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Reuse of steel slag in bituminous paving mixtures

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ABSTRACT

This paper presents a comprehensive study to evaluate the mechanical properties and environmental suitability of electric arc furnace (EAF) steel slag in bituminous paving mixtures. A variety of tests were executed on samples of EAF slag to characterize the physical, geometrical, mechanical and chemical properties as required by UNI EN specifications, focusing additionally on the volumetric expansion associated with hydration of free CaO and MgO. Five bituminous mixtures of aggregates for flexible road pavement were designed containing up to 40% of EAF slag and were tested to determine Marshall stability and indirect tensile strength. The leaching behaviour of slag samples and bituminous mixtures was evaluated according to the UNI EN leaching test. The tested slag showed satisfactory physical and mechanical properties and a release of pollutants generally below the limits set by the Italian code. Tests on volume stability of fresh materials confirmed that a period of 2–3 months is necessary to reduce effects of oxides hydration. The results of tests performed on bituminous mixtures with EAF slag were comparable with the performance of mixtures containing natural aggregates and the leaching tests provided satisfactory results.

1. Introduction

A recent study of the European Commission [1] showed that the percentage of primary slag per ton of steel produced in the UE is in the range of 12–15%, whilst the percentage of secondary slag is around 3%; these values are also confirmed by a research conducted in Germany in 2010 [2]. In Italy the production of primary slag in 2009 was estimated about 3 million tons [3]. More information about steel slag production is reported in other studies [4–6].

If not recovered, the steel slag is disposed of in landfills, thus increasing the amount of waste to be dumped. Reuse of steel slag as recycled material can be seen as a way to limit the amount of dumped wastes and allows to reduce the consumption of natural materials (i.e. natural aggregates). For these reasons, in the last two decades, a large number of experimental studies have been conducted to investigate the opportunity to partially substitute natural aggregates with steel slag as construction material [7–12].

The first studies on steel slag recovery in asphalt mixtures reported in literature dates back to the beginning of the 1970s [7]. Most of the researches in this field covered chemical, physical and geometrical properties [8,9,13–19]. In 2001, Motz and Geiseler [4] studied the possibility of reusing steel slag in road paving, focusing on the leaching tests to evaluate the environmental behaviour and on expansion tests to determine the volume stability. In 2003, a study conducted by Sorlini et al. [18], based on results of a previous research [20], was carried out to evaluate the steel slag recovery in road foundations. The slag was subjected to a chemical characterization in order to investigate the release of pollutants and the phenomenon of volume expansion. In 2010, De Windt et al. studied the kinetics of steel slag leaching through batch tests at liquid to solid ratios of 10 and 100 over a 30-day period and proposed a geochemical model validated with experimental data [21]. The evaluation of the mechanical properties on steel slag was done in several research projects [6,8,9,13,15,16,19], where results showed similar characteristics between the mixtures containing natural aggregates and steel slags.

In this study, an extensive experimental campaign was executed to investigate the possibility of steel slag recovery as a recycled aggregate for the production of bituminous paving mixtures. The experimental investigation included a geometrical, physical, mechanical and chemical characterization of electric arc furnace (EAF) slag and bituminous mixtures containing a fraction of slag. Special attention was given to the leaching properties and the volume stability due to the hydration of free lime and magnesium oxide.

2. Materials and methods

2.1. Steel slag

The experimental study was carried out on the slag of first fusion (i.e. primary slag), a by-product of the steel production process

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Table 1
Tests performed to investigate chemical properties of steel slag.

Test requirement (reference standard)			Steel slag sample								
			A		B	C	D	E	F	G	H
			0/20	14/32	0/32	0/32	0/100	0/32	0/32	14/32	0/22
M. D. '98 and	Chemical composition		x	x	–	–	–	x	–	–	–
M. D. 06/186	Oxides content (%)		x	x	–	–	x	x	–	–	–
	Lightweight organic contaminators (UNI EN 1744-1)		x	x	–	x	–	–	–	–	–
	Volume stability	Dicalcium silicate disintegration (UNI EN 1744-1)	–	–	–	x	–	–	–	–	–
		Iron disintegration (UNI EN 1744-1)	x	–	–	x	–	x	–	–	–
		Expansion of steel slag (UNI EN 1744-1)	–	–	–	–	–	–	–	–	x
UNI EN 13043	Magnesium oxide (UNI 196-2)		–	–	–	–	x	x	–	–	–
	Free lime	Complexometry method (UNI EN 1744-1)	x	–	–	–	–	–	–	–	–
		Acidimetry method (UNI EN 1744-1)	–	–	–	–	x	–	–	–	–
		Extraction with ethylene glycol (UNE 80243/86)	x	–	–	x	–	–	–	–	–
	Leaching test	Single stage test (UNI EN 12457-2)	x	x	x	x	x	–	x	x	–

at the "Feralpi S.p.A." factory, located in Lonato (Brescia, northern Italy). The steel is produced by EAF through direct fusion of ferrous scrap, reclaimed body parts of vehicles and the addition of lime, iron alloys, coal and oxygen. After collecting the slag from the furnace, a period of 3–4 months is allowed for aging in an unprotected open area and subsequently the material is sieved and transported to the company that operates the recovery. Aging and exposition to weather conditions are necessary to minimize subsequent volumetric changes due to oxidation. One month after transportation, the slag is crushed into two grain size fractions named "slag 0/20" (0–20 mm diameter) and "slag 14/32" (14–32 mm diameter).

Experiments were carried out on a number of samples obtained through the previously described process between July 2006 and July 2008. In the following discussion, slag samples will be labelled with letters from A to H (Table 1). Samples A, B, C, E, F and G (July 2006–December 2007) had grain size fractions "0/20" and "14/32" (in Table 1, label "0/32" indicates a mix, 50–50% by weight, of the two main fractions); sample D (January 2007) had grain size fraction 0–100 mm, obtained by mixing the above slag fractions with a coarser fraction provided by steel factory; sample H (July 2008), with grain size of 0–22 mm (required by UNI EN 1744-1), was selected for studying the effect of aging on the slag volumetric stability.

2.2. Bituminous mixtures

Five experimental bituminous mixtures for flexible road pavements were composed using quantities of aged steel slag as aggregate, available in the grain size ranges 0–20 mm and 14–32 mm. Two mixtures were prepared for the road base (respectively referred to as "Road base 30%" and "Road base 40%"), two mixtures for the base course (respectively "Base course 30%" and "Base course 40%") and one mixture for the wearing course ("Wearing course 20%"). Mixtures of aggregates were composed using first fusion steel slag with a percentage in the range of 20–40% by weight and natural aggregates of various size and shape (see Table 2 for mixture composition). The asphalt binder used was traditional bitumen of class 50/70 (UNI EN 1426:2002 or CNR BU n. 24/71); aggregates were hot-mixed (approximately 160 °C) with 3.8–5.5% of bitumen depending on the type of pavement layer (Table 2).

2.3. Experimental program

In the Italian legislation, the reference for the recovery of special wastes (such as steel slag) is the Legislative Decree 2006/152 [22], amended and supplemented by Legislative Decree 2008/04. The specific law that rules over the recovery and reuse of some special wastes, including steel slag, is the Ministerial Decree dated February 5th 1998 [23], amended and supplemented by Ministerial Decree 2006/186 [24]. Since 2004, the aggregates obtained from natural or recycled materials have been certified with the CE mark, in accordance with UNI EN 13043:2004 [25] if used for the realization of roads, airfields and other trafficked areas.

In compliance with UNI EN 13043:2004, a large number of tests were carried out to evaluate geometrical, physical (mechanical) and chemical properties of the steel slag.

2.3.1. Geometrical and physical properties of steel slag

Geometrical properties comprise size, shape and angularity of the aggregates. Particle size is essential for the subsequent composition of the mixtures of aggregate, whereas shape and angularity are essential parameters for obtaining mixtures of high stability and roughness; the presence of elements with sharp edges gives the material a high friction angle, it affects the roughness of the surface layers and reduces pavement rutting under the traffic load [26].

Table 2
Experimental bituminous mixtures: grain size composition and quantity of bitumen.

Aggregates	Particle size (mm)	Mixtures – percentage composition (% by weight)				
		Road base 30%	Road base 40%	Base course 30%	Base course 40%	Wearing course 20%
Slag						
Slag 0/20	0–20	15	20	30	40	20
Slag 14/32	14–32	15	20	–	–	–
Natural aggregate						
Filler	0–0.075	5	5	5	5	7
Crushed 0/4	0–4	24	22	30	30	32
Crushed 2/8	2–8	15	10	15	10	20
Crushed 6/14	6–14	–	–	10	8	21
Crushed 10/20	10–20	11	12	10	7	–
Round 14/32	14–32	15	11	–	–	–
Bitumen class 50/70 (% by weight)		3.8	4.2	4.5	4.8	5.5

Regarding the physical properties, the value of the Los Angeles test (UNI EN 1097-2 Tests for mechanical and physical properties of aggregates—Part 2: Methods for the determination of resistance to fragmentation) is required for the assessment of the resistance to fragmentation. The micro-Deval test (UNI EN 1097-1 Tests for mechanical and physical properties of aggregates—Part 1: Determination of the resistance to wear (micro-Deval)) provides a measure of the resistance to wear by friction, and the accelerated polishing coefficient is used to assess the ability of the material to be consumed on the surface and its ability to become slick. In addition, it is necessary to determine the particle surface absorption, the affinity between aggregate and bitumen, the sensitivity to frost action (depending on material nature and structure) and the behaviour in case of high temperature changes (during mixing with bitumen and road construction).

2.3.2. *Chemical properties of steel slag*

The chemical characterization of the steel slag was carried out with tests listed in Table 1, in agreement with the requirements of the Ministerial Decree February 5th 1998, for the recovery of non-hazardous waste. The release of pollutants was evaluated through the compliance test provided by the Ministerial Decree 2006/186 and according to the method UNI 12457-2 [27] of extraction in a single stage in demineralized water (liquid/solid ratio, L/S = 10) for a period of 24 h. Chemical requirements were also investigated according to UNI EN 13043.

The following three tests were performed to evaluate the presence of chemical components that affect volume stability: determination of dicalcium silicate and iron disintegration of air-cooled blast-furnace slag and direct measurements of steel slag expansion. The latter test is the most significant for this type of waste and allows to detect its predisposition to expansion due to a late hydration of lime and magnesium oxide. A testing time of 7 days (168 h), for EAF slag, must be allowed and the values of expansion should be compared with the categories specified in UNI EN 13043. The analysis of free CaO, which, together with MgO, may be responsible for the volume expansion of the slag, was carried out with the complexometry method, the acidimetry method and, according to the Spanish standard UNE 80243/86 [28], by extraction with ethylene glycol.

Five expansion tests were performed – 15, 30, 60, 120 and 190 days after production – on slag sample H (July 2008), specifically selected for studying the effects of aging on volume stability. The expansion tests were carried out following the method UNI EN 1744-1 [29] and first proposed by Motz and Geiseler in 2001 [4]. The results were compared with the limit value proposed by ASTM D 2940-98 "Standard specification for graded aggregate material for bases or subbases for highways or airports" [30].

2.3.3. *Physical–mechanical properties and leaching of bituminous mixtures*

The following documents were adopted as a reference: Bulletin n. 178/95 National Research Council (CNR BU 178/95) [31], a popular national standard that identifies road pavement types; the standard Technical Specifications document of the Province of Brescia [32]; the standard Technical Specifications of the "Brescia-Verona-Vicenza-Padova Motorway" Company [33].

The tests carried out for the characterization of the experimental bituminous mixtures comprise both the Marshall test for studying the characteristics of stability, and the indirect tensile strength test on specimens of wearing course bituminous mixtures. The percentage of residual voids was measured, after compaction, in order to assess the leaching properties of conglomerates. In addition, the release of pollutants was verified through the compliance test of extraction in a single stage provided by the method UNI 12457-2.

3. Results and discussion

3.1. *Tests performed on steel slag*

3.1.1. *Results of the geometrical and physical characterization tests*

The results of the characterization tests, performed on samples A and B of slag 0/20 and 14/32, are summarized in Table 3; a comparison with typical values referring to natural aggregates is proposed. Fig. 1 shows the grain size distribution curves of the fractions studied. Regarding the geometrical requirements of the aggregates, the test results for the assessment of the flakiness and shape indexes indicated that, due to the crushing process during maturation stages, the percentage of flat or non-polyhedral elements is fairly limited (1–6%), contributing to ensure high stability characteristics of the mixtures.

In terms of physical requirements, the Los Angeles test gave values of about 22–23%, whilst the micro-Deval test resulted in the range 6.5–9.5%, showing that the steel slag has a fair resistance to fragmentation and wear and can be used in any layer of a flexible pavement; the results were below the 25% limit set by the Technical Specifications of the Province of Brescia, although it appeared higher than typical values obtained with traditional aggregates such as basalt and porphyry. Since the result of the Los Angeles test is one of the most important parameters for road use, tests of resistance to fragmentation were performed weekly on the material collected in the period from January 2007 to the end of April

Table 3
Tests results to determine geometrical and physical properties of slag.

Geometrical and physical requirements	Unit	Steel slag sample				Natural aggregates
		A		B		
		0/20	14/32	0/20	14/32	
Flakiness index (EN 933-3)	–	4	6	1	3	–
Shape index (EN 933-4)	–	4	3	2	4	–
Percentage of crushed and broken surfaces (EN 933-5)	%	100	100	100	100	–
Resistance to fragmentation, Los Angeles (EN 1097-2)	%	22	23	23	23	10–20
Resistance to wear, micro-Deval (EN 1097-1)	%	6.5	8.6	9.3	9.5	5.0–8.0
Resistance to polishing (EN 1097-8)	–	0.44	–	0.47	–	0.40–0.50
Aggregate unit weight (EN 1097-6)	kN/m^3	20.97	16.70	20.92	16.32	–
Specific gravity (EN 1097-6)	kN/m^3	39.1	39.0	39.6	39.2	26.0–28.0
Particles water absorption (EN 1097-6)	%	1.7	1.5	2.2	2.0	1.0–2.0
Freeze–thaw resistance (EN 1367-1)	%	0.3	0.5	1.1	2.1	0.2–0.8
Thermal shock resistance (EN 1367-5)	%	1	–	2	–	1–3
Aggregate–bitumen affinity (prEN 12697-11)	%	15	–	10	–	5–10

Note: – = test not carried out/data not available.

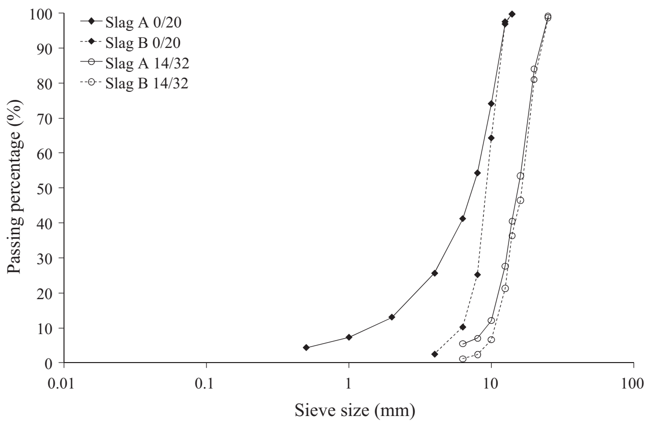

Fig. 1. Grain size distribution curves of steel slag samples A and B.

2007 and the results confirmed the fair mechanical properties of the material. Results were also comparable with the values obtained in other recovery research projects [4,14,15,18,20]. The result of the Los Angeles test may be affected by the structure of the slag and the presence of inner voids in the grains due to the cooling process.

The values of the accelerated polishing coefficient (APC) were in the range 0.44–0.47 and comparable to those of natural materials such as porphyry (APC = 0.45–0.48) or basalt (APC = 0.42–0.45); the particle water absorption was between 1.5 and 2.2%, in the range of traditional materials for the construction of road pavements. Other features, including the freeze–thaw resistance and the aggregate–bitumen affinity, were comparable with the values usually obtained from natural aggregates. The value of the aggregate unit weight was approximately 20.9 kN/m^3; the specific gravity of the grains, instead, was in the range from 39.1 to 39.6 kN/m^3, approximately 1.5 times the specific gravity of natural soil (Table 3).

3.1.2. *Results of the chemical characterization*

High concentrations of total chromium, barium, iron, manganese and aluminium were found in the chemical composition of the slag (Table 4). For most of the elements (Cu, Cr_{tot}, Zn, Ba, Co, V, Fe, Mn) a greater concentration was identified in sample A and E with grain size range 14–32 mm, whilst concentration of other elements, such as Cu, Cr_{tot}, B, did not vary with grain size. The different results in different samples are due to the heterogeneous characteristics of the materials fed into the electric arc furnace.

The total content of oxides (SiO_2, CaO, Al_2O_3, MgO and FeO, see Table 4) was in the range 59.8–89.2%; only in three cases this percentage was higher than the minimum value of 80% required by the Ministerial Decree of 1998 for the recovery of such wastes with a simplified procedure [23,24]. The greater percentage was due to the oxides of calcium, silicon and iron and, generally, metal and oxide concentrations were higher in the 14/32 fraction than in the 0/20 one. The concentration of lime (expressed as total CaO) and magnesium oxide (MgO), which are the most significant parameters for volume stability, were in the range 16–22% and 2–3%.

The analysis of free lime was carried out according to different methods. The Spanish method [28] provided a value of 0.07% on sample C and a value equal to zero on sample A of slag 0/20. The acidimetry method [29] on slag D showed a concentration of free lime of 0.33% and the only sample analysed with the complexometry method [29] did not provide any results. Data obtained were lower than the limit value of 4% indicated in the literature [4] and reported by German law as the limit for the recovery of slags; furthermore, these values were lower than those reported in a previous study by Sorlini et al. on the same residues [18].

The dicalcium silicate disintegration was evaluated by the analysis of the slag surface that, exposed to UV radiation, always showed a uniform colour, typical of the stable samples and not subjected to the phenomena of disintegration.

The evaluation of the iron disintegration, due to the hydrolysis of iron and manganese sulphides in the sample placed in water for 2 days, did not show significant phenomena of cracking or crushing.

Coarse lightweight organic contaminants, larger than 2 mm, were analysed in two samples and they always resulted lower than the maximum value of 0.1% allowed for the category m_{LP} 0.1 of the standard UNI 13043.

Table 4
Steel slag chemical composition and percentage of oxides content.

Parameter	Unit	Steel slag sample				
		A		D	E	
		0/20	14/32	0/100	0/20	14/32
Lead (Pb)	mg/kg	26.6	30.0	–	29.3	25.9
Antimony (Sb)	mg/kg	<0.005	<0.005	–	53.200	59.300
Copper (Cu)	mg/kg	1.1	250.1	–	272.8	323.6
Cadmium (Cd)	mg/kg	3.5	4.5	–	21.7	21.3
Total chromium (Cr_{tot})	mg/kg	2,428.3	4,850.4	–	871.3	933.6
Arsenic (As)	mg/kg	<0.001	<0.001	–	<0.001	0.400
Selenium (Se)	mg/kg	<0.01	<0.01	–	<0.01	<0.01
Mercury (Hg)	mg/kg	<0.001	<0.001	–	<0.001	<0.001
Zinc (Zn)	mg/kg	199.5	215.8	–	259.7	301.2
Barium (Ba)	mg/kg	1,276.7	1,412.7	–	1,252.1	1,233.7
Beryllium (Be)	mg/kg	<0.001	<0.001	–	<0.001	<0.001
Cobalt (Co)	mg/kg	1.1	4.8	–	3.7	5.1
Nickel (Ni)	mg/kg	16.6	187.5	–	156.1	105.4
Vanadium (V)	mg/kg	222.6	268.8	–	307.2	368.9
Aluminium (Al)	mg/kg	33,875.7	35,761.4	–	30,222.5	29,959.5
Boron (B)	mg/kg	217.60	225.70	–	<0.01	<0.01
Iron (Fe)	mg/kg	256,713	359,353	–	301,466	34,229
Manganese (Mn)	mg/kg	27,845	34,875	–	32,776	35,361
Total silicon (SiO_2)	%	12.90	17.20	10.25	18.59	19.10
Calcium oxide (CaO)	%	18.65	22.10	17.93	18.28	16.46
Aluminium oxide (Al_2O_3)	%	5.32	6.35	7.20	5.80	5.84
Magnesium oxide (MgO)	%	2.00	2.35	3.10	2.53	2.02
Iron oxide (FeO)	%	20.92	29.84	50.71	35.71	36.71

Table 5
Concentrations of the pollutants in the leachate, obtained in compliance with UNI EN 12457-2.

Parameter	Unit	Steel slag sample							Limits of M. D. 06/186
		A		B	C	D	F	G	
		0/20	14/32	0/32	14/32	0/100	0/32	14/32	
pH	–	7.1	6.8	9.9	10.9	11.7	11.2	11.3	5.5–12.0
Mercury	μg/L	<1.0	<1.0	0.9	<1.0	<1.0	<1.0	<1.0	1.0
Vanadium	μg/L	118	120	91	180	77	110	120	250
Selenium	μg/L	<10.0	<10.0	1.0	<1.0	<5.0	<5.0	1.5	10.0
Zinc	mg/L	<0.01	0.07	<0.01	<0.01	<0.01	0.07	<0.01	3.00
Total chromium	μg/L	6	15	8	<5	<10	15	30	50
Copper	mg/L	0.007	0.010	<0.005	<0.010	<0.010	<0.010	<0.010	0.050
Barium	mg/L	0.27	0.43	0.23	0.26	0.30	0.05	0.30	1.00
Arsenic	μg/L	<1	<1	<5	<10	<10	<10	<10	50
Cadmium	μg/L	<1.0	<1.0	<0.5	<3.0	<3.0	<3.0	<3.0	5.0
Fluorides	mg/L	0.15	0.16	0.40	0.20	0.10	1.00	0.10	1.50
Chlorides	mg/L	2.0	2.9	2.7	1.0	<1.0	3.0	1.0	100.0
Sulphates	mg/L	6.8	12.0	5.2	<1.0	3.0	3.0	3.0	250.0
Nitrates	mg/L	1.4	5.1	1.5	3.0	<3.0	0.5	<1.0	50.0
DOC	mg/L	21.3	29.7	9.0	<1.0	11.0	<5.0	<1.0	30.0

Note: for all samples the following concentrations were also found: no asbestos, Pb < 5 μg/L, Ni < 10 μg/L, Be < 1 μg/L, Co < 5 μg/L, and CN < 50 μg/L.

3.1.3. *Results of the leaching test*

The leaching tests (UNI EN 12457-2) performed on all available samples provided values below the limits indicated in the Ministerial Decree 2006/186 (Table 5). For most of the parameters, higher pollutant concentrations were measured in the finest grain size fraction slag, due to its higher specific surface. Vanadium, total chromium and nitrate showed a variable concentration amongst the different samples. The release of organic matter (dissolved organic carbon, DOC) of slag sample A reached concentrations close to the limit, whilst it remained well below in other cases.

3.1.4. *Volumetric expansion test results*

The results of the volumetric expansion, obtained from five tests carried out on slag H (specifically selected for studying the aging effects on the volumetric stability), are shown in Fig. 2 as a function of time in a logarithmic scale, to illustrate that significant expansion occurs within 12 h of the test. Each curve was obtained from tests performed at different time intervals after slag production (15, 30, 60, 120 and 190 days) and represents the average of two tests carried out on specimens obtained from the same sample. Fig. 3 shows the volumetric expansion measured at the end of each performed test, as a function of the slag aging period, and it indicates that the volumetric expansion ε_v (at the end of the test) is in inverse proportion to the slag aging time: Test 1, carried out on the "fresh slag" (approximately 15 days of aging), gave $\varepsilon_v \approx 0.6\%$ at 168 h; Test 5, performed on the aged one (approximately 6 months after tapping), gave a $\varepsilon_v \approx 0.1\%$. Only Tests 3, 4 and 5 met the requirement of ASTM D 2940-98 "Standard specification for graded aggregate material for bases or subbases for highways or airports". To ensure acceptable volume stability, an aging period of at least 2–3 months is therefore advisable [34].

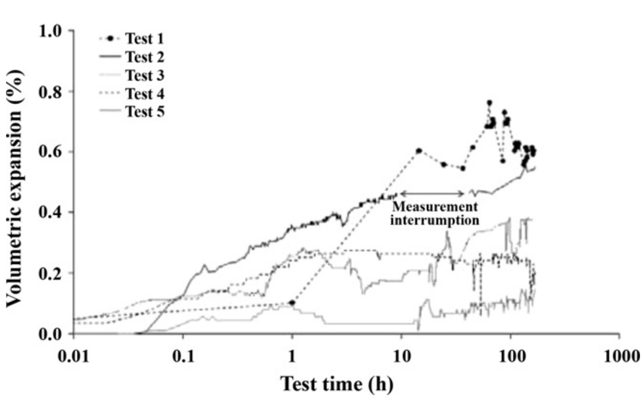

Fig. 2. Volumetric expansion as a function of test time.

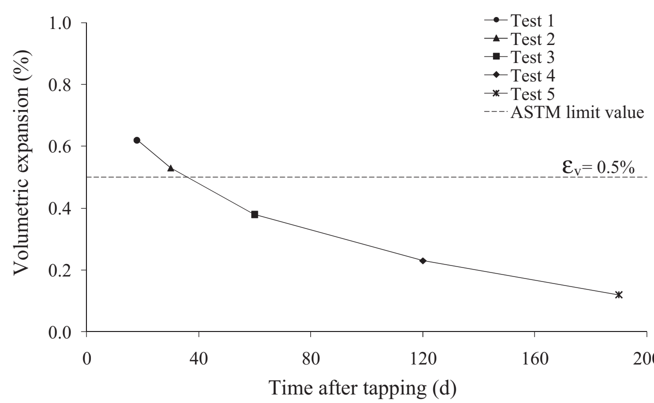

Fig. 3. Volumetric expansion as a function of aging time.

3.2. *Results of tests on bituminous mixtures*

Tables 6–8 show the results of the tests on conglomerate samples for road base, base course and wearing course, prepared by using steel slag and natural stone aggregates in percentages indicated in Table 2. Each table refers to a type of conglomerate with a given quantity of slag. The slag sample identification letter is reported and a comparison with acceptance limits given by the CNR Bulletin 178/95 and other reference documents is suggested. In addition, for each type of mixture, the comparison with results of the same tests conducted on mixtures with natural aggregates is proposed.

Tests performed on bituminous mixture samples for the road base (slag percentage of 30 and 40%, Table 6) provided values above minimum requirements set by the CNR Bulletin n. 178/95 and by the Technical Specifications documents. In particular, for both mixtures, the stability and stiffness values, obtained in the Marshall test, were significantly higher than the limits of acceptance. The comparison with the data obtained from mixtures with natural aggregates showed that the performance of the experimental bituminous mixtures was similar or even better than the traditional mixtures. Compared with the natural aggregate mixtures, the experimental ones gave a higher percentage of residual voids

Table 6
Road base test results and comparison with natural aggregate mixtures.

Parameter	Unit	Mixture Road base 30%	Mixture Road base 30%	Mixture Road base 40%	Natural aggregates mixture	Reference values	
Slag content	% by weight	30	30	40	0	CNR BU 178/95[a]	Motorway spec.
Slag sample		A	B	A	–		
Marshall stability	daN	1,564	1,721	1,694	1,558	>800	>900
Marshall flow	mm	2.7	2.9	2.9	3.2	1.5–3.0	–
Marshall stiffness	daN/mm	595	591	595	511	>250	>250
Residual voids	%	5.6	5.1	4.4	2.9	4.0–7.0	4.0–7.0
Voids filled with bitumen	%	62.3	66.4	71.3	77.3	<80.0	–
Apparent density	g/cm^3	2.633	2.685	2.725	2.496	–	–

[a] Similar values are adopted in Brescia Province Technical Specifications.

Table 7
Base course test results and comparison with natural aggregate mixtures.

Parameter	Unit	Mixture base course 30%	Mixture base course 30%	Mixture base course 40%	Natural aggregates mixture	Reference values	
Slag content	% by weight	30	30	40	0	CNR BU 178/95[a]	Motorway spec.
Slag sample		A	B	A	–		
Marshall stability	daN	1,681	1,660	1,709	1,487	>1,000	>1,100
Marshall flow	mm	2.8	2.8	2.7	2.3	1.5–3.0	–
Marshall stiffness	daN/mm	602	607	639	657	>300	>300
Residual voids	%	6.9	6.9	6.0	2.4	3.0–6.0	3.0–7.0
Voids filled with bitumen	%	61.3	61.5	66.2	82.3	<80.0	<80.0
Apparent density	g/cm^3	2.571	2.608	2.648	2.469	–	–

[a] Similar values are adopted in Brescia Province Technical Specifications.

(4.4–5.6% rather than 2.9% of the natural aggregate mixture), and a lower percentage of voids filled with bitumen (62–71% against the 77% of the natural aggregate mixture). Due to the high specific gravity of the steel slag, the density of the experimental mixtures was 7–9% higher than the traditional mixtures.

Tests performed on bituminous mixture samples for the base course (steel slag percentage of 30 and 40%, Table 7), provided acceptable results as well. The stability and stiffness values, obtained by the Marshall test, were significantly higher than the limits of acceptance, indicated by the CNR Bulletin n. 178/95 and by the Technical Specifications, and even better than the values obtained from the tests done on the natural aggregate mixture. The residual voids resulted high and the apparent density of the Marshall test specimens were 6–8% higher than mixtures with natural aggregates.

A summary of test results performed on samples of wearing course is reported in Table 8. Satisfactory results were obtained from this experimental mixture. In particular, values of Marshall stability (even after submersion in a water bath at 60 °C for 24 h) and indirect tensile strength were higher than the limits of acceptance, showing suitable characteristics of mechanical resistance, comparable to the performance of traditional mixtures. The value of the apparent density was 7% higher than the natural aggregate mixture.

As expected, the release of pollutants from the experimental bituminous mixtures, complied with UNI EN 12457-2, was below the limits of the Ministerial Decree 2006/186 for all samples. The concentrations of all pollutant elements were widely below the limits, as reported in Table 9. The presence of the steel slag determined an increase in pH, concentration of vanadium, zinc, total chromium, fluorides, chlorides and nitrates for all mixtures. The most critical parameter, even if widely below the limit, was again vanadium, for which no enclosing or binding effect due to the bitumen was appreciated.

Table 8
Wearing course test results and comparison with natural aggregate mixtures.

Parameter	Unit	Mixture Wearing course 20%	Mixture Wearing course 20%	Natural aggregates mixture	Reference values	
Slag content	% by weight	20	20	0	CNR BU 178/95[a]	Motorway spec.
Slag sample		A	B	–		
Marshall stability	daN	1,806	1,734	1,506	>1,200	>1,200
Marshall flow	mm	2.9	2.8	2.8	1.5–3.0	–
Marshall stiffness	daN/mm	624	615	528	>350	>350
Residual voids	%	4.8	2.4	2.0	3.0–6.0	3.0–6.0
Voids filled with bitumen	%	73.2	84.5	86.0	<80.0	–
Apparent density	g/cm^3	2.550	2.601	2.456	–	–
Stability after submersion	%; daN	95.5; 1,725	94.0; 1,636	–	–	–
Indirect tensile strength	N/mm^2	1.05	0.97	–	>0.70	0.60–1.00

[a] Similar values are adopted in Brescia Province Technical Specifications.

Table 9
Concentrations of the pollutants in the leachate, obtained in compliance with UNI EN 12457-2.

Parameter	Unit	Natural aggregates mixtures			Mixtures with steel slag			Limits of M. D. 2006/186
		Road base	Base course	Wearing course	Road base	Base course	Wearing course	
Bitumen	%	4.2	4.8	5.5	4.2	4.8	5.5	–
pH	–	8.4	8.8	8.4	10.5	9.5	10.6	5.5–12.0
Vanadium	μg/L	2.4	9.6	2.8	147.4	99.0	146.0	250.0
Zinc	mg/L	0.003	0.002	0.001	0.002	0.018	0.023	3.000
Total chromium	μg/L	2.2	7.5	2.6	16.1	12.2	6.0	50.0
Copper	mg/L	0.001	0.002	0.037	0.002	<0.001	<0.001	0.050
Barium	mg/L	0.079	0.028	0.242	0.120	0.035	0.041	1.000
Beryllium	μg/L	<1	<1	<1	<1	<1	3	10
Arsenic	μg/L	<1.0	4.0	4.4	2.3	<1.0	5.0	50.0
Fluorides	mg/L	0.043	0.040	0.043	0.152	0.260	0.260	1.500
Chlorides	mg/L	0.500	0.446	0.421	0.734	2.300	2.300	100.000
Sulphates	mg/L	3.250	2.859	3.133	6.081	1.700	2.700	250.000
Nitrates	mg/L	0.378	0.474	0.267	15.665	0.900	3.500	50.000

Note: for all samples the following concentrations were also found: no asbestos, Pb < 5 μg/L, Ni < 10 μg/L, Se < 10 μg/L, Co < 5 μg/L, CN < 50 μg/L, Hg < 1 μg/L, Cd < 1 μg/L, and DOC < 10 mg/L.

4. Conclusions

Several tests were executed to characterize physical, geometrical, mechanical and chemical properties of EAF slag; five bituminous mixtures of aggregates (containing up to 40% of EAF slag) were designed and tested. From a mechanical point of view, the fragmentation and wear resistance provided acceptable results (22–23% and 6.5–9.5% respectively); the values of the accelerated polishing coefficient (0.44 and 0.47) and water absorption (1.5–2.2%) were comparable with values obtained with natural materials, such as porphyry and basalt. The bituminous mixtures containing steel slag showed mechanical characteristics similar or even more satisfactory than the mixtures obtained using natural aggregates (measured values of Marshall Stability generally higher than 1600 daN, average Marshall flow of 2.8 mm). From a chemical point of view, slag samples had a relevant content of total chromium (up to 4850 mg/kg), barium (up to 1413 mg/kg), aluminium (in the range 30,000–35,000 mg/kg), iron (up to 359,353 mg/kg) and manganese (in the range 28,000–33,000 mg/kg). The release of pollutants from the leaching test cannot be regarded as negligible although it resulted lower than the limits indicated in the Ministerial Decree 2006/186: for instance the release of mercury in sample B was 0.9 μg/L (with a limit of 1.0 μg/L), vanadium in sample C was 180 μg/L (with a limit of 250 μg/L), total chromium in sample G was 30 μg/L (with a limit of 50 μg/L) and DOC in sample A was 29.7 mg/L (with a limit of 30 mg/L). Free lime and magnesium oxide concentrations, responsible for expansive phenomena, were 16–22% and 2–3% respectively. Measurements of volumetric expansion (ε_v = 0.62%, obtained from fresh material 15 days after tapping) resulted in inverse proportion to the aging time and suggest that a period of 2–3 months must be allowed before reuse. The release of pollutants measured in leaching tests performed on the experimental bituminous mixtures resulted acceptable, except for total chromium (16.1 μg/L) and vanadium (147.4 μg/L), and generally lower than that of the slag alone.

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