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RE-USE OF INDUSTRIAL WASTES IN CEMENT BOUND MIXTURES FOR ROAD CONSTRUCTION

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Abstract

The paper describes the main results from a study of cement bound mixtures for road foundations with the aggregate matrix consisting of industrial wastes, i.e. foundry sands (FS), electric arc furnace (EAF) steel slags and bottom ash from municipal solid waste incineration (MSWI), combined in five different proportions. The laboratory investigation involved a preliminary analysis of the chemical, leaching, physical and mechanical properties of the industrial wastes, followed by a mechanical characterization of the cement bound mixtures. The mix design was conducted in terms of Proctor, compression and indirect tensile tests. Lastly the dynamic elastic modulus of the mixtures was investigated through ultrasonic tests, at different seasoning times. The results were entirely satisfactory for all the mixtures, especially for the one composed of 50% foundry sand, 10% bottom ash and 40% steel slag, with a compression strength of up to 5.28 MPa at 7 days and a corresponding indirect tensile strength of 0.498 MPa. The results met the main national Specifications, thus demonstrating the feasibility of recycling industrial by-products as substitutes for conventional natural aggregates in the production of hydraulically bound mixtures for road foundations.

Key words: bottom ash, cement bound mixtures, foundry sand, road foundations, steel slag

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1. Introduction

The reuse of industrial by-products in road construction represents an alternative to two relevant questions: the serious issue related to the disposal of these wastes and the necessity to look for alternative types of lithic materials, with respect to the conventional materials used for road infrastructure. However, there has not yet been a wide consensus about the recycling of waste materials because their mechanical properties are not well known and fully understood. More than this, such materials represent a potential environmental issue, which has to be investigated and verified case by case.

Based on such considerations, an experimental study has been carried out to design and investigate the performance of cement bound mixtures for road foundations prepared using exclusively industrial wastes. Such mixtures require to be densified in order to achieve the maximum strength, that is ensured by the interlocking of the grains, after the compaction. The hydraulic binder, namely the cement, has just to guarantee, over time, the compacted configuration between the aggregate grains achieved during the densification process (Pasetto and Baldo, 2010). This technology is typically used for foundation layers of highway and motorway pavements. Given the significant depths involved, notable quantities of wastes can be recycled.

The studied materials were the so-called "marginal aggregates" (Omran et al., 2009; Zăman et al., 2009); they included waste spent foundry sand, Electric Arc Furnace (EAF) steel slag and bottom ash from Municipal Solid Waste Incineration (MSWI).

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There have been a number of studies and applications (Manso et al., 2011; Polanco el al., 2011; Setién et al., 2009) on the use of steel slags in concrete mixtures for civil construction. Research has also been conducted on the use of foundry sand (Siddique and Noumowe, 2008; Siddique and Singh, 2011; Singh and Siddique, 2012) or MSWI bottom ash (Aberg et al., 2006; Fortezza et al., 2004; Kayabali and Bulus, 2000; Pasetto and Baldo, 2012) as a building material. However, the suitability of the use of integrated use of EAF steel slags, foundry sand and MSWI bottom ash in hydraulic bound mixtures, known as "cement bound granular material", still requires careful evaluation. In the present experimental investigation, the considered wastes have been studied individually; subsequently, hydraulically bound mixes prepared with various quantity of them, have been mechanically characterized.

2. Material type and methodologies

Three different industrial by-products have been analyzed and used to produce cement bound mixtures, considering five different combinations of granular components.

Producing steel, by means of an electric arc furnace (EAF), a particular type of waste is obtained, namely the steel slag. The smelting of various types of metal wastes, along with specific smelting agents (most od the times limestone and dolomite), into the electric arc furnace, leads to the production of a main by-product, namely the steel slags.

At the beginning of the steel production cycle, the slags are floating on the surface of the metal bath. They are then poured out of the furnace into a discharge tank, where they are left to cool slowly and solidify. During the cooling process, which can be speeded up with jets of water, the thermal shock causes the molten casting to shatter into macro blocks. These are then reduced in size using impact hammers, to render them compatible with the successive treatments of deferrization and further particle-size reduction. The EAF slag considered immediately after the cooling process (fresh EAF slag), is frequently characterized by a relevant content of calcium oxide (CaO). Such free calcium oxide can undergo to hydration reactions, which involve a volumetric expansion and in turn a fracture of the particles. The utilization of "fresh" slags has been the main reason of the unsuccess frequently observed in the past in the utilization of the steel slag in road pavements (Dunster, 2002). In order to avoid such problem, it is suggested to apply to the EAF slags a stabilization process, given by the crushing and the exposure of the EAF slags to the air, for at least three months; in this way the hydration reactions have the possibility to occur before the utilization in the road construction.

Another reaction related to volumetric expansion involves the dicalcium silicate (C_2S) phase. The C_2S phase is commonly present in all types of steel slags, and is typically abundant as the main phase in ladle slags. C_2S exists in four well-defined polymorphs: α, α', β and γ. At temperatures below 500 °C, β-C_2S starts transforming into γ-C_2S. This leads to a volumetric expansion of up to 10%, and if the cooling of the EAF steel slag takes place slowly, a significant amount of dust is produced, as a consequence of the breaking of the crystals. This phase conversion and the associated dust are typical for ladle slags (Shi, 2004), which are different from those used in this study. At the end of the curing process, known as stabilization, any metal left in the slags is separated using magnets, to recover scraps that may be further re-utilized in the steel production process, as well as to avoid technical problems in the final phase of particle-size reduction of the slags.

The analysis of the steel slags considered in this investigation, conducted with the x-ray fluorescence, has shown a composition mainly given by 30% of FeO, 28% of CaO, 18% of SiO_2, 7% of MgO and 5% of Al_2O_3.

The US steelmaking industries produce 10-15 million tons of steel slag every year. About 50 to 70% of the total steel slag generated in the USA is recycled as aggregate for road construction. The EAF slag that is not recycled (up to 40% of the total amount) is stockpiled at the steel plants, or dumped in authorized disposal sites (Yildirim and Prezzi, 2011). Europe produces almost 12 million tons of steel slags annually (Mladenović et al., 2009); 65% of this is recycled in a broad range of applications, mostly related to transport infrastructure construction. In Italy the production was estimated at about 3 million tons in 2009 (Sorlini et al., 2012), most of which was dumped.

Spent foundry sand is a waste produced by the iron and steel industry, usually characterized by a high heterogeneity. It comes from the utilization of the high-quality silica or lacustrine sand which constitute the casting moulds used in the manufacturing of metallic or non-metallic products; details can be found in the literature (Pasetto and Baldo, 2015).

At the end of the casting phase it is possible to separate and recycle the sand. After the fine particles are removed, lumps broken and the remaining metal extracted, the sand is returned to the depot. Up to 90-95% of the sand can be recycled in this way after every casting. Once the smelting procedure is finished and at the conclusion of the service "life" of the sand, the material undergo its disposal and is qualified as "spent" sand.

The spent foundry sand considered in the present research was silica sand wrapped by a thin layer of carbon, which comes from the production process and powders. They were mainly composed of 85% of SiO_2, 5% of Al_2O_3 and 1% of Fe_2O_3. The annual production of foundry sand is approximately 9 million and 12 million tons in Europe and the USA, respectively; it is mainly disposed of in waste containment facilities (Guney et al., 2006), while only 30-32% is currently reused in construction.

The incineration of Municipal Solid Wastes (MSWs) provides by-products that can mainly be classified as bottom ash and fly ash (Kayabali and Bulus, 2000). The former, corresponding to 25% of the weight of the wastes to be incinerated, thus being the principal product of the process, is mainly composed of silica (Si), iron (Fe), calcium (Ca), aluminium (Al), sodium (Na) and potassium (K) oxides, so has a composition similar to that of various natural materials. Its metallic fraction can be recovered; the remainder is usually stockpiled in dumps or, less frequently, recycled. Bottom ash can be re-utilised in the construction of new infrastructure, especially in bitumen and cement bound mixtures, because the binder covers the grains and prevents the release of heavy metals. Fly ash is not usually used in road construction because of the high content of heavy metals. 755,000 tons of bottom ash was produced in Italy in 2003, with a recycling rate of only 20%. Production in France and Germany amounted to 2,995,000 and 3,140,000 tons respectively; the corresponding recycling rates in road and civil construction were 79 and 65% (Crillensen and Skaarup, 2006).

All the materials used in the experiments were supplied by a private company located in the province of Padua (North-eastern Italy). The feasibility of recycling waste materials in road infrastructure is strongly dependent on the evaluation of any toxic compounds present in the non-conventional aggregates, because of the potential leaching of heavy metals (Aliakbari-Beidokhti et al., 2017; Predescu et al., 2017). Table 1 summarizes the toxicological characteristics of the industrial wastes, in terms of release of heavy metals, measured by the Toxic Characteristic Leachability Procedure (TCLP), following the method in Standard EN 12457-2.

The environmental compatibility (leaching) of the aggregate was checked by means of the TCLP, coupled to the Inductively Coupled Plasma–Atomic Emission Spectrometer (ICP/AES) characterization (Pasetto and Baldo, 2016; Siddique et al., 2010).

Grading curves of the three aggregates were determined by sieving and gave evidence to the differences highlighted in Table 2. Table 3 reports the physical-mechanical properties of the marginal materials, as well as the test protocols adopted, which are specific to the road sector.

The cement utilized in the present research was a Portland cement CEM II/B LL 32.5R. According to the regulations, the water utilized in the trials was pure. Based on the relevant literature (Pasetto and Baldo, 2015; Xuan et al., 2012) the mix design of cement bound materials for road constructions requires the identification of the type of lithic material, the grading curve design and the optimization of both the water and hydraulic binder percentages (Pasetto and Baldo, 2015; Xuan et al., 2012).

The lithic structure has been fully made by the by-products considered. With the aim to maintain the original grading composition of the waste materials involved, the design grading curves have been obtained after simple mixing, in various amounts, of the recycled aggregates. Hence, during the mixing phase, all the industrial by-products considered have been utilized maintaining their original grading composition, avoiding to select individual fractions.

Table 1. Heavy metal leaching concentrations of the industrial wastes

Element	***TCLP leaching concentration***			
	EAF slag	***Foundry sand***	***Bottom ash***	***Legal thresholds***
Copper (Cu)	0.004 mg/l	< 1 µg/l	< 0.001 mg/l	< 0.05 mg/l
Cadmium (Cd)	< 1 µg/l	< 0.4 µg/l	< 0.0002 µg/l	< 5 µg/l
Lead (Pb)	19.5 µg/l	< 1 µg/l	22.8 µg/l	< 50 µg/l
Zinc (Zn)	< 0.001 mg/l	< 0.01 mg/l	< 0.1 mg/l	< 3.0 mg/l
Chromium (Cr)	32.7 µg/l	< 1 µg/l	8.9 µg/l	< 50 µg/l
Nickel (Ni)	< 3 µg/l	< 1 µg/l	< 0.5 µg/l	< 10 µg/l
Mercury (Hg)	< 1 µg/l	< 0.1 µg/l	< 0.1 µg/l	< 1 µg/l
Selenium (Se)	< 5 µg/l	< 1 µg/l	< 4 µg/l	< 10 µg/l
Arsenic (As)	< 5 µg/l	1.14 µg/l	< 1.3 µg/l	< 50 µg/l
Barium (Ba)	0.2 mg/l	0.0039 mg/l	0.8	< 1 mg/l

Table 2. Grading curves

Sieve size (mm)	***Passing percentage (%)***		
	EAF slag	***Bottom ash***	***Foundry sand***
31.5	100.0	100.0	100.0
16	95.4	100.0	88.0
8	75.0	87.3	76.4
4	46.8	74.1	72.8
2	25.9	60.9	52.7
1	13.4	47.7	31.9
0.5	6.6	34.5	17.6
0.25	3.1	21.2	9.3
0.125	1.2	8.0	4.8
0.063	0.3	4.5	1.5

Table 3. Physical and mechanical characteristics

Physical ÷ Mechanical properties	***Standard***	***EAF slag***	***Bottom ash***	***Foundry sand***
Los Angeles coefficient (%)	UNI EN 1097-2	15	-	-
Equivalent in sand (%)	UNI EN 933-8	83	50	27
Shape Index (%)	UNI EN 933-4	10	-	15
Flakiness Index (%)	UNI EN 933-3	12	-	5
Grain bulk density (g/cm^3)	CNR 64/78	4.14	2.59	2.76
Grain dry density (g/cm^3)	CNR 63/78	3.92	2.53	2.64
Porosity of the grains (%)	CNR 65/78	5.31	2.32	4.35
Particle voids content (%)	CNR 65/78	48.72	65.22	49.24
Sieve passing (2.00 mm) (%)	CNR 23/71	27.2	58.8	57.7
Sieve passing (0.42 mm) (%)	CNR 23/71	4.8	28.1	21.0
Sieve passing (0.075 mm) (%)	CNR 23/71	0.6	4.2	0.5
Plasticity Index (-)	UNI CEN ISO/TS 17892-12	0	0	0

The densification properties of the integrated granular mixtures have been investigated using the Proctor densification procedure (EN 13286-2), to evaluate the maximum dry density as well as the water percentage. According to up to date literature studies (Pasetto and Baldo, 2013, 2015), the design cement percentages have been identified performing Unconfined Compressive Strength (UCS) tests on cylinders prepared for each type of mixture, using the selected cement and the quantity of water determined with the Proctor trials. Such design approach led to the determination of the optimum mixture based on the achievement of minimum UCS value prescribed in the specifications (Pasetto and Baldo, 2013, 2015; Xuan et al., 2012).

Then, the mix design approach described above has been integrated by indirect tensile strength trials (EN 13286-42), performed on a further battery of cylinders of the considered mixtures (Pasetto and Baldo, 2010).

Mechanical properties were determined after dynamic tests, finalized to evaluate the elastic modulus by means of the ultrasonic procedure (EN 12504-4). The method makes use of specimens with the same shape and size as those employed for compressive and indirect tensile strength tests. Even if the test has been developed for concrete, it is admissible to extend its applicability to cement bound granular mixtures, due to the close similarity between the two types of materials, namely an aggregate matrix bound by hydrated cement.

3. Results and discussions

Based on the Italian Law, the recycled materials investigated can be classified as non-hazardous, special non-toxic and non-noxious wastes. All the recycled aggregates analysed were solid materials and odour-free. The steel slags and bottom ash were characterized by grey colour; instead, the foundry sand was mainly black. The pH is 12.6 for bottom ash, 11.1 for EAF slags and 8.6 for foundry sand.

Table 4 summarizes the toxicological characteristics of the EAF slag and foundry sand, in terms of initial concentrations of heavy metals, measured with the ICP-AES methodology (Inductively Coupled Plasma – Atomic Emission Spectrometer), following the Standard EPA-Method 6010C. The initial concentration of heavy metals in the two metallurgical wastes differs, with the foundry sand containing more copper and nickel. The EAF slag contains more zinc and chromium, with the content of the latter being highest, but anyhow less than 0.4% of the total volume.

Table 4. Heavy metal contents of the EAF slag and foundry sand

Element	***Initial concentration (mg/kg)***	
	EAF slags	***Foundry sand***
Copper (Cu)	221	580
Cadmium (Cd)	< 0.5	< 1
Lead (Pb)	37.7	27
Zinc (Zn)	589	35
Chromium – Total (Cr)	3,534	485
Nickel (Ni)	37.6	368
Mercury (Hg)	< 0.5	< 0.5
Selenium (Se)	17.4	< 1
Arsenic (As)	5.5	19.2
Beryllium (Be)	< 0.5	< 1
Antimony (Sb)	33.6	< 2
Thallium (TI)	40.7	< 1

Volumetric stability tests have been conducted on the EAF slags, following the Standard EN 1744/1 part 15.3. The results demonstrated null expansion (0%) at the end of the 168 hours prescribed by the standard.

Table 1 reports the results of the leaching analysis carried out. It can be seen that the recycled aggregates investigated were characterized by a release of heavy metals by leaching within the thresholds of the environmental regulations prescribed in Italy (Legislative Decree no. 152/2006). Hence, considering that all the recycled materials used for the preparation of the mixes didn't show toxicological issues, it has been considered unnecessary to carry out leaching tests on cement bound samples.

The recycled aggregates were characterized by non-determinable Atterberg Limits (Liquid Limit and Plastic Limit, based on CEN ISO/TS 17892-12). Such result, along with the percentages of passing through 2 mm, 0.42 mm, 0.075 mm sieves (Table 3), allowed to classify the recycled materials, on the basis of the HRB-AASHTO method, as A1 soils. This means that the recycled materials investigated can be utilized in road infrastructures (foundry sand and bottom ash have been classified as A1-b soil, whereas steel slags as A1-a soil). Given the results reported in Table 3 and according to the Italian acceptance requisites, the EAF slags, as well as the bottom ash, have presented an Equivalent in Sand value higher than the minimum threshold fixed at 35%. On the contrary, the foundry sand has presented an Equivalent in Sand value lower than the acceptance threshold.

The cubical morphology of the EAF slag grains, as well as that of the foundry sand particles (Shape and Flakiness Indexes characterized by low values), enables a strong interlocking effect within the hydraulic mixtures. The Los Angeles test displayed a good resistance of the EAF slags to abrasion and fragmentation, providing a coefficient much lower than the acceptance requirements (30% for foundation layers). Both the high density and mechanical strength of the steel slags are fundamental characteristics in order to ensure resistance to degradation, which develops under the roller compaction during laying and the subsequent continuous traffic loading.

The bulk and dry density of both the bottom ash and foundry sand are decidedly lower than that of the steel slags. The volumetric properties of the grains (particle voids and porosity) resulted as quite similar for the metallurgical wastes, whereas the data recorded for the bottom ash were consistently different.

The grading curves reported in Table 2 show that both the finest fractions, i.e. the foundry sand and bottom ash, as well as the steel slags, have a basically continuous grading. Table 5 reports the composition studied for the design grading curve of the cement bound mixes, that has been identified considering various ratios of the recycled materials. In fact, also according to the aggregate supplier request, the research intended to investigate the contribution of different by-products, differently dosed, to the performances of the mixture.

In order to properly identify the composition of the mixtures, a three-number code was assigned, giving the foundry sand, bottom ash and steel slag dosage (percentage) respectively. The slag content in the first three mixtures (Mix 50/10/40, Mix 40/20/40, Mix 30/30/40) was fixed at a constant rate (40%), then progressively reduced. This was done to guarantee a minimum percentage of coarse aggregate, i.e. steel slags, in all the mixes, which represent the major portion of the aggregate structure and were characterized by better mechanical and physical characteristics.

The CIRS Specification (MIT-CIRS, 2000), in the study of cement bound mixes prepared with industrial by-products, allows to identify the best suited grading envelope on the basis of ad-hoc laboratory investigations. It was therefore decided to set up a new design grading envelope (Fig. 1), hereinafter called "Reference envelope", compatible with the grading characteristics of different types of recycled aggregates. Fig. 1 shows that the resulting grading curves for the design mixes are within the proposed reference envelope.

The modified Proctor test provided the results presented in Table 6. The optimal water content (OWC) increased with the cement content, while higher values of dry density (ρ_d) were observed in the mixtures with more slags and cement. Tables 6, 7, and 8 present the results of the mix design and performance tests for the mixtures with the various cement contents considered (3, 4, 5% on the weight of the aggregates) and respective optimal water percentages, for three ageing times: 7, 28 and 90 days.

In the preparation, densification and curing of the samples, none of the mixes investigated showed expansion or failure phenomena, given by the inclusion of free CaO that could be underwent to hydration or carbonation of slag aggregate, which is quite usual for by-products not subject to sufficient ageing (Dunster, 2002).

The trend resulted as increasing with ageing time and binder content, as reported in the literature for other cement stabilized materials (Sherwood, 1995), so the mix with the minimum UCS compatible with the acceptance requirements of the CIRS – Italian Ministry of Infrastructure Specification (that sets a range of acceptable values at 7 days of seasoning between 2.5 and 7.5 MPa: MIT-CIRS, 2000), was identified as the optimum one, for each formulation.

All the mixtures already showed mechanical properties values above the required minimum threshold with a 3% cement content, with very high UCS values (up to 3.93 MPa for the Mix 50/10/40); therefore, the lowest binder content used in the investigation can be identified as the optimal cement dosage. The UCS resulted greatly affected by the mixture composition (hence by the recycled material type) (Table 6), as already observed for both conventional and recycled hydraulically bound mixtures (Pasetto and Baldo, 2013, 2015; Sherwood, 1995).

Table 5. Aggregate type and composition of the mixtures

Waste aggregates	***Mixtures***				
	MIX 50/10/40	***MIX 40/20/40***	***MIX 30/30/40***	***MIX 40/30/30***	***MIX 40/40/20***
Foundry sand (%)	50	40	30	40	40
Bottom ash (%)	10	20	30	30	40
EAF slags (%)	40	40	40	30	20

Table 6. Proctor test results and mechanical properties at 7 days ageing

Mixtures	*OWC (%)*	*ρ_d (g/cm^3)*	*UCS (MPa)*	*ITS (MPa)*	*E_D (MPa)*
Mix 50/10/40; 3% Cem	9	2.37	3.93	0.375	8,204
Mix 50/10/40; 4% Cem	10	2.38	4.61	0.460	8,741
Mix 50/10/40; 5% Cem	11	2.42	5.28	0.498	9,674
Mix 40/20/40; 3% Cem	9	2.35	3.72	0.361	7,626
Mix 40/20/40; 4% Cem	10	2.36	4.18	0.422	8,170
Mix 40/20/40; 5% Cem	11	2.38	4.57	0.449	9,111
Mix 30/30/40; 3% Cem	9	2.23	3.54	0.332	6,831
Mix 30/30/40; 4% Cem	10	2.28	3.95	0.388	7,381
Mix 30/30/40; 5% Cem	11	2.31	4.36	0.423	8,320
Mix 40/30/30; 3% Cem	8	2.19	3.11	0.307	5,892
Mix 40/30/30; 4% Cem	9	2.21	3.58	0.348	6,437
Mix 40/30/30; 5% Cem	10	2.22	3.93	0.398	7,369
Mix 40/40/20; 3% Cem	10	2.13	2.72	0.275	5,084
Mix 40/40/20; 4% Cem	11	2.15	3.03	0.307	5,589
Mix 40/40/20; 5% Cem	12	2.18	3.37	0.325	6,531

Table 7. Mechanical properties at 28 days ageing; mixtures at 3% cement

Mechanical parameter	*MIX 50/10/40*	*MIX 40/20/40*	*MIX 30/30/40*	*MIX 40/30/30*	*MIX 40/40/20*
UCS (MPa)	4.54	4.31	4.18	3.73	3.25
ITS (MPa)	0.455	0.436	0.424	0.371	0.337
E_D (MPa)	8,885	8,317	7,532	6,573	5,755

Table 8. Mechanical properties at 90 days ageing; mixtures at 3% cement

Mechanical parameter	*MIX 50/10/40*	*MIX 40/20/40*	*MIX 30/30/40*	*MIX 40/30/30*	*MIX 40/40/20*
UCS (MPa)	5.45	5.18	4.77	4.22	3.83
ITS (MPa)	0.531	0.513	0.478	0.412	0.381
E_D (MPa)	9,504	8,916	8,117	7,200	6,372

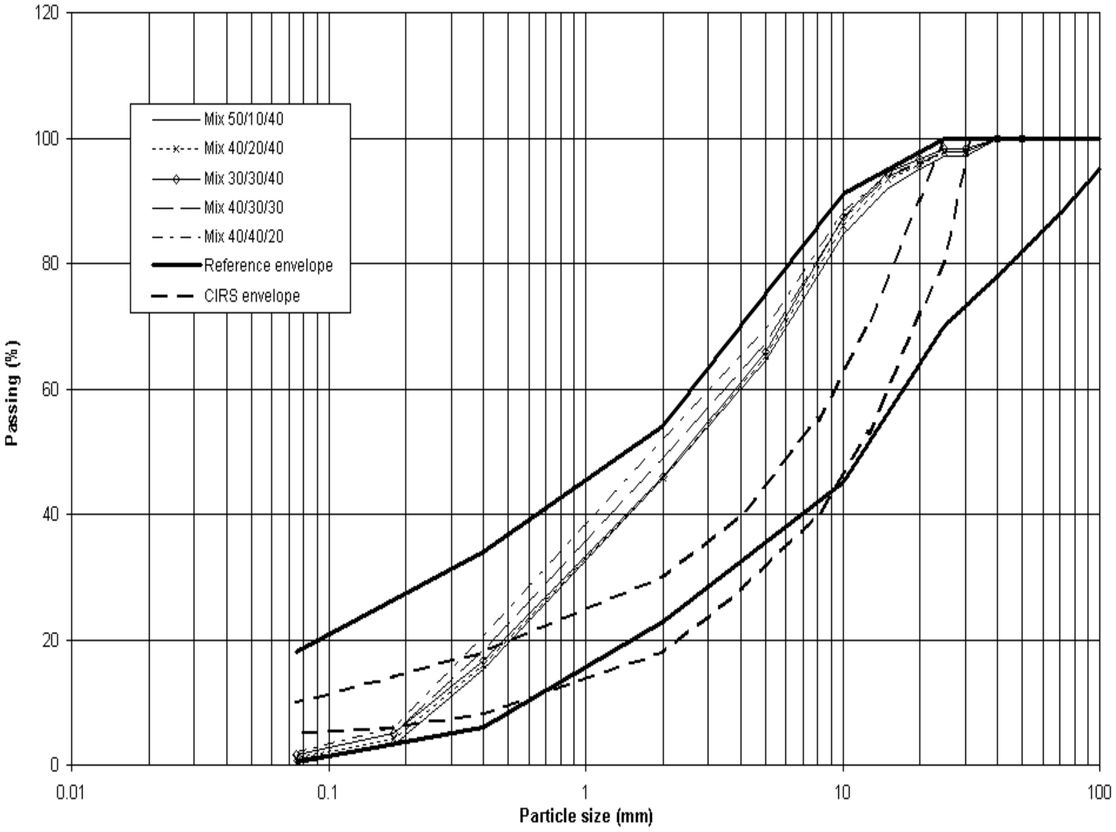

Fig. 1. Mixtures and reference envelope grading curves

However, given that all the mixes have satisfied the minimum acceptance values, it is possible to identify the best suited proportion of the mixes, depending on the particular case considered.

For the cement percentage resulted as optimal in the mix desing procedure (3%), the indirect tensile strength (ITS) after 7 days of curing was equal to 0.375 MPa for the Mix 50/10/40, which is much higher than the minimum value (0.25 MPa) prescribed by CIRS Specifications for acceptance of the mixture (MIT-CIRS, 2000). Hence, the EAF slag-foundry sand-bottom ash ratios and the hydraulic binder percentages, can be changed within the considered limits, without issues in terms of strength performance. Even the Mixture 40/40/20 at 3% of hydraulic binder, has shown compressive strength and indirect tensile strength results above the regulation requisites (9% and 10% respectively).

The mechanical properties of the mixtures were investigated at 28 and 90 days of ageing, at the optimal cement content (3%). The UCS and ITS values of the Mix 50/10/40 resulted still the highest among the mixtures considered (Tables 7 and 8). As expected (Sherwood, 1995), a significant evolution of the strength can be observed in relation to the seasoning time. For example, the Mix 50/10/40 developed increases of 39% and 42%, for UCS and ITS respectively, in the range between 7 and 90 days of ageing. For all the mixtures investigated, it has been feasible to establish a linear correlation between the *UCS* and the *ITS*, as reported in the literature for similar materials (Babic, 1987). A regression analysis of the experimental data was therefore performed using a linear model of the type (Eq. 2):

$$ITS = mUCS + q \qquad (2)$$

where *m* and *q* are regression coefficients, depending on the type of material. Fig. 2 presents the experimental data and interpolation curves, while Table 9 reports the most significant regression coefficient (m) and coefficient of determination R^2.

For Mix 40/20/40 and Mix 40/30/30 the compressive strength was almost 10 times the indirect tensile strength. Considering Mix 50/10/40 and Mix 40/40/20, the ratio between UCS and ITS resulted next to 11, whereas for Mix 30/30/40 came to 9.

The ranking of the mixtures outlined by the compressive and indirect tensile strength tests was confirmed by the Elastic Modulus evaluation (Tables 6, 7 and 8): the Mix 50/10/40 was characterized by the highest stiffness. A high stiffness should contribute favourably to the global structure of a flexible pavement, because at the same stress level, as the stiffness increases, lower strains develop, with beneficial effects for the subgrade beneath the foundation layer.

However, an excessively high stiffness could lead to failure by cracking, due to brittle behaviour. Therefore, in the pavement design procedure, the Elastic Modulus data should be carefully analysed, in order to identify the cement bound mixture best suited to the stiffness of the bituminous layers and resilient modulus of the subgrade.

Table 9. ITS – UCS regression results

Mixture	***m (-)***	***R^2***
Mix 50/10/40	0.0932	0.9573
Mix 40/20/40	0.1007	0.9828
Mix 30/30/40	0.1157	0.9753
Mix 40/30/30	0.0996	0.9775
Mix 40/40/20	0.0926	0.9550

The Elastic Modulus results at 28 and 90 days of curing, have shown a further performance improvement over the time.

For all the mixes analyzed, a correlation was identified between the *UCS* and the dynamic Modulus E_D, adopting, for the interpolation of the laboratory results, the power law equation, reported in the following (Eq. 3):

$$E_D = cUCS^d \qquad (3)$$

where *a* and *b* represent interpolation coefficients, associated to the type of mix. Fig. 3 presents the laboratory results and the regression curves, for each mix. The interpolation coefficients, as well as the values of the coefficient of determination (R^2), are reported in Table 10; it can be observed the strong influence of the composition of the mixes on both the coefficients.

Table 10. E_D – UCS regression results

Mixture	***c (-)***	***d (-)***	***R^2***
Mix 50/10/40	4.1621	0.4593	0.9507
Mix 40/20/40	3.9054	0.5205	0.7853
Mix 30/30/40	3.0440	0.6457	0.8327
Mix 40/30/30	2.5365	0.7400	0.8767
Mix 40/40/20	2.5288	0.7162	0.7970

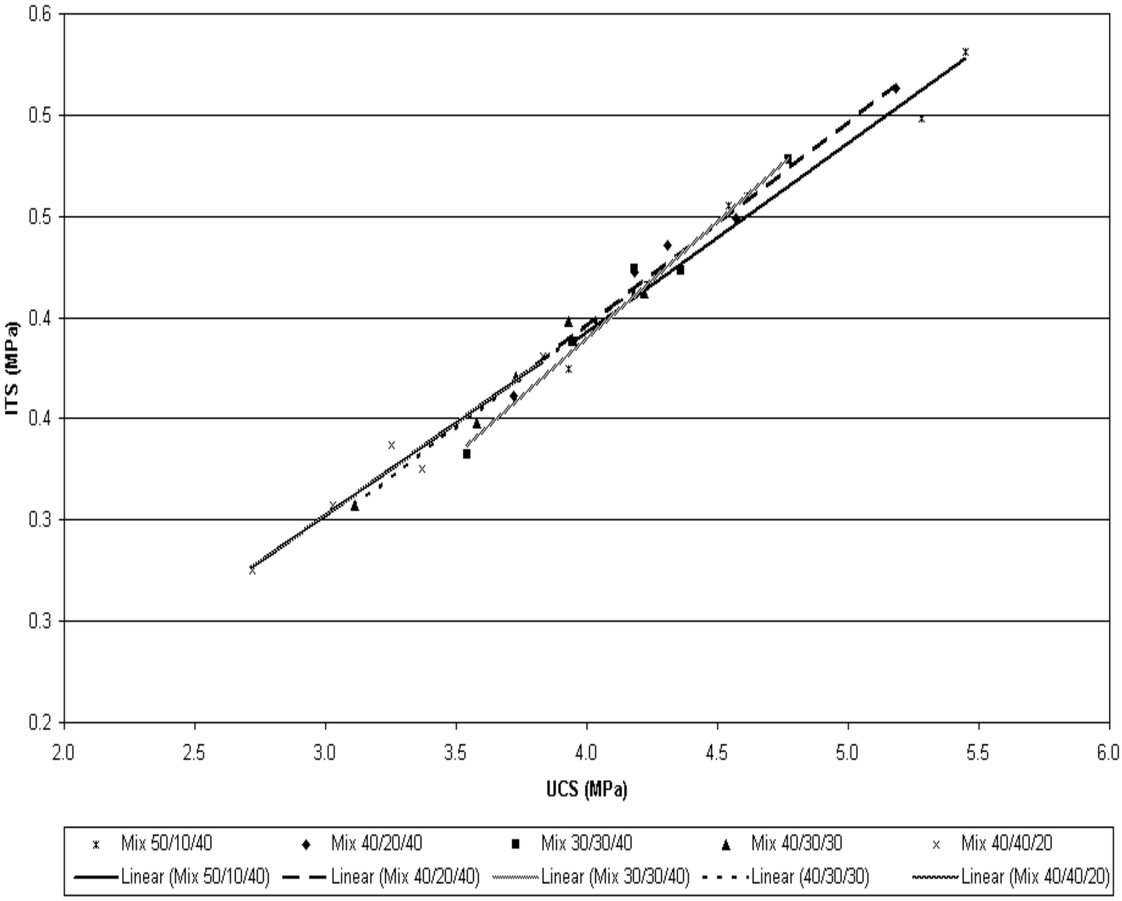

Fig. 2. ITS vs UCS

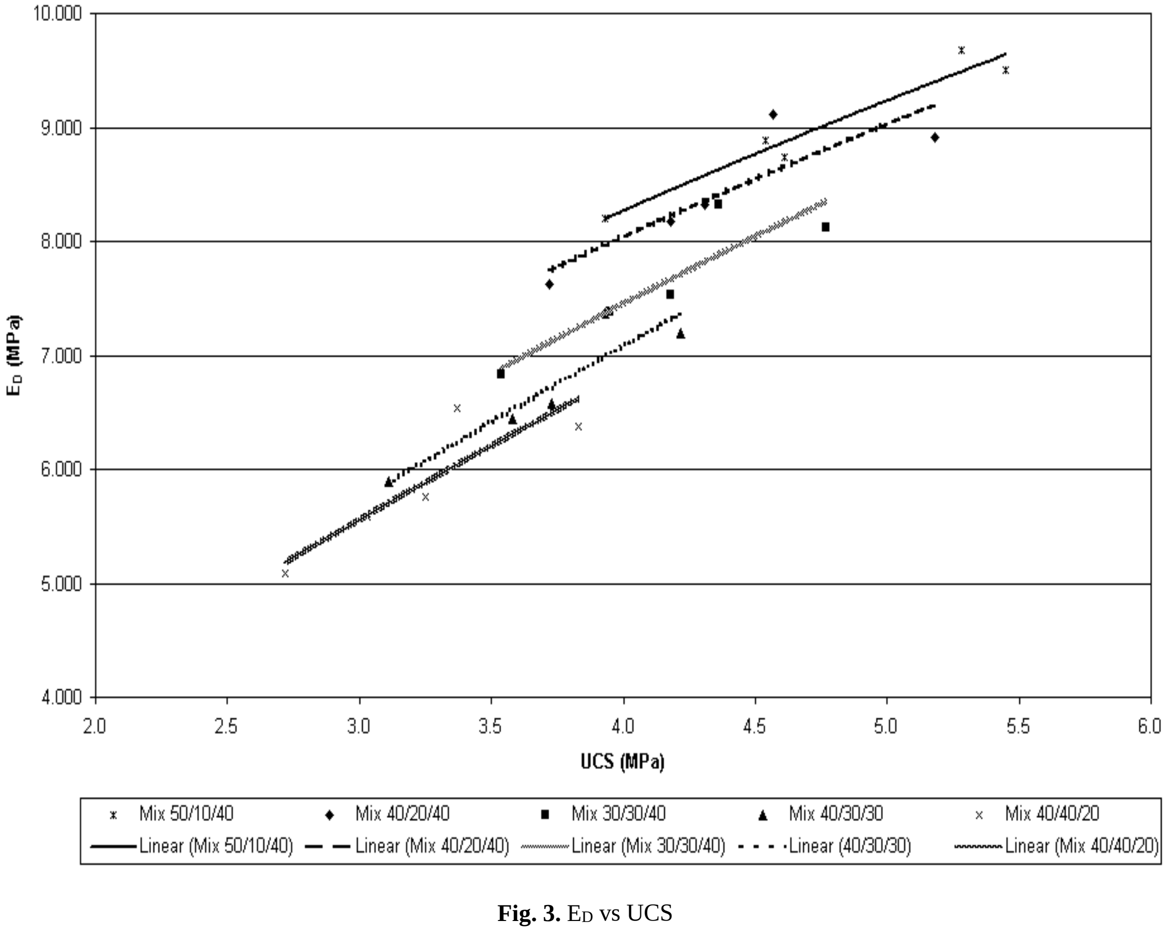

Fig. 3. E_D vs UCS

4. Conclusions

The paper describes a study on hydraulically bound mixes, to be used in the road construction, characterized by a lithic matrix entirely prepared with industrial by-products, namely foundry sands, bottom ash and EAF.

The materials analyzed resulted characterized by toxicological, physical and strength characteristics fully acceptable to produce hydraulically bound mixes to be applied in the road construction.

The proposed mix design procedure, based on UCS and ITS trials, has allowed to indentify mixes produced using only recycled aggregates, in five different ratios, which have fully satisfied the Italian acceptance requisites.

The highest performances have been achieved by Mix 50/10/40, with compressive strength and indirect tensile strength at 7 days of curing up to 5.28 MPa and 0.428 MPa respectively, in relation to the hydraulic binder percentage.

The ratio between compressive and indirect tensile strength was within the range 9 to 11, in realtion to the EAF slag-foundry sand-bottom ash ratios. A very good Dynamic Elastic Modulus result has been observed for the mix characterized by the best results in the mix design, i.e. Mix 50/10/40.

The results of the elastic modulus trials have given further credit to the compressive strength investigation. In fact, significant correlations have been identified between UCS data and elastic modulus data for all the mixes.

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