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Recycling of waste aggregate in cement bound mixtures for road pavement bases and sub-bases

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HIGHLIGHTS

- Cement bound mixtures (CBMs) with natural aggregate are used in road foundations.
- Six types of CBMs have been optimized, using five different waste materials.
- Physical–mechanical and leaching properties of the materials were investigated.
- Several tests have been carried out to characterize the mechanical performance.
- Not conventional CBMs give a relevant contribution to the bearing capacity.

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ABSTRACT

This paper discusses the results of a study aimed at designing cement bound mixtures for road construction, made with steel slag, ladle furnace slag, waste foundry sand, glass wastes and coal ash.

The mixtures were designed by means of Proctor, compression and indirect tensile tests. Their performance was investigated in terms of elastic modulus, through ultrasonic tests at different curing times. Satisfactory results were obtained, compression and indirect tensile strength at 7 days being up to 7.56 MPa and 0.78 MPa respectively, depending on the composition of the mixtures.

1. Introduction

The recycling of solid waste materials (SWM) in civil construction has been widely investigated in the last decades, as documented by several studies [1–19]. Among the different types of SWM, industrial by-products represent some of the most interesting for civil engineering applications [1–19].

Sas et al. [1] recently studied some chemical and physical–mechanical properties of steel slags used as material for a road subbase. From a chemical point of view, they stated that the steel slags can be used in pavement structures with no toxicological hazards, because the high contents of zinc and chromium measured are strongly associated with the slag internal microstructure. They reported satisfactory results in terms of California bearing ratio, as well as Young's modulus and resilient modulus, for some significant moisture contents and compaction conditions, with respect to the road subbase acceptance requisites. Manso et al. [2] verified the satisfactory durability of cement concretes made with electric arc furnace steel slags, with regard to the most severe environmental agents, ice and moisture. They also studied the toxicological potential, in terms of heavy metals, of both the steel slags and cement concretes. They found higher concentrations of toxic substances in the smaller particles of crushed steel slags, but also reported a cloistering effect of the cement concrete on the leaching behaviour, which therefore resulted as admissible within the regulations. Qiang et al. [3] analyzed the influence of ground basic

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Abbreviations: UCS, unconfined compression strength; ITS, indirect tensile strength.

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oxygen furnace steel slags on both mechanical resistance and durability of cement concrete. They found that cement concrete with more than 30% of steel slag presented a lower compressive strength than a reference cement mixture without steel slag, at a water/cement ratio of 0.5. Reducing the water/cement ratio to 0.35, cement concrete with and without steel slag gave the same results. However, for low water/cement ratio, the steel slags had less influence on the drying shrinkage of the cement concrete, as well as on its permeability to chloride ions. The carbonation resistance of the cement concrete was also less affected by a high volume of steel slags at low water–cement ratio. Papayianni and Anastasiou [4] investigated the feasibility of recycling high contents of fly ash and ladle furnace slag as binders, and electric arc furnace slag as aggregates, for the production of cement concrete; their findings were very interesting, being characterized by high compressive strength, abrasion resistance and fracture toughness. Anastasiou et al. [5] investigated cement concretes made with fly ash as hydraulic binder instead of cement, recycled fine aggregates from construction and demolition wastes, as well as steel slag, instead of coarse conventional aggregates. They found that the use of the fine aggregates reduced strength and durability of the cement concrete and increased porosity. However, combining steel slag with the fine aggregates made it feasible to partially reduce the strength and durability loss. The substitution of 50% of cement with fly ash, along with a high volume of steel slag and fine aggregates, led to satisfactory results in terms of both strength and durability of the concrete. Etxeberria et al. [6] studied the mechanical behaviour of cement concretes made with two different types of foundry sand, electric arc furnace slags and blast furnace slag, as substitutes for raw sand and aggregates. They conducted slump tests, compressive and tensile tests, elastic modulus tests, verifying satisfactory results for the cement concrete made with the industrial by-products, in comparison with a conventional cement concrete. Ondova and Stevulova [7] evaluated the use of fly ash from coal combustion wastes, as partial substitute for cement in road cement concrete. Adequate compressive strength, as well as frost and chemical resistance, was achieved for the road cement concrete prepared using up to 15% of coal fly ash as binder. The authors also stated the environmental and economic advantages related to the recycling of coal fly ash. Guney et al. [8] conducted a laboratory study on soil-foundry sand mixtures, stabilized with cement and lime, for road subbase. Compressive strength, California bearing ratio, hydraulic conductivity, as well as leaching tests were done in order to verify the performance of the mixes. It was found that the mechanical behaviour was strictly related to the curing time, compaction energy, cement and lime contents. No hazardous leaching was found for the mixes with foundry sand investigated in the study.

Experiments on the use of foundry sand in controlled low-strength materials and concrete were conducted by Siddique et al. [9,10]. The results of leaching tests showed high concentrations of zinc, copper and lead, above the regulatory thresholds, so demonstrating hazardous behaviour of the raw material, if used without any additive. Siddique et al. [11] replaced natural sand, up to 20% by weight, in the production of cement concrete, studying its compressive and tensile strength at different curing times, as well as elastic modulus and ultrasonic pulse velocity. The results were quite satisfactory, with some improvement in the mechanical strength and durability of cement concrete containing the foundry sand. Topçu and Canbaz [12] used glass waste, up to 60% by weight, as coarse aggregate for cement concrete. It was verified that glass waste did not significantly affect the workability of the concrete, but it led to a limited, but not negligible, reduction in strength. The alkali–silica reaction (ASR), i.e. the chemical reaction that develops between the silica-rich glass grains and the alkali in the pore solution of concrete, was also considered. Meyer et al. [13] thoroughly discussed the ASR, which causes cracks upon expansion, weakens the concrete and shortens its life. They defined a number of measures to reduce the damaging effects of ASR: the use of glass wastes as fine aggregate in cement concrete production appears to be promising and technically feasible. Gautam et al. [14] conducted laboratory tests to study the recycling of glass wastes as both coarse and fine aggregate for cement concrete. They found that the use of glass wastes for fine aggregate replacement, up to 20% by weight, led to an increase in the compressive strength after 28 days ageing, even if with marginal reductions in the mechanical resistance for further increments of the waste glass content. Ammash et al. [15] investigated the feasibility of glass wastes recycling, using the 0/5 mm fraction, dosed between 10% and 40% by weight, as a fine aggregate in cement concrete and mortar. When 20% of glass wastes were used, the compressive strength at 28 days ageing was very close to that of the reference concrete made with conventional aggregates. Marginal expansion phenomena were observed for mortars with more than 20% by weight of recycled aggregate. Shayan and Xu [16] outlined that the ASR problem in cement concrete made with waste glass was strictly related to the glass content and its particle size. They found a satisfactory compressive strength of concretes made with large amounts of both coarse and fine waste glass, when replacing 25% of cement with fly ash; indeed any pozzolanic material, such as fly ash, silica fume or ground furnace slag, allows an effective ASR-suppressant action to be achieved. The authors also successfully studied the replacement of fine glass powder used as pozzolanic material, at up to 30% of the cement content.

The above studies demonstrate that the recycling of specific industrial wastes, mostly considered individually, in cement concrete for civil engineering constructions, has been widely investigated. However, the known applications concern the use of single or paired by-products and not their extensive use. This paper describes the combined and simultaneous use of five different industrial by-products for the production of cement mixtures. The laboratory study was conducted in order to verify the feasibility of simultaneously recycling different waste materials: steel slag, ladle slag, foundry sand, coal ash and glass wastes, in the aggregate structure of cement bound mixtures for road pavement foundations. The analysis investigated the five waste materials individually, plus their mixtures in six different proportions.

2. Materials and methods

2.1. Materials

Five types of waste materials, i.e. steel slag, ladle slag, foundry sand, glass wastes and coal ash, were used at various percentages in six different aggregate structures for cement bound mixtures to be used in road foundations. All the waste materials were provided by private Italian companies, located in the province of Padua (North-eastern Italy, Veneto Region), specialising in the recovery, valorisation and re-utilization of industrial by-products for road infrastructure.

The steel slags are a by-product of the steel industry based on electric arc furnaces (EAF). There are two types of EAF slags, from different suppliers, and named EAF B and EAF C. Ladle slag (LFS), also named "white slag", is the waste material that can be recovered in a ladle furnace for secondary metallurgy, after the casting process. Spent foundry sand (SFS) is a by-product of the steel and iron industry, usually characterized by a quite heterogeneous composition, recovered after the repeated use of high quality silica or lacustrine sand for the casting moulds necessary in the smelting processes of metallic or non-metallic products. The recycled glass wastes (RGW) come primarily from broken wine bottles, therefore coloured glass, which cannot be recycled by melting down for the production of new glass. Fly ash (CFA) is a fine dust, basically a by-product from the combustion of pulverized coal, which is transported from the combustion chamber by exhaust gases.

Portland cement CEM II/B LL 32.5R was used as hydraulic binder for all the cement bound mixtures in the investigation. The water used was transparent and without harmful contents of glucose, salts, acids, alkalis, other chemical or organic substances, as prescribed by the regulations.

2.2. Methods

2.2.1. Aggregates analysis

In order to be recycled in road infrastructures, any waste material has to be investigated for toxic compound concentrations, because of potential heavy metals leaching. The toxicological properties of the recycled aggregates were therefore investigated, in terms of initial concentrations of heavy metals, by means of the ICP-AES methodology (Inductively Coupled Plasma – Atomic Emission Spectrometer). The leachate was also evaluated by the TCLP (Toxic Characteristic Leachability Procedure). This is a commonly used test for analysing the leaching properties of hazardous waste materials, and was conducted on the aggregates before any other physical–mechanical testing, in order to evaluate their environmental compatibility. The TCLP involves end-over-end agitation, a 20:1 liquid-to-solid ratio and an equilibrium time fixed at 18 h. A sample of at least 100 g is extracted using a proper leaching solution; after agitating it for 18 h, the extracts are separated from the solids by means of a glass fibre filter [9] and then analysed. The inductively coupled plasma–atomic emission spectrometer (ICP–AES) methodology was used for this.

The most relevant physical–mechanical properties of the recycled materials were evaluated, following the proper test protocols that are specific to the road sector: grading analysis (UNI EN 933-1 [20]), equivalent in sand (UNI EN 933-8 [21]), shape and flakiness index (UNI EN 933-4 [22], UNI EN 933-3 [23]), Los Angeles coefficient (UNI EN 1097-2 [24]), particle density (UNI EN 1097-6 [25]), plasticity index (UNI CEN ISO/TS 17892-12 [26]).

2.2.2. Mix design procedures

The main phases in the mix design of cement bound mixtures with granular behaviour (i.e., materials necessitating compaction when being laid), once the type of aggregate materials has been selected, are the grading curve design, followed by water and cement content optimization [27].

The aggregate structure was entirely composed of the waste granular materials considered in the study and, aiming to rework the recycled aggregates as little as possible, the design grading curves of the mixes were those resulting from the combination of the raw materials in different quantities. Therefore, at the mixing stage, the recycled aggregates were combined in their original conditions, each with its particular grading curve, without a specific division of the single fractions.

The compaction characteristics of the integrated granular mixtures were analyzed by means of Proctor compaction tests (EN 13286-2 [28]), in order to evaluate the maximum dry density and corresponding water content. This value can be assumed in the optimization of cement bound mixtures in order to limit the tests related to the 7-day ageing times.

The water and cement percentages were identified by testing the Unconfined Compressive Strength (UCS) of a series of cylindrical samples (150 mm in diameter and 120 mm in height) prepared using the same type of granular material, same grading assortment, but different water and cement contents (the amount of hydraulic binder was varied at intervals of 0.5% by weight of the aggregate, in the range 2.0–4.0%), following the operative procedures in regulation CNR 29/72 [29], developed by the Italian National Research Council. It is often usual to identify the design cement content as the percentage that leads to the minimum compressive strength prescribed in the specifications [27], but, in order to design high performance mixtures, it is preferable to look for the highest UCS compatible with the maximum acceptance requisites. The optimization procedure adopted in the study therefore identifies the mixture with the highest UCS as design mix.

In order to take into account other significant structural characteristics of the materials, the UCS based mix design procedure was completed by indirect tensile strength tests [30,31]. A second series of cylindrical samples, prepared for each of the six cement bound mixtures analysed, therefore underwent indirect tensile strength tests (UNI EN 13286-42). The Indirect Tensile Strength (ITS) was determined using the well-known equation:

$$\mathrm{ITS} = \frac{2P_{\max}}{\pi d h} \tag{1}$$

where $P_{\max}$ is the failure load [N] of the specimens under diametral compression, d and h are average values of the diameter [mm] and height [mm] of the samples respectively.

The performance of the cement bound mixtures was further investigated in terms of elastic modulus, by dynamic non-destructive tests (UNI EN 12504-4 [32]), based on measurement of the propagation time of ultrasonic impulses through the specimens. The procedure uses cylindrical samples prepared in the same way as those to be tested under uniaxial and diametral compression. The dynamic modulus (E_D) was determined on the basis of the following equation:

$$E_D = V^2 \cdot Q \cdot \frac{(1+n)\cdot(1-2n)}{1-n} \tag{2}$$

where Q is the dry density of the sample [Mg/m^3], n the dynamic Poisson's ratio [–] (for non-structural cement concretes, it can be equal to 0.30), V the propagation speed of ultrasonic impulses [km/s], calculated as ratio between the height of the specimen and the measured propagation time.

3. Results and discussion

3.1. Materials characterization

The waste aggregates investigated are solid odour-free materials. The foundry sand appears basically black, whereas the other recycled materials are greyish in colour. The pH resulted as equal to 9.7 and 11.5 for the EAF slags Type C and B respectively, 12.1 for the ladle slag, 8.8 for the foundry sand, 11.1 for the coal ash and 7.6 for the glass wastes. Table 1 reports the chemical composition of the waste aggregates in terms of oxides, determined by X-ray fluorescence.

The initial concentration of heavy metals resulted as being quite different in the various waste materials (Table 2), that of the EAF slag Type B being higher in terms of antimony, thallium and especially chromium (total). The foundry sand contained more lead, zinc and nickel. The coal ash had the highest copper, selenium, arsenic and beryllium concentrations, whereas the glass wastes showed the lowest initial concentrations of each heavy metal analysed.

The results of the leaching tests, reported in Table 3, demonstrate that the release of heavy metals is within the thresholds of the environmental regulations in force in Italy (Legislative Decree No. 152/2006). Therefore, by Italian Law, the waste aggregates are "non-hazardous, special non-toxic and non-noxious" refuse. Given that the aggregates of the mixtures do not present toxicological problems, it was considered unnecessary to perform further leaching tests on samples with cement added.

Table 4 reports the physical–mechanical characteristics of the aggregates. The Atterberg Limits (Liquid Limit and Plastic Limit according to CEN ISO/TS 17892-12) were non-determinable and this, in relation to the values of passing through 2, 0.4 and 0.075 mm sieves, allowed the waste aggregates to be classified, on the basis of the HRB-AASHTO methodology, as A1 soils, which can be used in road infrastructure (steel slag and ladle slag can

Table 1
Chemical composition of the waste aggregates.

Oxide content (%)	Aggregate type					
	EAF B	EAF C	SFS	LFS	CFA	RGW
FeO	30.4	33.7	–	1.5	–	–
Fe_2O_3	–	–	0.8	–	16.4	0.2
CaO	27.7	28.6	0.2	48.2	12.8	10.1
SiO_2	17.5	13.1	86.2	14.9	44.5	71.5
MgO	6.6	3.6	0.2	15.1	4.4	2.5
Al_2O_3	4.8	9.2	4.8	14.2	19.5	2.1

Table 2
Heavy metals content of the waste aggregates.

Element	Initial concentration (mg/kg)					
	EAF B	EAF C	SFS	LFS	CFA	RGW
Copper (Cu)	243.0	81.3	89.3	107.0	304.6	5.5
Cadmium (Cd)	<1.0	<0.5	1.6	<0.5	2.3	0.6
Lead (Pb)	<1.0	22.1	65.8	7.1	54.8	23.8
Zinc (Zn)	194	60.9	384	63.3	217.4	30.2
Chromium, total (Cr)	4631.0	447.0	585.0	599.0	292.7	5
Chromium, hexavalent (Cr)	<5.0	<5.0	<5.0	<5.0	1.8	<5
Nickel (Ni)	9.2	45.6	184.0	27.6	143.8	2.8
Mercury (Hg)	<1.0	<0.5	<0.5	<0.5	<1.0	<0.5
Selenium (Se)	9.0	7.6	<2.0	5.3	62.7	<2.0
Arsenic (As)	<5.0	6.7	5.0	14.7	23.7	<2.0
Beryllium (Be)	0.7	<0.5	<0.5	0.6	4.5	<0.5
Antimony (Sb)	35.6	6.2	6.0	7.3	5.6	<2.0
Thallium (Tl)	33.2	<0.5	<0.5	<0.5	<1.0	<0.5

Table 3
Heavy metals content of the waste aggregates after leaching.

Element	TCLP leaching concentration						
	EAF B	EAF C	SFS	LFS	CFA	RGW	Limits
Copper (Cu)	<0.001	<0.001	0.012	0.001	<0.05	<0.05	<0.05 mg/l
Cadmium (Cd)	<1.0	<1.0	<1.0	<1.0	<5.0	<5.0	<5 μg/l
Lead (Pb)	<5.0	<5.0	8.2	10.7	<50.0	<50.0	<50 μg/l
Zinc (Zn)	<0.001	0.004	0.07	<0.001	<3.0	<3.0	<3 mg/l
Chromium (Cr)	8.0	38.0	8.0	1.3	<50.0	<50.0	<50 μg/l
Nickel (Ni)	<3.0	<3.0	5.3	<3.0	<10.0	<10.0	<10 μg/l
Mercury (Hg)	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1 μg/l
Selenium (Se)	<10.0	<5.0	<5.0	<5.0	<10.0	<10.0	<10 μg/l
Arsenic (As)	<5.0	<5.0	10.3	<5.0	<50.0	<50.0	<50 μg/l
Barium (Ba)	0.94	0.5	0.02	0.002	<1.0	<1.0	<1 mg/l

Table 4
Physical and mechanical characteristics of the aggregates.

Properties	EAF B	EAF C	SFS	LFS	CFA	RGW
Los Angeles coefficient (%) EN 1097-2	19	58	–	–	–	–
Equivalent in sand (%) EN 933-8	79	71	32	52	–	67
Shape index (%) EN 933-4	2	8	3	5	–	–
Flakening Index (%) EN 933-3	5	11	1	2	–	–
Particle density (Mg/m^3) EN 1097-6	3.71	2.25	2.11	2.23	2.01	2.47
Plasticity index (–) CEN ISO/TS 17892-12	0	0	0	0	0	0
ASTM 10 sieve passing (%)	3.5	42.6	63.6	44.9	100.0	76.5
ASTM 40 sieve passing (%)	0.9	18.2	28.6	20.9	100.0	22.0
ASTM 200 sieve passing (%)	0.4	4.4	0.9	4.8	70.8	2.07

be assimilated to an A1-a soil, while foundry sand and glass wastes to an A1-b soil), with the exception of the coal ash that has to be classified as A4 soil.

Assuming as reference the acceptance requisites for aggregates to be used in cement bound mixtures for road foundations prescribed by Italian regulation CNR 29/72, and according to the data reported in Table 4, steel slag, ladle slag and glass wastes presented a cleaning level (Equivalent in Sand) above the acceptance requisite, equal to 35%. Instead, the Equivalent in Sand for foundry sand was 9% lower than the acceptance threshold.

EAF B slag had the highest mechanical resistance values (Los Angeles coefficient) as well as particle density, while EAF C slag presented the worst physical properties related to particles' morphology (Shape Index, Flakiness Index). The density of the particles in the EAF B slag was much higher than that of the other aggregates. This suggested limiting the EAF B slag content in the mixes to up to 25% by weight of the aggregates, to avoid an excessive increase in density, with the consequent higher transport costs.

The grading analysis of the aggregates (Fig. 1) outlined a similar particle size distribution for LF and EAF C slag. Both resulted as being coarser than the foundry sand, even if EAF B slag was the coarsest aggregate. The waste glass can be classified basically as fine aggregate, with 22% passing the 0.425 mm sieve size and almost 30% of the grains being below 0.60 mm; it should therefore be suitable in order to reduce the ASR effect, which is strictly related to the glass grain size. The coal ash resulted as being a very fine material and so, from the grading point of view, it can be considered as an artificial filler.

3.2. Grading and composition of the mixtures

The authors have already demonstrated and discussed the good mechanical behaviour of cement bound mixtures made with EAF slags and limestone aggregate [33]. Therefore, in this research the feasibility was studied of using only waste aggregates in cement bound mixtures, without significant reduction of their resistance to failure.

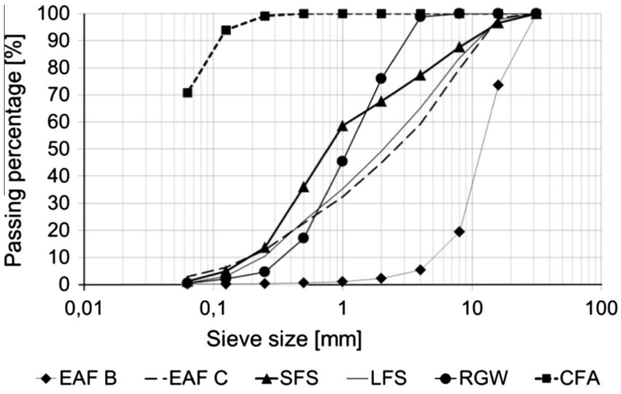

Fig. 1. Waste aggregates grading curves.

According to the results from the original aggregates, as regards the design grading curve of the cement bound mixtures, it was evaluated advantageous to use the waste materials in different proportions, as reported in Table 5. This was in order to verify the possibility of using the various aggregates in different amounts, considering their availability in the production plant, as explicitly requested by the producer.

The steel slags were used as primary component, since, in order to guarantee an appropriate grading distribution of the mixtures, a significant quantity of coarse aggregate is required. Between the two types of steel slags, the more valuable from a mechanical and physical point of view, i.e. EAF B slag, was used in a lower amount, because of its lower availability with respect to the EAF C. The foundry sand was integrated into the aggregate structure

Table 5
Aggregate type and composition of the mixtures (%).

Mixture	EAF B	EAF C	SFS	LFS	CFA	RGW
Mix 1	15	25	40	8	2	10
Mix 2	20	30	30	8	2	10
Mix 3	25	35	20	8	2	10
Mix 4	15	25	30	8	2	20
Mix 5	20	30	20	8	2	20
Mix 6	25	35	10	8	2	20

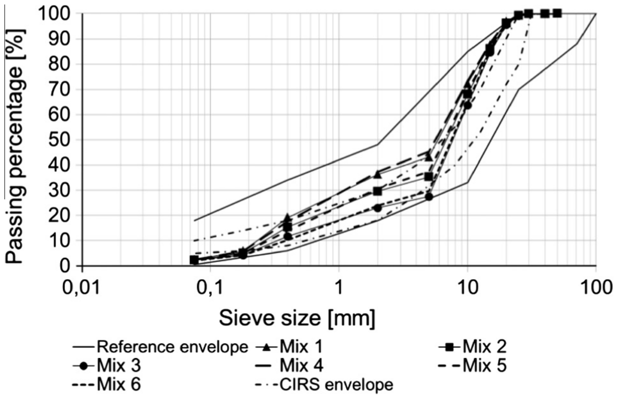

Fig. 2. Design grading curves of the cement bound mixtures.

Table 6
Proctor test results.

Mixture	OWC (%)	ρd (g/cm^3)
Mix 1	6.0	2.373
Mix 2	7.0	2.472
Mix 3	7.0	2.515
Mix 4	5.5	2.465
Mix 5	6.5	2.540
Mix 6	6.5	2.579

Table 7
Mechanical properties at 7 days ageing.

Mixture	UCS (MPa)	ITS (MPa)	Ed (MPa)
Mix 1	6.37	0.69	11,351
Mix 2	6.85	0.72	11,590
Mix 3	7.33	0.74	11,882
Mix 4	6.55	0.70	11,417
Mix 5	7.01	0.75	11662
Mix 6	7.56	0.78	11,997

Table 8
Mechanical properties at 28 days ageing.

Mixture	UCS (MPa)	ITS (MPa)	Ed (MPa)
Mix 1	8.18	0.77	11,818
Mix 2	8.27	0.81	11,907
Mix 3	8.34	0.96	12,274
Mix 4	8.24	0.80	11,910
Mix 5	8.33	0.88	12,031
Mix 6	8.40	1.02	12,390

Table 9
Mechanical properties at 90 days ageing.

Mixture	UCS (MPa)	ITS (MPa)	Ed (MPa)
Mix 1	8.87	0.91	12,111
Mix 2	8.95	0.96	12,210
Mix 3	9.06	1.05	12,512
Mix 4	8.95	0.95	12,227
Mix 5	9.08	1.02	12,343
Mix 6	9.12	1.16	12,698

of the cement bound mixtures, in order to complete the grading assortment, using an increasing quantity, up to 40% by weight of the aggregate.

Three mixtures (Mix 1, Mix 2, Mix 3) were made with 10% of glass wastes; this amount was raised to 20% in a second group of mixes (Mix 4, Mix 5, Mix 6), in order to investigate the influence of the glass aggregate. For each of the two groups, three different percentages of steel slags and foundry sand were used (Table 5). For each of the 6 different aggregate structures designed, the ladle slag and coal ash contents were always kept fixed at 8% and 2% respectively.

In the conventional mix design methods of cement bound mixtures for road construction, the design grading curve usually falls within specific reference grading envelopes that, as discussed by [27], may also differ consistently according to the various national contexts. Indeed, the design grading envelope used in the most relevant Italian Technical Specifications (ANAS, Società Autostrade per l'Italia, Motorway Brescia-Padova, CIRS – Ministry of Infrastructure and Transport), having been elaborated on the basis of tests using traditional materials, is not completely suitable for recycled aggregates, such as those studied (Fig. 2). Concerning this, previous studies [30,31] proved that it is also feasible to obtain good mechanical performances (in terms of indirect tensile strength and resistance to compression) with grading curves that differ from the conventional grading envelopes. It was therefore decided to establish a new design grading envelope (Fig. 2), hereinafter named "Reference envelope", admissible with the grading properties of various types of recycled aggregates. Indeed, the CIRS Specification (one of the most up-to-date in Italy [34]), in the mix design of cement bound mixtures made with recycled materials, allows to deviate from the requisites for traditional aggregates, using experimental data from specific investigations.

Fig. 2 shows that the resulting grading curves for the design mixtures are within the proposed reference envelope.

3.3. Mix design and performance characterization

The results of the modified Proctor test are reported in Table 6. The optimal water content (OWC) was within the range 5.5–7%, while higher values of dry density (ρd) were found for the mixes with more EAF slag Type B and glass wastes, according to their higher particle densities.

The mix design and performance tests results are shown in Tables 7–9, at 7, 28 and 90 days ageing respectively. For each mixture, the highest UCS values at 7 days ageing were achieved for a cement content equal to 4% by weight of the aggregate, which, considering the mix design procedure adopted in the study, therefore resulted as being the optimal cement percentage, in terms of mechanical strength.

All the mixtures presented UCS values, at 7 days ageing, well above the minimum acceptance requisite (2.5 MPa); the highest values (7.56 MPa) were achieved for Mix 6. The influence of the mix composition (and therefore of the waste material type) on the UCS, resulted as being relevant (Tables 7 and 8), as reported also for other cement-treated materials [27]. The achievement of the minimum thresholds for any type of mixture is extremely important, because it demonstrates the feasibility of adapting the single mixture to specific design conditions.

With the cement percentage determined as optimal in the compressive strength tests (4%), the indirect tensile strength (ITS) after 7 days ageing was equal to 1.02 MPa for Mix 6, well above the minimum value (0.25 MPa) required by the CIRS-Ministry of Infrastructure Specification [34]. The quantities of steel slag and foundry sand can therefore be changed within the considered range (Table 5), without any penalization in terms of mechanical strength, for both the contents of glass wastes. Even the "least valuable" of the designed mixtures, i.e. Mix 1, showed much higher UCS and ITS values (155% and 176% respectively) than the minimum acceptance requisites.

The compressive strength and indirect tensile strength data at 28 and 90 days ageing (Tables 7 and 8 respectively) confirmed the excellent performances of the mixtures with 4% cement and demonstrated the expected evolution of the mechanical strength in relation to ageing time [27], up to 28% and 31%, for UCS and ITS respectively, depending on the mixture type.

For all the mixtures analysed, a consistent linear relationship was verified between UCS and ITS, as mentioned in the literature for similar cement bound materials [30,31]. The regression analysis of the experimental values was performed using a linear model of the type:

$$ITS = m\mathrm{UCS} + q \tag{3}$$

where m and q are regression coefficients related to the type of material. The experimental data and interpolation curves, for the various mixtures, are shown in Fig. 3, whereas the most relevant regression coefficient (m) and coefficient of determination R^2, are reported in Table 10.

The ratio between compressive and tensile strength was within the range 9–10, depending on the mixture composition, and therefore very close to the UCS–ITS ratio for conventional cement bound mixtures, usually equal to 10 [27].

As there are no indications in the local regulations on the minimum acceptance thresholds for mixtures in terms of Elastic Modulus, the results can only be considered useful for a comparative analysis of mixtures' performance.

The Dynamic Elastic Modulus values resulted as quite similar for the different mixtures, with stiffness, at 7 days ageing, varying within the range 11,351–11,997 MPa. The highest stiffness was achieved for the mixture identified as the best one in the mix design phase (Mix 6). As already observed for both the mechanical strength tests, data at 28 and 90 days ageing showed the expected increase of the Elastic Modulus. A high stiffness should contribute favourably to the bearing capacity and durability of the pavement since, at the same stress level, fewer strains develop when stiffness increases, with beneficial effects for the subgrade beneath the foundation layer. However, an excessively high stiffness could lead to cracking failure, due to brittle behaviour. Therefore, in the pavement design procedure, the Elastic Modulus data should be carefully analysed in order to identify the optimal cement bound mixture with respect to the stiffness of the bituminous layers and the resilient modulus of the subgrade.

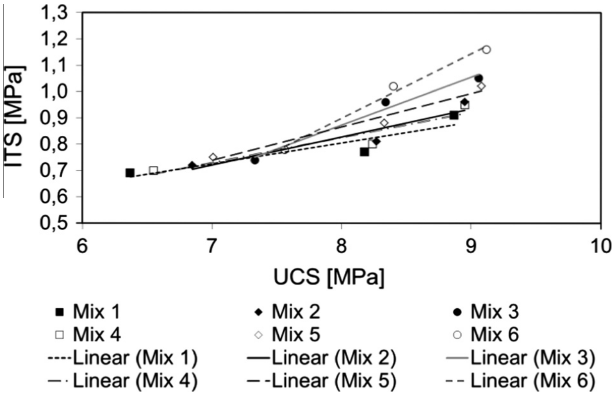

Fig. 3. ITS vs UCS.

Table 10
ITS – UCS regression results.

Mixture	m (–)	R^2
Mix 1	0.0791	0.8416
Mix 2	0.1065	0.8862
Mix 3	0.1817	0.9802
Mix 4	0.0960	0.8847
Mix 5	0.1268	0.9683
Mix 6	0.2448	0.9887

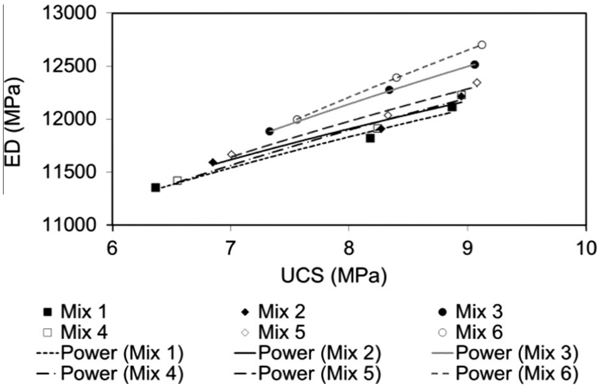

Fig. 4. E_D vs UCS.

Table 11
E_D – UCS regression results.

Mixture	c (–)	d (–)	R^2
Mix 1	8010.0	0.1876	0.9786
Mix 2	8096.3	0.1855	0.9560
Mix 3	7302.9	0.2445	0.9995
Mix 4	7655.3	0.2120	0.9829
Mix 5	7679.5	0.2138	0.9822
Mix 6	6502.0	0.3029	0.9999

As reported in the literature, the estimation models of elastic modulus are usually based on the UCS data [30,31]. Therefore, for all the mixtures considered, a correlation was elaborated between the UCS and the dynamic Modulus E_D using, for the regression analysis of the experimental values, a power law model of the type:

$$E_D = c\mathrm{UCS}^d \tag{4}$$

where c and d are regression coefficients, related to the type of material. Fig. 4 presents the experimental data and interpolation curves. The regression coefficients and coefficient of determination R^2 are reported in Table 11. Both regression coefficients were demonstrated to be considerably dependent on the composition of the mixtures.

For all the cement bound mixtures investigated, there were no phenomena of crumbling or uneven expansion during the preparation, compaction or ageing (up to 90 days) of the cylindrical samples, potentially ascribable to the ASR problem related to the use of glass wastes, or the presence of free lime subject to hydration or carbonation in the steel slag grains, as instead reported in other studies [33,35] for certain types of steel slags not or insufficiently seasoned.

With respect to the ASR problem, the use of fine glass wastes and the integration in the cement bound mixtures of a pozzolanic material such as fly ash (2% by weight of the aggregate) probably contributed to preventing the ASR damage.

For the steel slags, it should be mentioned that both the EAF slags used had been exposed to the air and environmental conditions for more than 3 months, so that the hydration reactions of the calcium oxide had taken place prior to the final use.

4. Conclusions

An investigation on cement bound mixtures for road foundations, with the aggregate structure completely composed by industrial wastes, has been presented and discussed.

The recycled aggregates considered in the analysis, i.e. steel slags, foundry sand, ladle slag, coal ash and glass wastes, presented toxicological, physical and mechanical characteristics that make the materials suitable to be reused in cement bound mixtures for road foundations.

The mix design procedure, based on compressive and indirect tensile strength tests, allowed mixtures to be formulated made only with recycled aggregates in six different grading combinations, thus useful in terms of both environmental and economic impact, which fulfil the acceptance requisites of the Italian road technical Standards.

The highest mechanical strengths were recorded for Mix 6, which has a steel slag-foundry sand ratio equal to 6/1 and a cement percentage of 4%, with 7 days UCS and ITS values up to 7.56 MPa and 0.78 MPa respectively.

For the 6 mixtures investigated, the UCS–ITS ratio resulted as within the range 9–10, depending on the specific composition.

The performance analysis, by means of the Dynamic Elastic Modulus evaluation, verified and confirmed the highest performances of the mixture that resulted as being the best one in the mix design phase, i.e. Mix 6.

Moreover, significant correlations were established between the UCS and the elastic modulus data, for all the mixtures studied.

The research belongs to a wider framework of theoretical, experimental and regulatory studies being conducted by the authors, aimed at describing the chemical, physical and mechanical properties of recycled materials and their potential applications in road pavements. The construction of sustainable road infrastructure requires a deeper understanding on the engineering properties of recycled aggregates; in this sense, the results of the study can be useful for designing high performance cement bound mixtures for road pavement foundations, using up to 5 different waste materials.

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