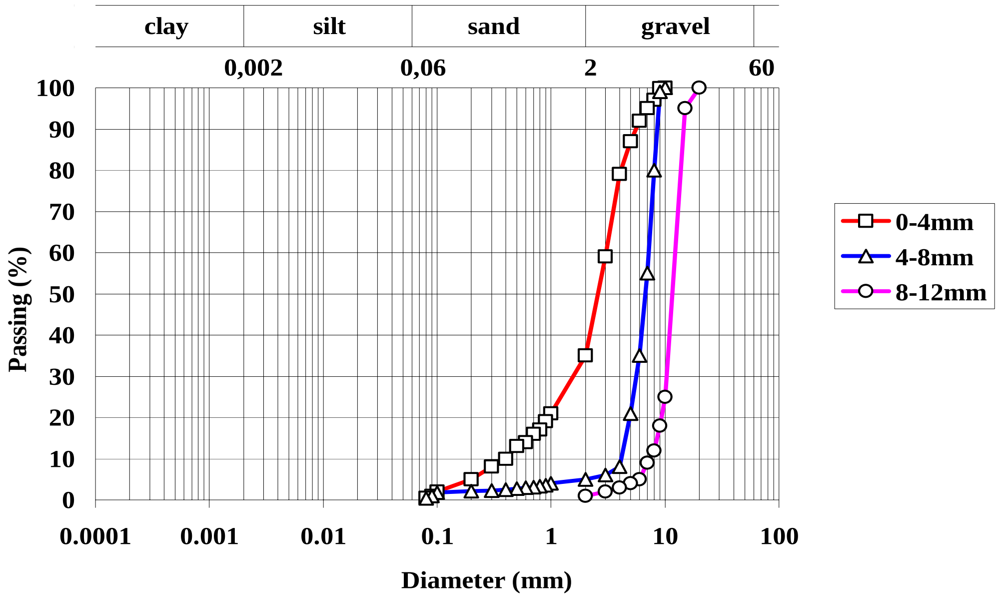

Figure 2: Sieve analysis of the commercial sizes of EAF slag

Chemical composition

The chemical composition of the slag and of its derivates is made of calcium, ferric, aluminium, magnesium and siliceous oxides, which in a whole reach on average the 90% of the weight of the material (Tab.1).
The main component form a quantitative point of view is steel, and this influences some physical-mechanical characteristics, as the absolute gravity which varies from 33.0 to 40.0 kN/m^3. The steel presence into the slag is mainly due to the action of the oxidizing surround of the electric-arc furnace on the liquid metallic bath This element is present as Fe^{2+} (3.26%-25.08%) and as Fe^{3+} (Fe_2O_3, 1.71%-22.4%) or as Fe0 (0.22%-0.6%).
Some elements as Ca or Si derives from raw materials added to the bath (additives), others from the attack of the liquid bath to the firebricks of the furnace (Mg) and some others are impurities connected with the quality of the ferrous wreck used (Cr, Ti, Cu, etc.).
The steelwork slag are to be considered as igneous rocks which are originated from volcanoes eruptions. From a mineralogical point of view the slag is mainly made of larnite ($2CaO-SiO_2$), which is a solid solution of $2CaO-Fe_2O_3-2CaO-2Al_2O_3-Fe_2O_3$ and wustite (solid solution with variable composition based on FeO, CaO, MgO, MnO).
To minor extents a bivalent solid solution of metallic ions (Ca, Fe, Mn, Mg) and alite ($3CaO-SiO_2$) is present. Wustite and ferrite solidify at lower temperatures than those of silicates and constitute the interstitial material between silicates.

Environmental compatibility

The slag produced by the steelwork industry is seen, according to the Italian Standards, as a not dangerous waste material (Cfr. D.M. 05/02/1998 point 4.4) and can be disposed or saved after authorization.
If the recover activity aims at the construction of embankments, subsoil and road ballasts, so when the slag touches the ground, it will have to pass the cession test of the annex 3 of D.M. 05/02/1998.
From the point of view of disposal or use of rehabilitated materials touching the ground, there are some problems on the soil, ground and water pollution possibilities because of the infiltration due to rainfalls.
Amongst the most relevant polluting substances, which can be present into the infiltrating stuff, heavy materials are to be considered. For these elements the total quantities present into the waste are not as important as their mobile fractions, the finest ones, which depend on several chemical and chemical-physical conditions such as pH, the substance composition, the redox potential, etc.
The limitations to the cession test imposed by the Italian Standards are widely respected by EAF slag: for this purpose Tab.2 is reported with both the D.M. 05/02/98 limits and the values obtained from the 8 eluations stages provided for the same laws on the EAF slag used for the investigations.

Table 1: Chemical composition of the EAF slag

Typical Chemical Constituents			
Tot Fe	10-32 %	TiO_2	4-12 %
CaO	25-45 %	P_2O_5	0.01-0.6 %
Free CaO	≤ 4 %	Na_2O	0.4-0.5 %
SiO_2	10-18 %	K_2O	0-0.2 %
Al_2O_3	3-8 %	S	0-0.2 %
MgO	4-13 %	C	0-0.5 %

Table 2: Mean values of the cession tests on the EAF slag

	Limits D.M. 05/02/1998	Mean values
Cianydes g/l	50	< 40
COD mg/l	30	< 30
Chlorides mg/l	200	5,5
Nitrates mg/l	50	4,9
Fluorides mg/l	1.5	< 1.5
Sulphates mg/l	250	50.5
Tot Chromium µg/l	50	20
Zinc mg/l	3	0.16
Arsenic µg/l	50	< 8
Barium mg/l	1	0.7
Beryllium µg/l	10	< 4
Cadmium µg/l	5	< 4
Cobalt µg/l	250	< 40
Mercury µg/l	1	< 1
Nickel µg/l	10	< 8
Lead µg/l	50	14
Copper mg/l	0.05	< 0.05
Selenium µg/l	10	< 8
Vanadium µg/l	250	170

The recovery activity of the dross for environmental purposes, seen as a reconstruction activity for the superficial asset of the territory in which the steelwork sub-product is subjected to an intimate mixing with the natural ground, has further limitations imposed by the D.M. 25/10/1999 from the point of view of the decontamination of the polluted ground.
In this case the prescriptions provide for the respect of further limitations connected with the sieve particles <2mm. Moreover, also this limitation is generally always respected for EAF slag.

THE INVESTIGATION

In the experimental phase three binary admixtures performance were evaluated, made of natural reference ground with three different weight dosages of the slag, respectively 10%, 15% and 20%. Subsequently, once the optimal percentage was assessed to be 20%, two further ternary admixtures were manufactured, with constant slag dosage of 20% and two different weight percentages, referred still to the silt ground, of hydrated lime equal to, respectively, 2% and 4%.

The reference natural ground

The reference natural ground is silt with sandy clay according to sieve analysis performed after sieve and sedimentation (Fig. 3).
The water limit WL is equal to 27.17%, while the plastic one WP is 18.19%, and therefore the plasticity index IP is equal to 8.98%.
Referring to Casagrande's classification, the examined ground is included into the area called soil without cohesion.

The calculation of the group index IG has given a value of 8. The Proctor constipation trials (AASTHO Mod.) performed on the reference ground allowed a determination of the optimum humidity value, equal to 10.50%, in presence of a maximum dry density of 1,98g/cm^3 (Fig.4).
At the end the mechanical characterization, executed by the CBR test after 7 days of seasoning, was reduced to 26.15% which did not change at 28 days seasoning but reduced to 3.71% after 4 days under water in presence of a swelling equal to 1.70%. From the just mentioned values it is possible to derive the reduced possibility of road use for this ground.

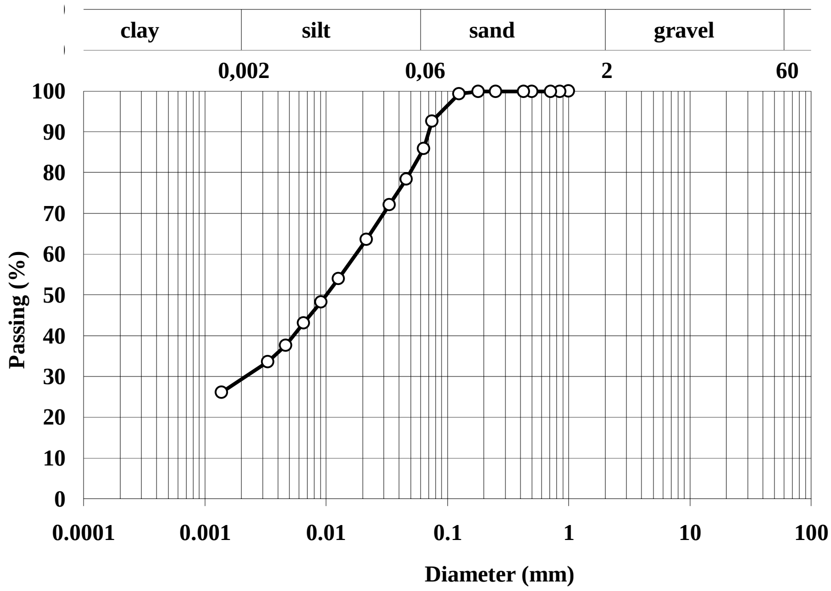

Figure 3: Sieve analysis of the natural ground

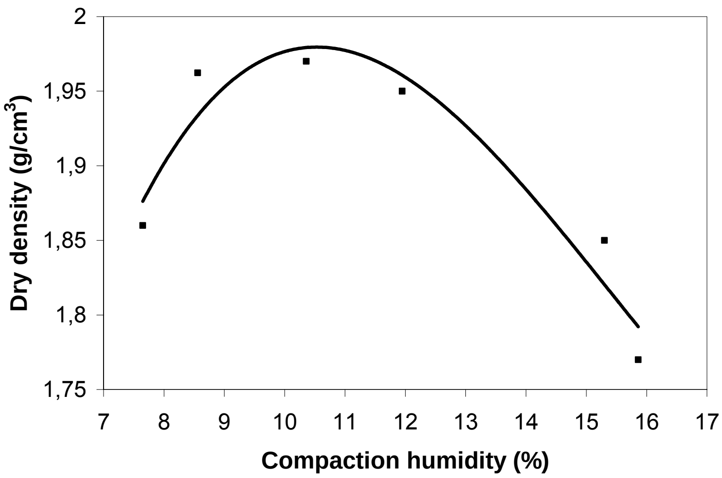

Figure 4: Compaction curve of the natural ground

Binary admixtures

The analysis of the Proctor's compaction curves (Fig.5) made on the three binary admixtures makes evidence of the fact than if the slag dosage increases, the optimum humidity value decreases, which moves from the value of 10.6% for the admixture with 10% of EAF slag, to the maximum value of 10.30% for that with 20%, to the value of 10.20% for the 15% admixture. The maximum dry density equal to 2.08g/cm^3 is reached with the admixture with a percentage of slag equal to 15%, while the other two admixtures record values closed to each other, equal to 2.0g/cm^3.
The mechanical characterization of the admixtures has been conducted applying the CBR test on specimens manufactured with a humidity tenor equal to the optimum one, previously determined.
In order to evaluate the possible variations of the mechanical properties with time, after the slag addition, this test has been performed in two different moments and precisely on specimens subjected to 7 and 28 days

seasoning. Moreover the variation of the CBR index was evaluated, executing the water saturation of the specimens saturated at 7 days.
The CBR indices (Fig.6) determined in optimal conditions at 7 and 28 days seasoning, furnish for each of the binary admixtures analysed the following results:

- Silt with sandy clay and 10% of EAF slag - CBR (7gg) = 26,28% - CBR (28gg) = 30,01%;
- Silt with sandy clay and 15% of EAF slag - CBR (7gg) = 31,79% - CBR (28gg) = 31,89%;
- Silt with sandy clay and 30% of EAF slag - CBR (7gg) = 41,30% - CBR (28gg) = 41,33%.

These values highlight an increase of the bearing capacity with the increase of the weight percentage of the introduced slag.
In particular there is a strong increase in the case of the use of a quantitative weight of slag equal to 20% and in this case the CBR index is subjected to a percentage increase, compared to the corresponding value of the natural ground, higher than the 50%.
Moreover it is evident from the experimental results that there are no significant variations with time of the CBR indices. This circumstance excludes, therefore, the possibility that in the examined admixtures there were modifications of the structural bonds.

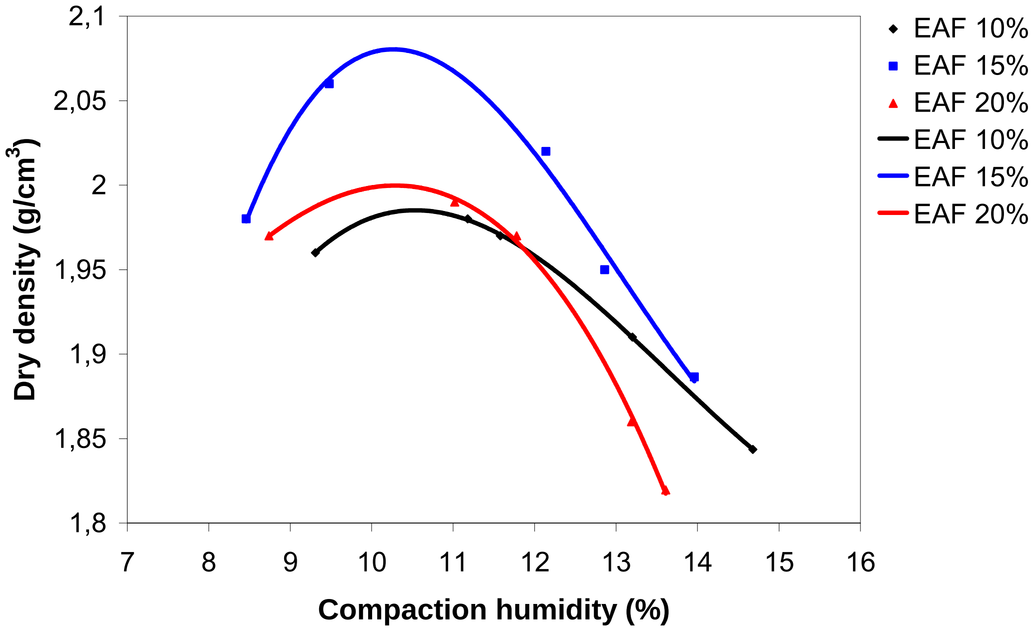

Figure 5: Compaction curve of the three binary admixtures

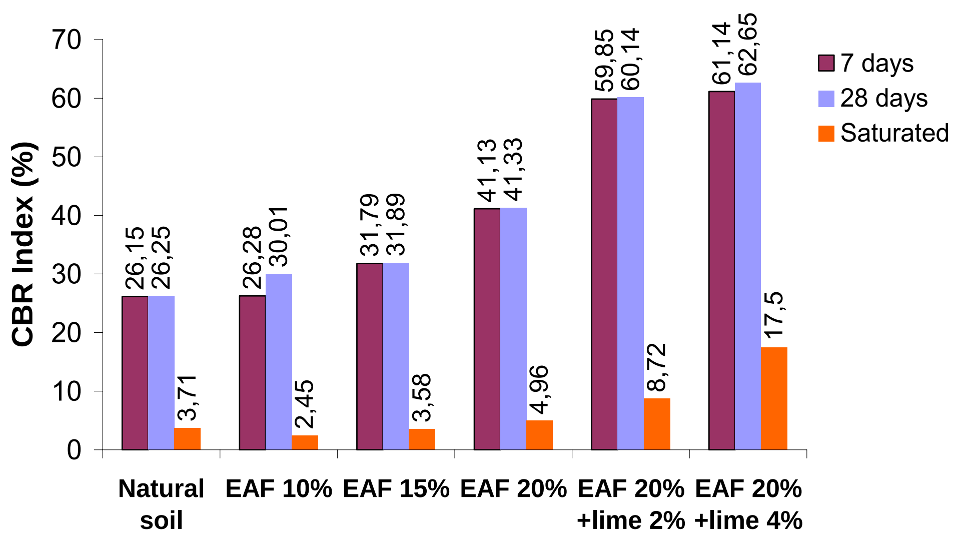

Figure 6: CBR index of the admixtures investigated at 7 and 28 days and after saturation

The CBR tests, performed on compacted specimens in optimal humidity conditions and brought to saturation after 7 days of seasoning, gives the following CBR indices (Fig.7):

- Silt with sandy clay and 10% of EAF slag - CBR = 2,45%;
- Silt with sandy clay and 15% of EAF slag - CBR = 3,58%;
- Silt with sandy clay and 20% of EAF slag - CBR = 4,96%.

These results show the significant sensitivity to water of the admixtures investigated, since there is a strong degradation of the bearing capacity compared to the values obtained in optimal conditions.
The swelling R (Fig.7) of the different admixtures was:

- Silt with sandy clay and 10% of EAF slag - R = 2.20%;
- Silt with sandy clay and 15% of EAF slag - R = 3,50% ;
- Silt with sandy clay and 20% of EAF slag - R = 3,90%.

These results show an increase of swelling with the increase of the weight percentage of the slag added.
In order to compensate the resistance decrease in saturated conditions and the reduction of the swelling, it was tried to improve the performances using hydrated lime, manufacturing two further admixtures with ternary composition.

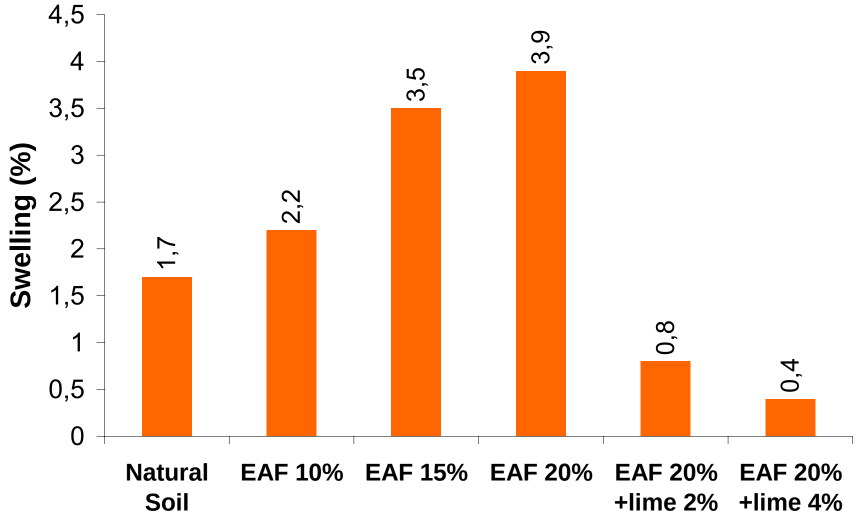

Figure 7: Swelling at saturation of the investigated admixtures

The ternary admixtures

The two ternary admixtures investigated were manufactured with a constant content of slag (20%), as this quantity in the binary admixtures allowed the achievement of the best mechanical performances, and to different weight percentages, referred always to the natural ground, of hydrated lime equal to respectively 2% and 4%.
The compaction curves executed on the ternary admixtures (Fig.8) highlight that the optimal water content changed from 9.4% of the admixture with 2% lime, to 10.2% of that with 4%.
Still referring to this test it was found that the increase of the lime dosage involves slight decrease of the CBR index not only compared to specimens with a water content equal to the optimum one, but also with respect to the best binary composition (Fig.6)
The CBR indices determined in optimal conditions on specimens at 7 and 28 days of seasoning give the following results:

- 2% lime weight ternary admixture - CBR (7gg) = 59,85% - CBR (28gg) = 60,14%;
- 4% lime weight ternary admixture - CBR (7gg) = 61,14% - CBR (28gg) = 62,65%.

The consequence is that there are no mechanical performances variations with time and that the two admixtures with different contents of hydrated lime have a very comparable CBR index. The increase of the bearing capacity of the two admixtures is also recorded in the test made in saturated conditions.
In this case the CBR index, for the ternary admixture with a hydrated lime content equal to 2%, is equal to 8.72%, while that with 4% of hydrated lime has a CBR index equal to 17.5%.

This result shows unambiguously that the positive influence on the mechanical performances due to the presence of the hydrated lime is fundamental, also in case of high humidity.
The strong sensitivity to water of the CBR index, both for natural ground and for binary admixtures, is reduced with the addition of hydrated lime. Indeed, the entity of swelling R(%) is reduced, presenting the following values (Fig.7):

- 2% lime weight ternary admixture - R = 0,80%;
- 4% lime weight ternary admixture - R = 0,40%.

In optimal conditions the two different lime dosages did not show relevant variations of the CBR index at saturation, but on the contrary the different dosages produce significant changes.

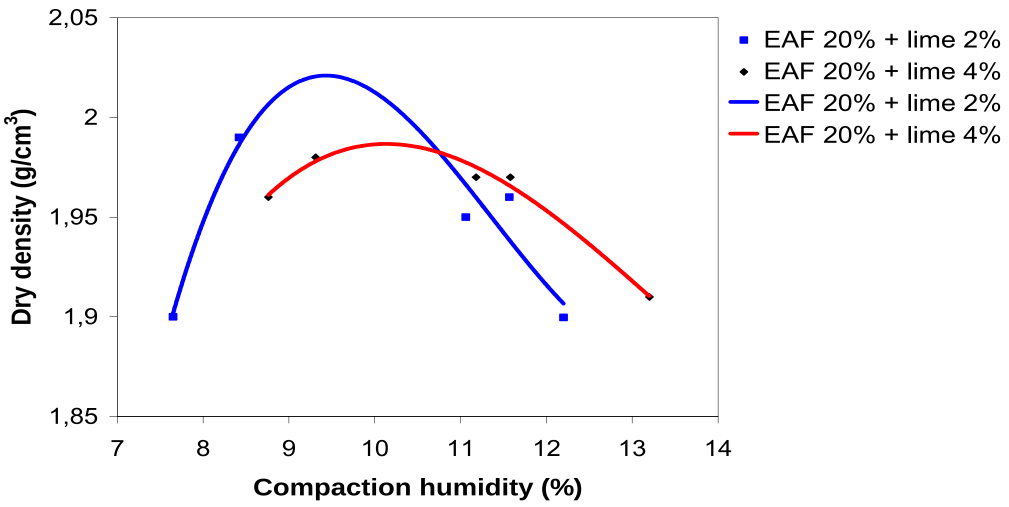

Figure 8: Compaction curve of the two ternary admixtures

Free lateral expansion compression tests

In order to find a performance frame of the different binary and ternary admixtures some free lateral expansion compression tests have been performed (ASTM D 2166/91).
For this reason a cylindrical specimen was used, the dimensions being 38mm and 76mm, respectively for the diameter and the height.
The seasoning of the specimens, as it happened for the CBR tests, was obtained sealing the specimens in waterproof coverings in order to avoid water evaporation and saving them in a humid environment, realised with humid sand at about 20°C.
In this way, stopping the contact with air, the lime carbonation and the reduction of the starting humidity were avoided.
The test results, expressed in terms of load (Fig.9) and of rupture strain (Fig.10) confirm the positive trend of performances found with the CBR tests; moreover, differently from these tests, they highlight a strong increase of the performances of the material seasoned at 28 days, compared to the 7 days one, which belongs to a higher activity of the slag for long periods.

CONCLUSIONS

The study investigated the possibility of using the smaller fraction (0-4mm) of the electric-arc furnace slag for the improvement of the grounds performances with poor physical and mechanical properties (silt with sandy clay).
The experimental results are more than positive because of the performance improvements obtained after stabilization.
Indeed, additions of 15% and 20% of EAF slag to the natural ground highlighted mechanical performance increases, from the point of view of the CBR index, both at 7 and 28 days of seasoning, of respectively about 23% and 58%.
The rupture load for free lateral compression, confirming the just mentioned trend, for the specimens tested at 7 days of seasoning, experienced a 20% increase for the admixture with 15% of EAF slag and of 62% for the 20% one.

After 28 days of seasoning there are strength peaks 2.5 times larger than those obtained at 7 days. This outcome is the confirmation of a higher cementing effect of the slag which the CBR test did not allow to measure.
Moreover, the CBR test at saturation showed a complete cancellation of the positive effects of the EAF slag to the natural ground, and in addition the saturation of the specimens which were to be tested demonstrated an excessive swelling, especially for a dosage of the EAF slag equal to 20%.
These experimental evidences induced the Authors to the manufacturing of two additional ternary admixtures made of natural ground, 20% in weight of EAF slag and 4% of hydrated lime, trying in a whole to recover for the decrease of performances due to the presence of water and to contain the admixture swelling.
The results obtained are flattering, indeed using the ternary admixture where a 4% lime has been adopted, it was recorded, compared to natural ground, an increase of the CBR bearing capacity at 7 days of some 54%, while in saturated conditions there was an increment equal to 370%.
Eventually, the swelling was considerably reduced, from 3.9% to 0.4%.
Therefore, considering that in any case the free lateral expansion compression tests performances improvements are to be investigated further from the point of view of the chemical-physical aspects, the Authors believe that the EAF slag can be positively adopted for the stabilization of the marginal grounds for road constructions.

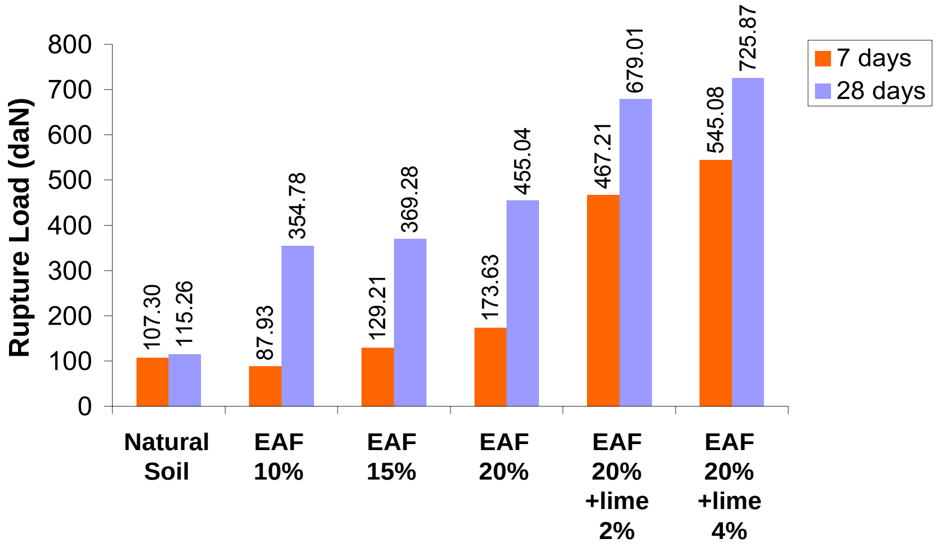

Figure 9: free lateral expansion compression tests at 7 and 28 days of seasoning – Rupture Load

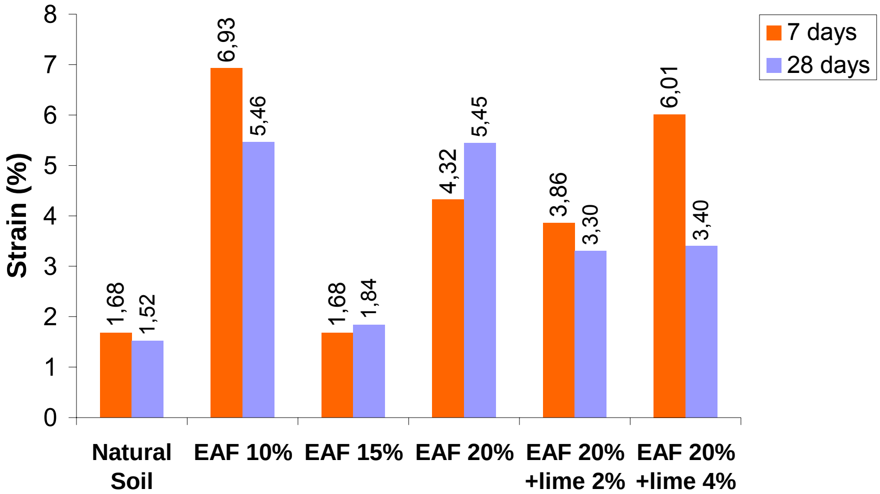

Figure 10: Free lateral expansion compression tests at 7 and 28 days of seasoning – Strains

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