Artificial Ballast Project: new materials for a new approach to railway infrastructure.

P. González Requejo[1], D. Losa Baur[1], A. Gutiérrez[1], A. Rincón[1], P. Iglesias[1]

[1]Fundación Caminos de Hierro, Madrid, Spain

Abstract

Innovation in railway infrastructure has been developed along mutually exclusive paths either with ballasted track or slab track. Until now, no intermediate solution has been investigated where the science of materials and advanced simulation tools would allow the research, development and manufacturing of an "artificial ballast", as a new approach which should eventually combine the advantages of crushed-rock or natural ballast with the controlled design, manufacturing and construction features that characterize slab track. This Project is funded by the Spanish Administration within the multi-year Plan of Research, Development and Technology Innovation, 2008-2011 and should be the first step toward further investigation into related matters.

1. INTRODUCTION

The key point in this project lies in the definition of an artificial material from the "natural ballast" made of crushed rock, of which many properties and features are not yet fully understood.

The project has been involving different perspectives and fields of expertise as shown in Figure 1. On one hand, the research is focusing on finding suitable base materials for artificial ballast manufacturing, with focus on developing micro-concrete or high resistance mortars, with cement base and different additives. On the other hand, mass-production techniques are being investigated (casting, controlled crushing of base material,..), with alternatives for texture, roughness or indentations. At the same time, computer models are being developed to further define the geometric properties of grains that should lead to an improvement in the behavior of the ballast layer.

This paper summarizes the objectives of relevant sub-projects with emphasis on the analysis of the mechanical properties of the base material.

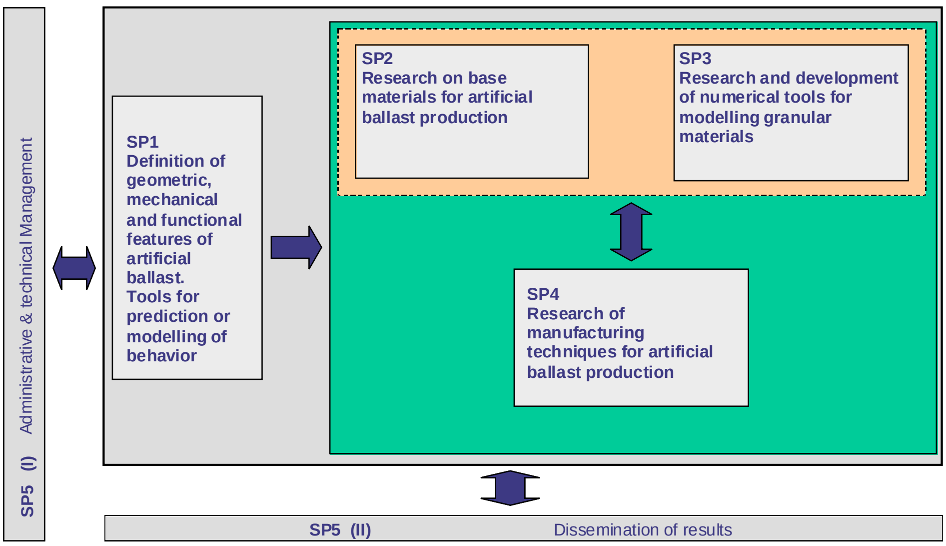

Figure 1. Functional blocks of the Artificial Ballast project

2. PURPOSE OF THE PROJECT

The “Artificial Ballast” idea comes from a concept which has been used in other fields of civil engineering and construction, i.e. the progressive substitution of natural materials by artificial materials with improved features and longer life cycles.

In the railway industry, such evolution has followed a top-down approach, i.e. first improving the quality of rail steels, then developing advanced fastening systems and replacing wooden sleepers with concrete sleepers or like in Japan, with “artificial wood” sleepers made of a polymer-fiber composite. The substitution of other components of the track is an ongoing field of research (e.g. bituminous sub-ballast layer).

The development of an effective solution such as the artificial ballast, seen in the medium or long term, is justified by the suitability of this adjustable geometry layer (through tamping operations) as the interface between a substructure where deformations can be in the centimeter range and a superstructure where admissible geometry irregularities are in the millimeter range.

Both scientific and technical advancements in the science and technology of materials, especially in micro-concretes and high-performance mortars, may foretell that such type of materials may be economically and technically feasible in the medium term as a substitute for rocks in ballast production.

3. STUDY ON MATERIAL MECHANICAL PROPERTIES

The identification of the mechanical characteristics of rocks used for natural ballast production is not rigorous, as seen further. A thorough analysis has been made of the several testing methods existing for rocks and values found in bibliographical references, which all show a great dispersion. [5] [8] [9] [14]

As the project is focusing for obvious economic reasons on developing micro-concrete and high resistance mortars, with cement base and different additives, the advancements on the definition of the mechanical properties of concrete and mortars have been analyzed, especially those related to the fracture toughness. [2] [4] [6]

Due to the limited scope of normalized tests for concrete, it has been deemed necessary to also complement this analysis by studying the techniques currently used for the characterization of properties of structural ceramic materials, both as regards the assessment of fracture toughness and the application of indentation techniques for assessing the surface hardness. [1] [10] [11] [15] [17]

3.1. ROCKS FOR NATURAL BALLAST

The Spanish standards for natural ballast [13] establish two types of structural characterization of the material: the compressive strength of the rock and the behavior of the granular matter obtained from rock crushing and sieving with the Los Angeles test.

This kind of assessment is quite insufficient in terms of science of materials and furthermore the Los Angeles test is an empirical test, in which complex impact and attrition phenomena are involved.

The mechanical properties of the rocks that comply with standards and may be used for ballast production are thus the starting point of this part of the project.

Therefore the research on the artificial material to be considered as a base material for the artificial ballast has been following the two approaches described below.

3.1.1. The “natural path”

The “natural path” means identifying the relevant mechanical parameters of “intact” rocks that are used for ballast production.

The values of these parameters shall be, as the first approach, those made mandatory for the foreseen artificial material, irrespective of whether all the mechanical parameters are necessary or some of them may be intrinsic properties of the natural material but not really needed for the proper mechanical behavior of the ballast layer as a track component.

3.1.2. The “analytic path”

The “analytic path” means finding the proper interpretation of these resistance parameters as regards the behavior of the ballast layer.

Therefore this approach shall need to:

- Discriminate which minimum values of these parameters derived from the analysis of rocks, must be complied with.

- Discriminate which values of these parameters derived from the analysis of rocks are intrinsic properties of the rock and could be reduced

- Differentiate all those characteristics that may be specifically improved, i.e. leading to substantial improvements in ballast layer behavior.

As a preliminary task prior to numerical simulations, a first analysis is made to link mechanical resistance parameters and the results of the Los Angeles test which is commonly accepted as a test for assessing the capacity of the ballast to support the efforts due to traffic loads and maintenance operations (tamping).

To this end, the project includes an analysis of quality control data from ballast-producing quarries in Spain and a specific group of tests both focused on identifying rocks from the point of view of:

- Rc: unconfined compressive strength

- Rt: tensile strength

- G: fracture toughness

- H: surface hardness

The test program is currently underway. Some results can be shown however with regard to the relation between the coefficient of Los Angeles (CLA) and the compressive strength (Rc) obtained with the Franklin test for a wide selection of rocks from different Spanish quarries (See Figures 2 and

3). These figures show that the result of the Los Angeles test cannot be associated exclusively with the compressive strength of the material.

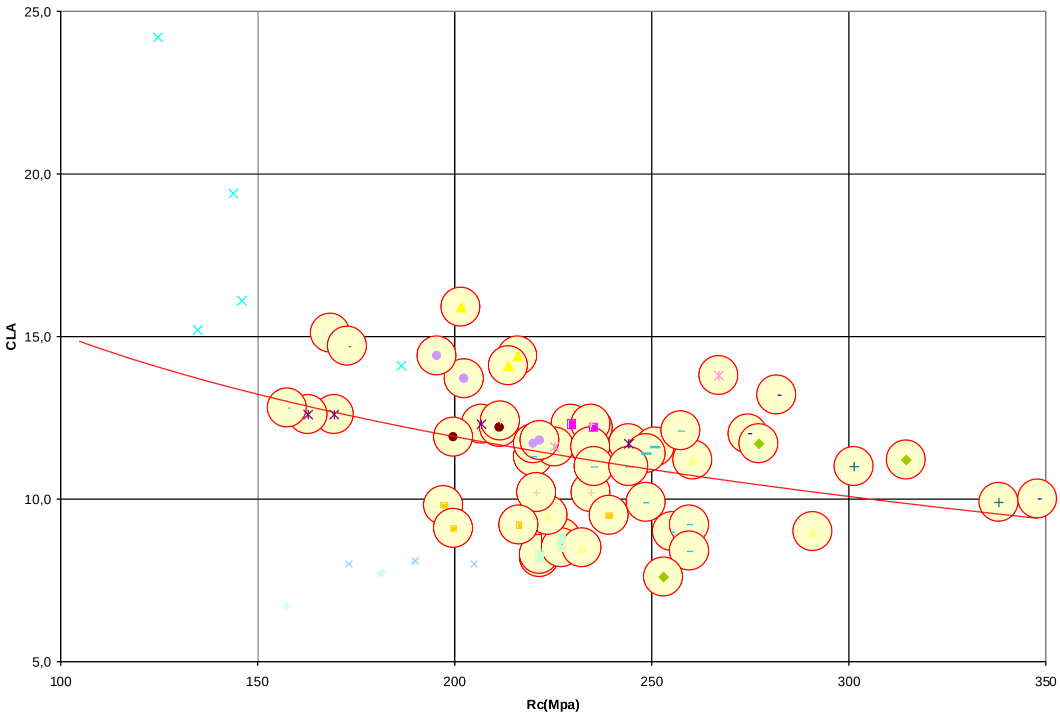

Figure 2. Results of Los Angeles test (CLA) vs compressive strength (Rc)

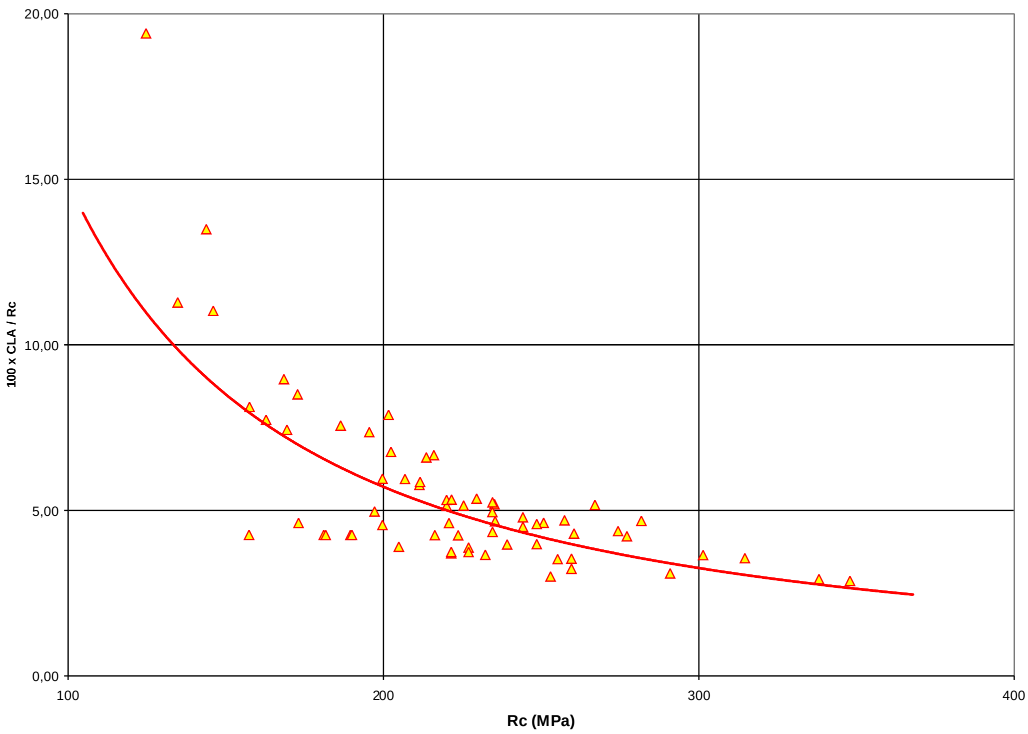

Figure 3. CLA/Rc ratio vs compressive strength (Rc)

3.2. MICRO-CONCRETE OR HIGH RESISTANCE/HIGH PERFORMANCE MORTARS FOR ARTIFICIAL BALLAST PRODUCTION

3.2.1. First assessment of the compressive strength

According to Spanish standards, rocks used for ballast production must have a minimum unconfined compressive strength Rc of 120 MPa, which could correspond to the minimum value set for a type 2 ballast (LA_{BR} 16) and adjusts reasonably well with the fitting curve shown in Figure 2.

The compressive strength of the artificial material could then be set as a “target” value of 175 MPa (according to the “natural path” mentioned earlier), as a threshold for Rc values found in rocks tested in ballast quarries (See Figure 2).

The industrial production of concrete or high-resistance mortars currently allows reaching up to a value of 70 MPa. Further introduction of various additives allows to exceed this limit which can then reach up to 100 MPa for high-performance concrete. It shall be pointed out that different resistances are being compared here: while for rocks average resistances (Rc) are being considered, for micro-concrete or mortars these are characteristic resistances.

The equivalent characteristic resistances obtained from the six central values of Franklin tests for rocks of five Spanish quarries are shown in Figure 4.

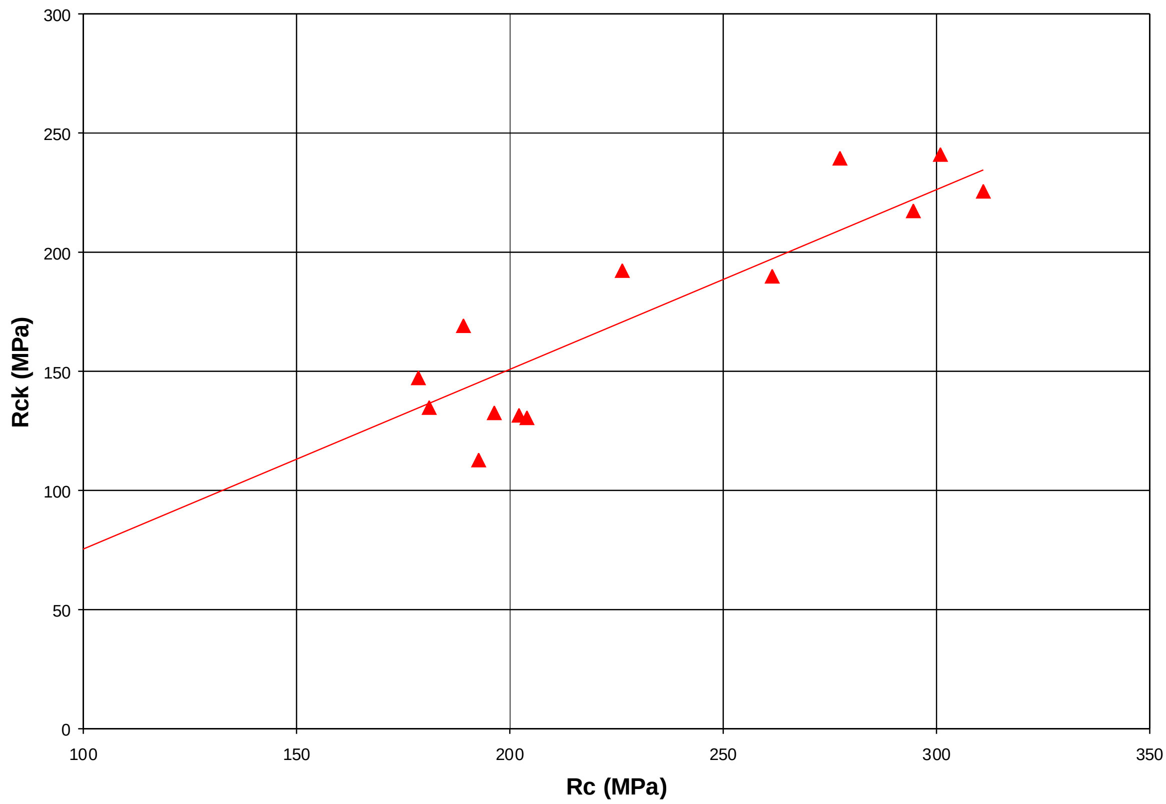

Figure 4. Characteristic resistance (Rck) vs compressive strength (Rc)

The dispersion of compressive strength values found with Franklin tests shall in any case be analyzed, as it is hard to tell whether such dispersion (and the subsequent decrease of characteristic values) is due to micro-cracks in the rock (due to the crushing process) or due to the Franklin test itself.

On the other hand, for micro-concrete or mortars, these are resistances at 28 days. In the case of manufacturing a material which will not be immediately used and with a lengthy curing period under ideal conditions, a substantial increase of resistance can be expected, between 20% and 40%.

Therefore, the target value of resistance first set at a Rc value of 175 MPa, could be reduced to values of a characteristic resistance (f_{ck} to 28 days) around 100 MPa, which is compatible with values reached for micro-concrete or high-performance mortars.

3.2.2. First assessment of Rt, G and H

For rocks used for ballast production, the Rc/Rt ratio is greater than 10, which implies that complying with minimum values of Rc for micro-concrete or mortars should generally guarantee that Rt values of reference rocks are exceeded. [12]

As regards toughness, the characteristics of concrete or mortars (K_{IC} around 1,5 MPa.$m^{1/2}$ and G around 100 N/m) are equal or greater than those of the reference rocks. [3] [7] [16] [18]

The alternatives for increasing the tensile strength and toughness of the artificial material are being currently investigated in the project.

As regards surface hardness, data from the rocks being considered also show dispersion. The test program of the project includes the assessment of the hardness of rocks from several Spanish ballast quarries with Vickers testing.

The assessment of surface hardness for micro-concrete or mortars is not usually made. This parameter shall be assessed for the artificial material which is being developed in the corresponding sub-project. In any case, the expected hardness of the artificial material (Vickers Hardness HV from 70 MPa to 400 MPa) could hardly attain values shown by rocks used for ballast (HV greater than 5.000 MPa). Therefore, it should be convenient to focus on the production of a micro-concrete with high surface hardness or to assess the possibility of increasing this hardness on the surface of grains with specific production processes or appropriate curing methods.

3.2.3. First assessment of LA for concrete

LA values obtained for recycled concrete (LA 40) are 2 or 3 times greater than the minimum value admissible for ballast (LA 16).

Such difference is relatively proportional to the different values of resistance of “conventional” concrete and rocks and does not seem to indicate the huge difference existing between them as regards surface hardness values. However, the above considerations should be confirmed with the test program foreseen in the project and the analysis of the geometry of both types of granular matter (it has been verified that for the same rock and grading envelope, the LA coefficient depends on the geometry of grains, i.e. the “form index” defined in Spanish standards).

3.3. TESTING FOR CHARACTERIZATION OF MECHANICAL PROPERTIES

The test program of the project intends to establish a rigorous comparison between natural (from three selected quarries) and artificial materials, considering the behavior parameters Rc, Rt, G, H and also the LA value, which despite its empirical nature, is a value of general reference.

As regards the Rc, Rt, G and H parameters, it has been tried to establish a common testing procedure and coherent test piece dimensions for both rocks and concrete.

For the LA test and due to the influence of grain geometry, this test shall be made crosswise, i.e. on one hand with “regular” geometry (cubes of rock with 4 to 5 cm sides) and on the other hand with random geometry (crushing of micro-concrete blocks).

4. GRAIN GEOMETRY AND SIMULATION MODELS

The full definition of the granular matter is too ambitious a goal to be fulfilled during this project. Therefore only an orientation or recommendations on the geometry will be made, taking into account the limitations of the base material (e.g. the size of mortars) and of the production process.

Within these limitations the production of artificial ballast may allow a wide range of possibilities (grading envelope, primary geometric shape of particles, surface indentations or roughness, combinations of grain geometries,...)

The practical impossibility of analyzing all these combinations via testing makes necessary computer simulations with numerical models that are being under way in the project in order to establish the abovementioned orientation or recommendations. The current simulations (see Figure 5) are based upon simple geometries, where contact laws are parametrized for spherical grains and three load scenarios should be simulated:

- Traffic loads with proper ballast-sleeper contact
- Traffic loads with degraded ballast-sleeper contact (hanging sleepers)
- Tamping.

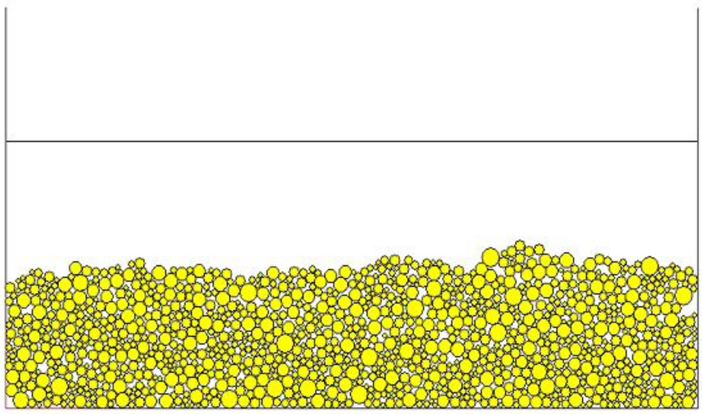

Figure 5. Models for ballast simulation.

5. MANUFACTURING TECHNIQUES

The project assesses the feasibility of different industrial production techniques of artificial ballast grains, mainly along the following options:

- Grain moulding, with particle geometry allowing an easy mould release
- Crushing of blocks of artificial material with preferred fracture planes
- Controlled “dilatation” breakage of blocks of artificial material

The curing techniques of ballast particles shall also be analyzed.

6. CONCLUSIONS

The Artificial Ballast project is the first step towards research into an artificial material that may be used in the medium term for construction of new railway lines or renovation of existing lines.

Besides the expected results, this project could be a starting point for further research on specific and more focused goals. The application of the science of materials (along with proper testing procedures) may represent a significant improvement as regards the characterization of rocks used for ballast production and should be the basis for the design of appropriate artificial materials such as very high performance micro-concrete or mortars.

The project allows to establish design criteria for the generation of granular matter with grains of controlled geometry within the limits set by production techniques but with a wide range of options as regards the grading envelope and the geometry of particles.

The current production of railway ballast in Spain is around 2 million cubic meters per annum of which about 60% are used for the construction of new lines and 40 % for renovation of existing lines. Ballast volume for renovation could even increase in the next few years as the life cycle of the ballast first installed on new high speed lines comes to an end.

Therefore the environmental and economic impact of the production of an artificial ballast is huge. On the environmental side several benefits can be pointed out, such as a diminished impact from existing quarries or new ones, transportation savings, improved track maintenance, increasing the ballast life cycle and the eventual utilization of recycled materials in the productive process of the new material.

References

[1] Anglada, M.J.et al. Fractura de materiales. Ediciones UPC. 2002.

[2] Appa Rao, G., Raghu Prasad, B.K. Fracture energy and softening behavior of high-strength concrete. Cement and Concrete Research 32 (2002) 247-252.

[3] Bear T.J., Barr B. Fracture toughness for concrete. International Journal of Fracture 13. 1.977. 92 – 96.

[4] Einsfeld, R. A., Velasco, M.. Fracture parameters of high-performance concrete. Cement and Concrete Research 36 (2006) 576-583.

[5] González de Vallejo, L.I. Ingeniería Geológica. Ed. Pearson. Prentice Hall. 2003.

[6] Guinea Tortuero, G.. Medida de la energía de fractura del hormigón. Tesis doctoral. Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos. Universidad Politécnica de Madrid. 1990.

[7] Hanson J.H., Ingraffea A.R. Behavior of concrete round double beam fracture toughness test specimens. Fracture Mechanics of Concrete Structures. Proceedings FRAMCOS-3. 441 – 452.

[8] Hudson, J. Comprehensive rock engineering. Principles, practice and projects. Volume 3: Rock testing and site characterization. Ed. Pergamon Press. Oxford. 1993.

[9] Jiménez Salas, J.A., de Justo Alpañés, J.L. Geotecnia y cimientos I. Propiedades de los suelos y de las rocas. Ed. Rueda. 1975.

[10] Juy Aguirre, A. Influencia de las tensiones residuales de mecanizado en las propiedades mecánicas de Y-TZP. Tesis doctoral. Universidad Politécnica de Cataluña. 2004.

[11] Pastor Caño, J. Fractura de materiales cerámicos estructurales avanzados. Tesis doctoral. Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos. Universidad Politécnica de Madrid. 1993.

[12] Petroski H.J., Ojdrovic R.P. The concrete cylinder: stress analysis and failure modes. International Journal of Fracture 34: 263-279 (1.987). 263 – 279.

[13] Pliego de prescripciones técnicas de materiales ferroviarios (PF). Capítulo 6: Balasto. Ministerio de Fomento. 2006.

[14] Ramírez Oyanguren, P., Alejano Monge, L. Mecánica de rocas: fundamentos e ingeniería de taludes. Máster internacional "Aprovechamiento sostenible de los recursos minerales". Escuela Técnica Superior de Ingenieros de Minas. Laboratorio de Mecánica de Rocas. 2008.

[15] Rocha Rangel, E., Díaz de la Torre, S.. Determinación de la tenacidad a la fractura mediante indentación Vickers. Ingenierías, April-June 2008, Vol. XI, Nº 39.

[16] Santos A.C.et al. Determinación de la tenacidad a la fractura en el hormigón convencional con probetas cilíndricas. Anales de la Mecánica de la Fractura, Vol. 18. 355 – 359.

[17] Villa, I. Un método analítico para el estudio del comportamiento en fractura de materiales cuasifrágiles. Tesis doctoral. Universidad Carlos III de Madrid. 2007.

[18] Wittmann F.H., Metzner I. Fracture toughness of concrete determined on large specimens. Materiaux et Constructions 25. 93 – 95.

Acknowledgments

Authors thank entities participating in the Artificial Ballast project (Universidad Politécnica de Madrid, INGECIBER S.A., IECA, OFICEMEN, Fundación de los Ferrocarriles Españoles) and also thank ADIF for data provided from Spanish ballast quarries.