# Cement Bound Mixtures with Metallurgical Slags for Road Constructions: Mix Design and Mechanical Characterization

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*Summary*

*Environmental, economical and technical problems have led to increasing attention towards the recycling of waste materials in the construction of road infrastructure.*

*This paper reports the results of a study carried out at the Experimental Road Laboratory of the University of Padua, aimed at designing cement bound mixtures for road construction, characterized by a stone matrix made exclusively with electric arc furnace steel slag, waste foundry sand and ladle furnace slag, used in different proportions.*

*The physical-geotechnical properties of the metallurgical slags have been evaluated by means of the most pertinent laboratory procedures of the road technical sector. Cement bound mixtures, characterized by five different proportions of artificial aggregates, have been designed in terms of Proctor, compression and indirect tensile strength tests. The mechanical characterization of the hydraulic mixes has been completed with the elastic modulus evaluation, through ultrasonic tests.*

*The excellent results (compression and indirect tensile strength at 7 days up to 7.23 MPa and 0.92 MPa respectively, depending on the mixture type), have met the main Italian Contract Specifications, demonstrating the possibility to successfully reuse different types of metallurgical slags, in the complete substitution of the natural aggregates, for the development of cement bound mixtures designed for road construction.*

*Keywords: steel slag, foundry sand, ladle furnace slag, cement bound mixtures, road construction*

## Introduction

This laboratory investigation was aimed at the design and experimental characterization of a mixture of aggregates, composed of waste materials obtained from the steel industry, to evaluate their physical-mechanical suitability as an aggregate in the formulation of cement bound mixtures, that necessitate compaction when being laid, for road foundations (Pasetto and Baldo, 2007, 2009, 2010). The materials considered were what are known as "marginal aggregates"; more specifically they are a waste foundry sand (or exhausted), Electric Arc Furnace (EAF) steel slags and Ladle Furnace (LF) slags. The analysis investigated the materials individually, plus mixtures of these components in different proportions (Javed and Lovell, 1995; Setien et al., 2009; Zaman et al., 2009).

## Materials and methods

Three types of artificial aggregate, that is foundry sand, steel slag and ladle slag, were used in the present investigation, at various dosages in five different mixtures.

Spent foundry sand is a by-product of the iron and steel industry, normally of heterogeneous composition, obtained after the repeated use of silica or lacustrine sand of high quality, for the casting moulds utilized in the smelting processes of metallic or non-metallic articles.

The steel slags considered are a by-product of the steel production process in electric arc furnaces (EAF). Two types of EAF slags have been used from different suppliers, and named EAF Type B and EAF Type C.

Ladle slag, also called "white slag", is the by-product that remains in the ladle furnace for secondary metallurgy, after the casting process.

Table 1 summarizes the toxicological characteristics of marginal aggregates, in terms of initial concentrations of heavy metals, measured with the ICP-AES methodology (Inductively Coupled Plasma – Atomic Emission Spectrometer), whereas Table 2 reports their leaching, determined by the TCLP (Toxic Characteristic Leachability Procedure). This is a commonly used test aimed at evaluating the leaching characteristics of hazardous waste materials, performed on the marginal aggregates investiated, before any other physical-mechanical testing, in order to establish their environmental compatibility. The TCLP requires end-over-end agitation, a 20:1 liquid-to-solid ratio and an equilibrium time equal to 18 hours. A sample of at least 100 g is extracted with

Table 1. Major heavy metal initial content of the marginal aggregates

Tabela 1. Początkowa zawartość głównych metali ciężkich w kruszywach

| Element | Initial concentration (mg/kg) | | | |
|---|---|---|---|---|
| | Foundry sand | EAF Type B | EAF Type C | LF slags |
| Copper (Cu) | 89.3 | 243.0 | 81.3 | 107.0 |
| Cadmium (Cd) | 1.6 | < 1.0 | < 0.5 | < 0.5 |
| Lead (Pb) | 65.8 | < 1.0 | 22.1 | 7.1 |
| Zinc (Zn) | 384 | 194 | 60.9 | 63.3 |
| Chromium – Total (Cr) | 585.0 | 4631.0 | 447.0 | 599.0 |
| Chromium – Hexavalent (Cr) | < 5.0 | < 5.0 | < 5.0 | < 5.0 |
| Nickel (Ni) | 184.0 | 9.2 | 45.6 | 27.6 |
| Mercury (Hg) | < 0.5 | < 1.0 | < 0.5 | < 0.5 |
| Selenium (Se) | < 2.0 | 9.0 | 7.6 | 5.3 |
| Arsenic (As) | 5.0 | < 5.0 | 6.7 | 14.7 |
| Beryllium (Be) | < 0.5 | 0.7 | < 0.5 | 0.6 |
| Antimony (Sb) | 6.0 | 35.6 | 6.2 | 7.3 |
| Thallium (TI) | < 0.5 | 33.2 | < 0.5 | < 0.5 |

Table 2. Major heavy metal leaching concentration of the industrial wastes

Tabela 2. Stężenie głównych metali ciężkich po ługowaniu w odpadach przemysłowych

| Element | TCLP leaching concentration | | | | |
|---|---|---|---|---|---|
| | Foundry sand | EAF Type B | EAF Type C | LF slags | Legal thresholds |
| Copper (Cu) | 0.012 | < 0.001 | < 0.001 | 0.001 | < 0.05 mg/l |
| Cadmium (Cd) | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 5 µg/l |
| Lead (Pb) | 8.2 | < 5.0 | < 5.0 | 10.7 | < 50 µg/l |
| Zinc (Zn) | 0.07 | < 0.001 | 0.004 | < 0.001 | < 3.0 mg/l |
| Chromium (Cr) | 8.0 | 8.0 | 38.0 | 1.3 | < 50 µg/l |
| Nickel (Ni) | 5.3 | < 3.0 | < 3.0 | < 3.0 | < 10 µg/l |
| Mercury (Hg) | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1 µg/l |
| Selenium (Se) | < 5.0 | < 10.0 | < 5.0 | < 5.0 | < 10 µg/l |
| Arsenic (As) | 10.3 | < 5.0 | < 5.0 | < 5.0 | < 50 µg/l |
| Barium (Ba) | 0.02 | 0.94 | 0.5 | 0.002 | < 1 mg/l |

a proper leaching solution. After agitating for 18 h, the extracts are separated from the solids using a glass fiber filter (Siddique et al., 2010). The extracts are subsequently analyzed in a laboratory, in our case by Inductively Coupled Plasma–Atomic Emission Spectrometer (ICP/AES) methodology.

Grading analysis of the marginal materials, conducted using the “dry process” (Italian CNR 23/71 Standard), provided the results reported in Table 3.

Table 4 reports the physico-mechanical properties of the marginal aggregates, plus the test protocols adopted, which are specific to the road sector.

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

The mix design of cement bound mixtures for road infrastructure, after the aggregate matrix has been defined, is based on the grading curve design, followed by the water and cement content evaluation (Pasetto and Baldo, 2007, 2009, 2010; Xuan et al., 2012).

The lithic matrix was exclusively composed by the marginal aggregates analysed in the study and, having decided to rework the material coming from the production plant as little as possible, the design grading curves assumed were those resulted by the combination, in different proportion, of the raw materials, limited to the fraction of interest, i.e. 0/25. Therefore, at the mixing stage, the foundry sand, steel slag and ladle furnace slag, have been used in their original conditions, each one with its specific grading assortment, without a specific selection of the single fractions.

The densification properties of the integrated granular mixtures have been studied by means of

Table 3. Marginal materials grading curves

Tabela 3. Krzywe uziarnienia materiałów marginalnych

| Sieve size (mm) | Passing percentage (%) | | | |
|---|---|---|---|---|
| | Foundry sand | EAF Type B | EAF Type C | LF slags |
| 40 | 100.0 | 100.0 | 100.0 | 100.0 |
| 30 | 100.0 | 100.0 | 100.0 | 98.7 |
| 25 | 97.3 | 96.3 | 99.0 | 97.9 |
| 20 | 94.1 | 89.2 | 96.7 | 94.3 |
| 15 | 90.6 | 69.9 | 90.0 | 89.8 |
| 10 | 85.8 | 37.3 | 78.5 | 80.0 |
| 5 | 75.2 | 10.4 | 59.3 | 61.8 |
| 2 | 63.6 | 3.5 | 42.6 | 44.9 |
| 0.4 | 28.6 | 0.9 | 18.2 | 20.9 |
| 0.18 | 5.9 | 0.6 | 8.3 | 10.2 |
| 0.075 | 0.9 | 0.4 | 4.4 | 4.8 |

Table 4. Physical and mechanical characteristics of marginal materials

Tabela 4. Fizyczne i mechaniczne charakterystyki materiałów marginalnych

| Physical ÷ Mechanical properties | Standard | Foundry sand | EAF Type B | EAF Type C | LF slags |
|---|---|---|---|---|---|
| Los Angeles coefficient (%) | EN 1097-2 | - | 19 | 58 | - |
| Equivalent in sand (%) | EN 933-8 | 32 | 79 | 71 | 52 |
| Shape Index (%) | EN 933-4 | 3 | 2 | 8 | 5 |
| Flakiness Index (%) | EN 933-3 | 1 | 5 | 11 | 2 |
| Grain bulk density (g/cm$^3$) | CNR 64/78 | 2.36 | 3.84 | 2.87 | 2.55 |
| Grain dry density (g/cm$^3$) | CNR 63/78 | 2.11 | 3.71 | 2.25 | 2.23 |
| Porosity of the grains (%) | CNR 65/78 | 10.59 | 3.39 | 21.60 | 12.55 |
| Particle voids content (%) | CNR 65/78 | 37.91 | 51.75 | 29.78 | 39.46 |
| Plasticity Index (-) | UNI CEN ISO/TS 17892-12 | 0 | 0 | 0 | 0 |

Proctor compaction tests (EN 13286-2), in order to determine the maximum dry density and corresponding water content. This value can be used to represent the first attempt percentage in the formulation of hydraulic mixtures, in order to reduce the experimental load linked to the 7-day seasoning times.

The water and cement contents were optimized by testing the Unconfined Compressive Strength (UCS) of a series of specimens produced with the same type of aggregate, same grading assortment, but different water and hydraulic binder contents (the amount of cement were varied at intervals of 0.5% on the weight of the aggregate, in the range 2.0 – 4.0%), following the procedures in regulation CNR 29/72. This optimization procedure identifies the mixture characterized by the highest UCS as design mix. Even if it is usual to identify the design cement content as the percentage that is related to the minimum compressive strength required in the specifications (Xuan et al., 2012), in order to design high performance mixtures it is convenient to look for the highest UCS, compatibly with the maximum acceptance thresholds.

In order to take into account other relevant structural properties of the materials, the mix design procedure in Regulation CNR 29/72 was rendered more complete and reliable with the execution of indirect tensile strength tests in parallel with those of unconfined compressive strength (Pasetto and Baldo, 2007, 2009, 2010). Therefore, a second series of cylindrical specimens, made using the procedure described above, underwent indirect tensile strength tests (EN 13286-42). The performance of the mixtures was verified in terms of elastic modulus, by means of dynamic tests (EN 12504-4). The dynamic modulus involves a non-destructive test, based on measurement of the time of propagation of ultrasonic impulses through the samples; the procedure requires specimens made in the same way as those to be used in the tests of compressive and indirect tensile strength.

## Results and discussion

By Italian Law, the waste aggregates considered are “non-hazardous, special non-toxic and non-noxious” refuse. They are solid material and odour-free. The EAF slags as well as LF slags are greyish in colour, whereas the foundry sand appears basically black. The pH is equal to 8.8 for foundry sand, 9.7 and 11.5 for EAF slags Type C and B respectively, 12.1 for LF slag.

The initial concentration of heavy metals in the waste aggregates differs, with that of the foundry sand being higher in terms of lead, zinc and nickel. The EAF Type B contains more antimony, copper and chromium. The LF slags presents the highest arsenic content.

The results in Table 2 demonstrate that, for the marginal materials analyzed, the release of heavy metals by leaching is within the limits of the environmental regulations in force in Italy (Legislative Decree no. 152/2006). Therefore, given that the constituents of the mixtures do not present toxicological problems, it was considered unnecessary to proceed with leaching tests on specimens with cement added.

The marginal materials resulted as practically unaffected by the action of water, presenting non-determinable Plastic Limit (according to CNR-UNI 10014/64), and this, in relation to the values for passing through sieves of 2 mm, 0.4 mm, 0.075 mm (Table 3), has led to the wastes being classified, based on the HRB - AASHTO methodology, as A1 soils, which can be used in road construction (foundry sand can be assimilated to an A1-b soil, while steel slags and ladle slags to an A1-a soil).

With reference to the acceptance requisites for materials to be used in hydraulic mixtures for road foundations laid down by Italian regulation CNR 29/72, and according to the data in Table 4, both steel slags and ladle slags are characterized by a cleaning level (Equivalent in Sand) above the acceptance requisite, set at 35%. Instead, for foundry sand, the Equivalent in Sand is below the mentioned requisite limit, with a difference of 9%. EAF Type B presented the highest values of mechanical resistance (Los Angeles coefficient) as well as unit weight, while EAF Type C was characterized by the worst physical requisites related to particles' morphology (Shape Index, Flakiness Index).

The specific weight of the grains of the EAF steel slags is much higher than that of the ladle slags and the foundry sand. This result suggested excluding mixes entirely composed of steel slags, to avoid an excessive increase in density, with the consequent higher transport costs. The volumetric properties of the grains (particle voids and porosity) resulted as being quite similar for the ladle slags and the foundry sand; the data recorded for the steel slags were consistently different.

In the light of the results from the original materials, as regards the design grading curve of the hydraulic mixtures it was considered advantageous to integrate the waste aggregates in different proportions, as reported in Table 5. This was in order to verify the feasibility of using the various materials in different proportions, in relation to their availability in the production factory, as explicitly requested by the producer. The marginal aggregates were integrated in the skeleton and formed 5 different mixes; the EAF slags were used as primary component because, in order to achieve an appropriate grading assortment of the mixtures, a predominant amount of coarse aggregate is needed.

The authors have already verified the excellent mechanical performances of hydraulic mixtures produced with EAF slags and limestone aggregate (Pasetto and Baldo, 2010). Therefore, in this research the possibility was investigated of using exclusively waste aggregates, with a significant amount of lower quality materials (like spent foundry sand and ladle furnace slag), taking care to guarantee the minimum resistance to failure of the final bound mixtures.

The modified Proctor test provided the results presented in Table 6. The optimum water content (OWC) resulted largely affected by the foundry sand content, while for the dry density (ρd), higher values were observed in correspondence of the mixes more rich of EAF Type B.

Table 7 presents the results of the mix design and performance tests for the mixtures (at 7 days ageing); the optimal cement content resulted equal to 4% on the weight of the aggregates, for all the mixtures investigated.

For all the mixes investigated, there were no problems, during the making, compaction or seasoning of the specimens, caused by uneven expansion or phenomena of disgregation, ascribable to the presence of free lime potentially subject to hydration or car-

Table 5. Aggregate type and composition of the mixtures

Tabela 5. Typ kruszywa i skład mieszanek

| Mixture | Foundry sand (%) | EAF Type B (%) | EAF Type C (%) | LF slags (%) |
|---|---|---|---|---|
| Mix 1 | 30 | 50 | 0 | 20 |
| Mix 2 | 40 | 50 | 0 | 10 |
| Mix 3 | 40 | 0 | 50 | 10 |
| Mix 4 | 10 | 70 | 10 | 10 |
| Mix 5 | 20 | 30 | 40 | 10 |

Table 6. Proctor test results

Tabela 6. Wyniki testu w aparacie Proctora

| Mixtures | Properties | |
|---|---|---|
| | OWC (%) | ρd (g/cm$^3$) |
| Mix 1 | 13.0 | 2,159 |
| Mix 2 | 15.5 | 2,100 |
| Mix 3 | 16.0 | 1,855 |
| Mix 4 | 5.5 | 2,677 |
| Mix 5 | 13.5 | 2,114 |

Table 7. Mechanical properties at 7 days ageing

Tabela 7. Właściwości mechaniczne w 7 dniu

| Mixtures | Properties | | |
|---|---|---|---|
| | Rc (MPa) | Rt (MPa) | Ed (MPa) |
| Mix 1 | 4.42 | 0.62 | 1,730 |
| Mix 2 | 4.06 | 0.42 | 1,748 |
| Mix 3 | 3.84 | 0.39 | 1,712 |
| Mix 4 | 7.23 | 0.92 | 1,982 |
| Mix 5 | 5.62 | 0.73 | 1,928 |

bonation in the steel slag particles, as instead reported by some researchers (Dunster, 2002) for certain types of steel slags not or insufficiently seasoned.

All the mixtures showed properties' values above the minimum threshold required, with very high UCS values (up to 7.23 MPa for the Mix 4). The influence of the mix composition (and therefore of the aggregate type) on the UCS is relevant (Table 7), as reported also for natural cement-treated aggregates (Sherwood, 1995), but the compliance of the requisites for any type of mixture, demonstrates the possibility of choosing the most suitable formulation of the mix for specific design needs.

With the binder content identified as optimal in the compressive strength tests (4%), the indirect tensile strength (ITS) after 7 days of ageing resulted as 0.92 MPa for the Mix 4, which is much higher than the minimum value (0.25 MPa) prescribed by CIRS-Ministry of Infrastructure Specification for acceptance of the mixture. Therefore, the steel slag-foundry sand-ladle furnace slag proportion, can be varied within the investigated range, without any detrimental effect in terms of mechanical resistance; even the Mix 3, namely the "less valuable" of the designed mixes, has presented UCS and ITS values largely higher (54% and 56% respectively) than the minimum acceptance thresholds.

For Mix 2 and Mix 3 UCS resulted about 10 times the ITS value. For Mix 4 and Mix 5, the ratio between compressive and tensile strength is close to 8, whereas it is equal to 7 for Mix 1.

The Dynamic Elastic Modulus tests demonstrated very similar values for the different mixtures, being stiffness above 1,700 MPa at 7 days of seasoning; the highest values were recorded for the mixture that resulted, in the mix design phase, the best one in terms of mechanical resistance (Mix 4).

## Conclusion

The paper discusses an experimental study concerning cement bound mixtures for road foundations, with the aggregate skeleton fully composed by industrial wastes, as foundry sands, steel slags and ladle furnace slags.

The marginal materials analyzed in the experimental investigation presented toxicological, physical and mechanical properties that make the materials suitable for producing cement bound mixtures for road foundations.

The proposed mix design procedure, based on compressive and indirect tensile strength tests, has identified mixtures made exclusively with marginal materials in five different proportions, thus interesting in terms of both environmental and economic impact, which entirely satisfy the requirements for acceptance in the Italian road technical Standards.

The best mechanical results (7 days UCS and ITS values up to 7.23 MPa and 0.92 MPa respectively) were achieved for the mixture made with 80% of steel slag and 10% of both foundry sand and ladle furnace slags.

The performance evaluation, in terms of Dynamic Elastic Modulus, has confirmed the high performances of the mixture identified, in the mix design phase, as the most resistant in mechanical terms.

The research have demonstrated that the use of industrial by-product in the aggregate matrix of cement bound granular mixtures, is a technically satisfactory option that fulfils the spirit of the "Zero Waste", target that the iron and steel industry has been aiming for in the last decade.

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## *Ograniczenia mieszanin cementu i żużli metalurgicznych do budownictwa drogowego – charakterystyka właściwości mechanicznych*

*Problemy środowiskowe, ekonomiczne i techniczne doprowadziły do wzrostu zainteresowania recyklingiem materiałów odpadowych w celu konstrukcji infrastruktury drogowej.*
*Referat przedstawia wyniki badań przeprowadzonych w Drogowym Laboratorium Eksperymentalnym Uniwersytetu w Padwie, które zajmuje się projektowaniem mieszanki cementu do budowy dróg charakteryzującej się macierzą skalną wykonaną wyłącznie z żużla z pieca łukowego, piasku formierskiego oraz żużla kadziowego użytych w różnych proporcjach.*
*Fizyczno-geotechniczne właściwości metalurgicznych żużli zostały określone dzięki najbardziej stosownym procedurom laboratoryjnym technicznego sektora drogowego. Zaprojektowano charakteryzujące się pięcioma różnymi proporcjami sztucznych kruszyw mieszanki oraz poddano je testom na sprężanie oraz pośrednim testom na wytrzymałość na rozciąganie. Charakterystyka mechaniczna mieszanek hydraulicznych została uzupełniona o określenie współczynnika sprężystości wzdłużnej poprzez testy ultradźwiękowe.*
*Znakomite wyniki (sprężania i wytrzymałość na rozciąganie w siódmym dniu wynosiły odpowiednio 7,23 MPa i 0,92 MPa w zależności od rodzaju mieszanki) spełniły wymogi prezentując jednocześnie możliwość pomyślnego ponownego użycia różnych rodzajów żużli metalurgicznych, będących zamiennikami naturalnych kruszyw, w celu rozwoju mieszanek do konstrukcji dróg.*



*Słowa kluczowe: żużle metalurgiczne, żużel z odlewnictwa, piasek odlewniczy, mieszanina cementu, konstrukcje drogowe*