BITUMINOUS BASE COURSES FOR FLEXIBLE PAVEMENTS WITH STEEL SLAGS

Marta Skaf Revenga
Department of Construction. University of Burgos, Spain
Javier Bartolomé González
University of Burgos, Spain
Hernán Gonzalo Orden
Department of Civil Engineering, University of Burgos, Spain
Alaitz Linares Unamunzaga
Department of Civil Engineering, University of Burgos, Spain
Vanesa Ortega López
Department of Civil Engineering, University of Burgos, Spain
Juan Manuel Manso Villalaín
Department of Civil Engineering, University of Burgos, Spain

ABSTRACT

The purpose of this research was to study the feasibility of incorporating steel slags into coarse bituminous mixtures. The objective was twofold: to reduce dependence on natural aggregates, and to provide a use for industrial by-products. The slags studied come from the manufacture of carbon steel in electric furnaces and are divided into two types: Electric Arc Furnace (EAF) slag and Ladle Furnace (LF) slag. The mixture designed is coarse bituminous concrete (AC22G), for base courses in flexible pavements.

In a first phase, the physical characterization of the materials was carried out to check their suitability. In a second phase, three types of mixes were designed: a control mix (made with natural limestone aggregates), a mix where LF slag was introduced to replace the filler and the fine fraction (sand) of the mix; and finally, the feasibility of manufacturing a totally sustainable mix was analyzed, which would fully incorporate EAF slag as coarse aggregate and LF slag as fine aggregate and filler. In a third and final phase, the designed mixes were subjected to different mechanical, water sensitivity, and durability tests.

The research demonstrated that the incorporation of EAF and LF steel slag as a substitute for natural aggregate in coarse bituminous mixtures is feasible, meeting regulatory requirements, improving sustainability in the construction industry, as well as reducing emissions, and contributing to climate change mitigation.

1. INTRODUCTION

Since the end of the 20th century, social pressure to protect the environment has forced the scientific community to study different ways of recycling the by-products generated in industrial processes (Revilla-Cuesta et al., 2020; Rodríguez-Fernández et al., 2019). This recycling would reduce the amount of waste generated and convert the residues into valuable and sustainable resources (Gonzalo-Orden et al., 2019; Martinho et al., 2018).

One of the most studied industrial by-products is iron and steelmaking slags (Teo et al., 2020). These materials were first considered as waste and they were mainly dumped in landfills, producing important landscape impacts and posing a pollution risk to runoff waters that came into contact with them (Riboldi et al., 2020).

The growth of the world steel industry, which from 1950 to the present has increased from 189 to 1,600 million tons of steel produced annually, has led to an equally significant increase in the production of slag (Branca et al., 2020). Today, a wide variety of applications for steel slags have been developed (Gökalp et al., 2018), but slag consumption is far from reaching its production, resulting in a surplus of this waste that continues to be stored in landfills.

Among the multiple uses of steel slag, the most widespread are: its reincorporation into the steel production process (Li et al., 2020; Varanasi et al., 2019) and its use in the construction sector, mainly as a substitute for natural aggregates and binders in the manufacture of concrete and cementitious composites (Brand and Fanijo, 2020; Piemonti et al., 2021) or bituminous mixtures (Li et al., 2018; Pasetto et al., 2017). One of the applications with the greatest potential is the incorporation of these materials in road pavements, replacing natural aggregates (Dondi et al., 2021; Maharaj et al., 2017).

A bituminous mixture is a combination of coarse aggregates (>2 mm), fine aggregates (0.063-2 mm), mineral powder or filler (<0.063 mm) and a hydrocarbon binder, so that all the particles are covered by a homogeneous film of binder. On the other hand, road pavements can be defined as a set of overlapping layers, relatively horizontal and several centimeters thick, composed of different materials, suitably compacted and supported on the natural ground. Bituminous mixtures can be used in the surface layer of the pavement (wearing course) or the inner layers (base course and binder course).

The purpose of this research was to study the feasibility of incorporating two types of steel slag in coarse bituminous mixtures that are used for the base layer of a road pavement. The objective of this research was twofold: to reduce the dependence on natural aggregates, whose extraction is harmful to the environment, and to give a use to industrial by-products, which reduces the volume of stockpiles and improves sustainability both in the construction and steel industries.

2. MATERIALS

The two types of slags studied in this research proceed from the manufacture of carbon steel:

- **Electric Arc Furnace (EAF) slag**: it originates during the melting process of the scrap in the primary metallurgy. It is a coarse material, with a rough texture and blackish gray color. It is mainly composed of calcium silicates and metallic oxides, the latter being responsible for its dark color and high density and hardness. Its good mechanical characteristics (hardness, absorption, roughness and angularity) and its particle size allow it to be used as coarse aggregate in concrete and bituminous mixtures (Skaf et al., 2017).
- **Ladle Furnace (LF) slag**: it is obtained during steel refining in ladles. It is a fine material, whitish in color and powdery in texture. It is mainly composed of calcium and magnesium silicates and aluminates, which provides it with soft hydraulic properties (Parron-Rubio et al., 2019). Due to its size, which is usually under 2 mm, it can be used as fine aggregate in construction, while its hydraulic properties mean that it can be used as a mineral powder to replace lime or cement traditionally used in bituminous mixtures (Terrones-Saeta et al., 2021b).

Fig. 1 – Ladle Furnace (LF) slag (left) and Electric Arc Furnace (EAF) slag (right) used in this research.

3. MIX DESIGN

For the investigation, an AC22G mix was adopted, which according to the Spanish standard PG-3 (2015) is defined as a coarse bituminous concrete with a maximum size of 22 millimeters. This type is one of the most commonly used in base layers of flexible and semi-rigid pavements.

The slags were introduced into the bituminous mix in two phases:

- The first type was a mix consisting partly of steel aggregate, with LF slag as fine aggregate and mineral powder, and traditional limestone aggregate as coarse aggregate. This mix was labeled CBB

- The second type was a 100% sustainable mix, composed entirely of slags, with EAF slag as coarse aggregate and LF slag as fine aggregate and filler (labeled as NBB).

Finally, it was necessary to manufacture a third traditional mix, composed entirely of limestone aggregate, to serve as a reference, to assess the effect of the slag incorporation. This standard mix was labeled CCC.

Fig. 2 – Specimens of CBB (left) and NBB (right) mixtures

4. PERFORMANCE OF THE MIXTURES

4.1 Volumetric properties

The incorporation of the slags generated a greater void content in the mix, which increased the optimum binder content to achieve the target air voids. The mixtures studied, CBB and NBB, required a 15% and 35% higher volume of bitumen, respectively.

This greater void content was attributed to the fact that the bituminous mastic (filler+binder) formed by the LF slag is more rigid than that formed by the limestone mineral powder, and therefore has a lower capacity to penetrate the voids in the aggregate (Pasetto et al., 2020). On the other hand, the greater roughness of the EAF slag reduces its compactability and results in a higher porosity within the mineral skeleton. These adverse effects could be partly compensated by increasing the binder temperature (Pasquini et al., 2020).

4.2 Stability

Stability was measured by the Marshall test (EN 12697-34) and is defined as the ability of a mixture to withstand traffic loads and resist the resulting stresses with tolerable deformations. This feature is of the most important in base layers.

The results of this test showed that the introduction of LF slag as fine aggregate and mineral powder improved the stability of the mix by 12% with respect to the standard mix, while its joint incorporation with EAF slag as coarse aggregate greatly improved stability (around 40%), as some other researchers have found (Terrones-Saeta et al., 2021a).

The increase in stability was attributed to the higher stiffness of the siderurgic mastic mentioned above and the high roughness of the EAF slag, which increases the internal friction in the mineral skeleton. The above combined effect managed to overcome the effect of the higher binder content, an unfavorable circumstance for the stability of the mix as it implies higher flexibility/lower stiffness of the pavement.

4.3 Indirect tensile strength

The Brazilian test (EN 12697-23), which analyzes the indirect tensile strength (ITS) of a bituminous mix, showed that the mix with LF slag as fine aggregate and filler had a slightly better tensile performance (6%) than the standard mix. This proves a good adhesion of the mastic to the

On the other hand, the introduction of EAF slag as coarse aggregate was unfavorable for the tensile behavior of the mix. The NBB mix had a 25% lower ITS than the standard mix. This circumstance is attributable to the greater discontinuity of the mix due to its higher porosity, which is highly adverse under tensile stress.

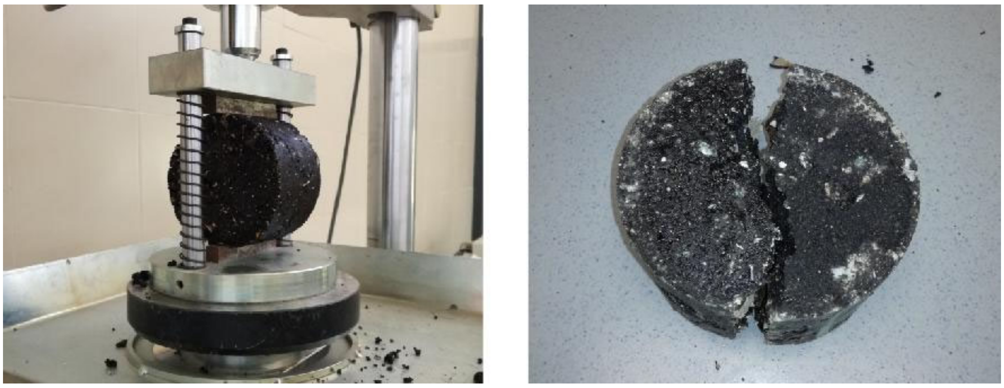

Fig. 3 – CBB mix during and after the ITS test

4.4 Abrasion resistance

Abrasion resistance was determined by the Cantabro test (EN 12697-17). The results of the mixtures studied were all excellent, with particle losses (PL) below 10% in both cases. In addition, both mixes gave results similar to those of the standard mix, so the incorporation of both the LF slag and the EAF slag did not have a detrimental effect on the wear resistance of the resultant mixes. The resistance to abrasion in slag mixtures has also proved to be excellent in other researches, and this feature is particularly relevant in open-graded and porous mixtures (Skaf et al., 2019).

4.5 Durability

The durability test results showed that the mechanical properties of the mixtures studied were hardly affected by the ageing process. For both mixtures, the loss of abrasion resistance after aging was below 3%.

These excellent results are in part due to the higher binder content of the slag mixes, but they also prove a good affinity of the LF slag to the binder, a quality mastic that provides good adhesion to the aggregates and improves the cohesion of the mixes and their resistance to ageing.

Fig. 4 – Specimens of the standard mix prior to testing, after the abrasion test and after the durability test (from left to right)

4.6 Water Sensitivity

Water damage is one of the primary causes of distress in flexible pavements, reducing their durability (Soenen et al., 2020). The moisture susceptibility test (EN 12697-12) showed that the incorporation of slag reduced the water sensitivity of the mix. This reduction was especially noticeable in the mix composed entirely of slag (NBB mix), whose mechanical properties were hardly affected by the action of water. This is due to the good affinity between the EAF slag and the binder, and also attributable to the higher binder content of these mixes (Pathak et al., 2020).

5. CONCLUSIONS

The main results of the investigation can be summarized as follows:

- The incorporation of LF slag as fine aggregate in coarse bituminous mixes is feasible, since it produces similar o superior results to those of the conventional mixes in most of the properties studied.
- The integral replacement of the traditional limestone aggregate with slags (EAF and LF) in base layers fulfilled all regulatory requirements in volumetric terms, stability, abrasion resistance and durability. However, the tensile strength performance was significantly worse than the conventional mix.
- The commercial use of the slags studied in this research should be subject to a prior study of the economic viability of two aspects: the higher cost of transporting EAF slag, due to its higher density, and the higher binder content that these mixtures require.

ACKNOWLEDGEMENTS

This work was supported by the Junta de Castilla y León (Regional Government) and ERDF [grant number UIC-231, BU119P17] and the University of Burgos [grant number SUCONS, Y135.GI].

REFERENCES

BRANCA, T.A., COLLA, V., ALGERMISSEN, D., GRANBOM, H., MARTINI, U., MORILLON, A., PIETRUCK, R., ROSENDAHL, S., (2020). Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in europe. Metals 10(3).

BRAND, A.S., FANIJO, E.O., (2020). A review of the influence of steel furnace slag type on the properties of cementitious composites. Appl. Sci. 10(22), 1-27.

DONDI, G., MAZZOTTA, F., LANTIERI, C., CUPPI, F., VIGNALI, V., SANGIOVANNI, C., (2021). Use of steel slag as an alternative to aggregate and filler in road pavements. Mater. 14(2), 1-13.

GÖKALP, İ., UZ, V.E., SALTAN, M., TUTUMLUER, E., (2018). Technical and environmental evaluation of metallurgical slags as aggregate for sustainable pavement layer applications. Transp. Geotech. 14, 61-69.

GONZALO-ORDEN, H., LINARES-UNAMUNZAGA, A., PÉREZ-ACEBO, H., DÍAZ-MINGUELA, J., (2019). Advances in the study of the behavior of full-depth reclamation (FDR) with cement. Appl. Sci. 9(15).

LI, C.C., LIN, C.M., CHANG, Y.E., CHANG, W.T., WU, W., (2020). Stabilization and crystal characterization of electric arc furnace oxidizing slag modified with ladle furnace slag and alumina. Metals 10(4).

LI, Q., QIU, Y., RAHMAN, A., DING, H., (2018). Application of steel slag powder to enhance the low-temperature fracture properties of asphalt mastic and its corresponding mechanism. J. Clean. Prod. 184, 21-31.

MAHARAJ, C., WHITE, D., MAHARAJ, R., MORIN, C., (2017). Re-use of steel slag as an aggregate to asphaltic road pavement surface. Cogent Eng. 4(1).

MARTINHO, F.C.G., PICADO-SANTOS, L.G., CAPITÃO, S.D., (2018). Feasibility assessment of the use of recycled aggregates for asphalt mixtures. Sustainability (Switzerland) 10(6).

MINISTERIO DE FOMENTO (2015). Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes. art. 542. Mezclas bituminosas en caliente tipo hormigon bituminoso, Ministerio de Fomento (Ed.). Ed. Liteam, Madrid.

PARRON-RUBIO, M.E., PEREZ-GARCIA, F., GONZALEZ-HERRERA, A., OLIVEIRA, M.J., RUBIO-CINTAS, M.D., (2019). Slag substitution as a cementing material in concrete: Mechanical, physical and environmental properties. Mater. 12(18).

PASETTO, M., BALIELLO, A., GIACOMELLO, G., PASQUINI, E., (2017). Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags. J. Clean. Prod. 166, 835-843.

PASETTO, M., BALIELLO, A., PASQUINI, E., SKAF, M., ORTEGA-LÓPEZ, V., (2020). Performance-Based Characterization of Bituminous Mortars Prepared With Ladle Furnace Steel Slag. Sustainability 12(5), 1777.

PASQUINI, E., GIACOMELLO, G., SKAF, M., ORTEGA-LOPEZ, V., MANSO, J.M., PASETTO, M., (2020). Influence of the production temperature on the optimization process of asphalt mixes prepared with steel slag aggregates only, Lecture Notes in Civil Engineering. Springer, pp. 214-223.

PATHAK, S., CHOUDHARY, R., KUMAR, A., (2020). Investigation of Moisture Damage in Open Graded Asphalt Friction Course Mixtures with Basic Oxygen Furnace Steel Slag as Coarse Aggregate under Acidic and Neutral pH Environments, Transportation Research Record. SAGE Publications Ltd, pp. 887-901.

PIEMONTI, A., CONFORTI, A., COMINOLI, L., SORLINI, S., LUCIANO, A., PLIZZARI, G., (2021). Use of iron and steel slags in concrete: State of the art and future perspectives. Sustainability (Switzerland) 13(2), 1-27.

REVILLA-CUESTA, V., SKAF, M., FALESCHINI, F., MANSO, J.M., ORTEGA-LÓPEZ, V., (2020). Self-compacting concrete manufactured with recycled concrete aggregate: An overview. J. Clean. Prod., 121362.

RIBOLDI, A., CORNACCHIA, G., GELFI, M., BORGESE, L., ZACCO, A., BONTEMPI, E., BONIARDI, M.V., CASAROLI, A., DEPERO, L.E., (2020). Grain size effect in elution test of electric arc furnace slag. Appl. Sci. 10(2).

RODRÍGUEZ-FERNÁNDEZ, I., LASTRA-GONZÁLEZ, P., INDACOECHEA-VEGA, I., CASTRO-FRESNO, D., (2019). Technical feasibility for the replacement of high rates of natural aggregates in asphalt mixtures. International Journal of Pavement Engineering.

SKAF, M., MANSO, J.M., ARAGÓN, Á., FUENTE-ALONSO, J.A., ORTEGA-LÓPEZ, V., (2017). EAF slag in asphalt mixes: A brief review of its possible re-use. Resources, Conservation and Recycling 120, 176-185.

SKAF, M., PASQUINI, E., REVILLA-CUESTA, V., ORTEGA-LOPEZ, V., (2019). Performance and Durability of Porous Asphalt Mixtures Manufactured Exclusively with Electric Steel Slags. Materials (Basel) 12(20).

SOENEN, H., VANSTEENKISTE, S., KARA DE MAEIJER, P., (2020). Fundamental approaches to predict moisture damage in asphalt mixtures: State-of-the-art review. Infrastructures 5(2).

TEO, P.T., ZAKARIA, S.K., SALLEH, S.Z., TAIB, M.A.A., SHARIF, N.M., SEMAN, A.A., MOHAMED, J.J., YUSOFF, M., YUSOFF, A.H., MOHAMAD, M., MASRI, M.N., MAMAT, S., (2020). Assessment of electric arc furnace (EAF) steel slag waste's recycling options into value added green products: A review. Metals 10(10), 1-21.

TERRONES-SAETA, J.M., SUÁREZ-MACÍAS, J., IGLESIAS-GODINO, F.J., CORPAS-IGLESIAS, F.A., (2021A). Development of high resistance hot mix asphalt with electric arc furnace slag, ladle furnace slag, and cellulose fibers from the papermaking industry. Appl. Sci. 11(1), 1-23.

TERRONES-SAETA, J.M., SUÁREZ-MACÍAS, J., IGLESIAS-GODINO, F.J., CORPAS-IGLESIAS, F.A., (2021B). Evaluation of the physical, chemical and environmental properties of ladle furnace slag for their utilization as filler in bituminous mixtures. Metals 11(3), 1-15.

VARANASI, S.S., MORE, V.M.R., RAO, M.B.V., ALLI, S.R., TANGUDU, A.K., SANTANU, D., (2019). Recycling Ladle Furnace Slag as Flux in Steelmaking: A Review. Journal of Sustainable Metallurgy 5(4), 449-462.