UNIVERSIDAD DE GRANADA

E.T.S. DE INGENIEROS DE CAMINOS, CANALES Y PUERTOS

DEPARTAMENTO DE INGENIERÍA DE LA CONSTRUCCIÓN Y PROYECTOS DE INGENIERÍA

OPTIMIZATION OF BITUMINOUS SUB-BALLAST IN RAILWAYS INFRASTRUCTURES UNDER SUSTAINABILITY CRITERIA

TESIS DOCTORAL

Luca Pirozzolo

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Luca Pirozzolo

SUPERVISORS:
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Granada, 2017

Declaration of authorship

Mr. Luca Pirozzolo, as PhD Candidate, and Dr. Mª Carmen Rubio Gámez and Dr. Fernando M. Moreno Navarro, as PhD Supervisors and Professors of the University of Granada in Spain,

Guarantee by signing this thesis:

that the research work contained in the present report, entitled Optimization of Bituminous Sub-Ballast in Railways Infrastructures under Sustainability Criteria, has been performed under the full guidance of the PhD Supervisors and, as far as our knowledge reaches, during the work, it has been respected the right of others authors to be cited, when their publications or their results have been used.

Granada, 27th April, 2017.

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ABSTRACT

In recent years, the railway sector has focused on more sustainable constructive techniques and more durable solutions such as the inclusion of bituminous sub-ballast in order to reduce track degradation whilst improving its quality. The use of bituminous layer in railways tracks is regarded as an appropriate solution for improving the strength of the section. In comparison with traditional granular sub-ballast, these materials allow for both an increase in bearing capacity and greater protection of the substructure. However, the fact that these materials are manufactured at a temperature of 160°C means that their application can incur significant construction costs, along with a rise in pollution and energy consumption. In this regard, there is a need for the use of new techniques to produce asphalt, such as the reuse of waste materials or manufacturing with low-temperature technology, both of which allow for lower energy expenditure without changing its in-service mechanical performance, as well as reducing the general costs of this layer. In this context, this thesis therefore aims to, on the one hand, study the possibility of using sustainable bituminous sub-ballast manufactured from waste materials such as crumb rubber, which is recycled rubber produced from scrap tires and reclaimed asphalt pavement (RAP) from road pavement at the end of their service life. A further aim is to study the possibility of using WMA manufactured at lower temperatures, as bituminous sub-ballast. To this end, this thesis is focused on evaluating the mechanical behaviour of bituminous materials (under both routine and adverse temperatures) in comparison with that presented by conventional sub-ballast. In particular, performance is examined with respect to the main requirements that need to be met by these materials (resistance to plastic and punching deformations, bearing capacity, stress dissipation, cracking resistance, and waterproof properties) for their use in railway tracks.

The results demonstrated that all the sustainable solutions studied, offer a suitable performance as sub-ballast for railways tracks from a mechanical behaviour point of view. In addition, they can offer advantages such as reducing greenhouse emissions, fuel consumption and waste as in the case of HWMA 100% RAP. furthermore, the use of rubberized bituminous mixtures (DRA and WRA) make more durable sub-ballast layer, at the same time that allow for waste recovery. Finally, the use of WMA, despite its performances was slightly lower respect the others solutions studied, achieved acceptable results for its use as a sub-ballast layer. Moreover, it is a solution that guarantees to reduce pollution and energy consumption thanks to its ability to reduce mixing and compaction temperatures.

Keywords: Railway, Bituminous sub-ballast, Granular sub-ballast, Warm mix asphalt, Half-Warm 100% recycled asphalt pavement, Reclaimed asphalt pavement, Crumb rubber.

RESUMEN

En los últimos años, el sector ferroviario se ha centrado en técnicas constructivas más sostenibles y soluciones más duraderas, como la inclusión de subalasto bituminoso para reducir la degradación de la vía y mejorar su calidad. El uso de la capa bituminosa en vías férreas se considera como una solución apropiada para mejorar la resistencia de la infraestructura ferroviaria. En comparación con el subalasto granular tradicional, las mezclas bituminosas permiten un aumento de la capacidad de carga y una mayor protección de la subestructura. Sin embargo, el hecho de que estos materiales se fabriquen a una temperatura de 160 °C significa que su aplicación puede incurrir en costes de construcción significativos, junto con un aumento de la contaminación y el consumo de energía.

Con respecto a esto, se necesitan nuevas técnicas para producir asfalto, como la reutilización de residuos o la fabricación con tecnología de baja temperatura, que permitan un menor gasto de energía sin cambiar su rendimiento mecánico en servicio, así como la reducción de los costes generales de esta capa. En este contexto, esta tesis pretende, por una parte, estudiar la posibilidad de utilizar subalastos bituminosos sostenibles fabricados a partir de materiales de desecho como polvo de caucho a proveniente de neumáticos fuera de uso y material recuperado de pavimentos asfalticos envejecidos, conocido por las iniciales RAP de su nombre en inglés "Reclaimed Asphalt. Otro objetivo es estudiar la posibilidad de utilizar Warm Mix Asphalt (WMA), mezclas fabricadas a bajas temperaturas, como el subalasto bituminoso. Con este fin, esta tesis se centra en evaluar el comportamiento mecánico de los materiales bituminosos (tanto en temperaturas rutinarias como adversas) en comparación con el presentado por el subalasto convencional. En particular, se examinan las prestaciones que deben cumplir estos materiales (resistencia a las deformaciones plástica y de punzonamiento, capacidad portante, disipación de presiones, resistencia a la fisuración y propiedades impermeables) para su uso en vías de ferrocarril.

Los resultados demuestran que todas las soluciones sostenibles estudiadas, ofrecen un rendimiento adecuado como subalasto para vías férreas desde el punto de vista del comportamiento mecánico. Además, pueden ofrecer ventajas como la reducción de las emisiones de gases, consumo de combustible y de residuos. Además, el uso de mezclas bituminosas con caucho (DRA y WRA) hacen más duradera la capa de subalasto, al mismo tiempo que permiten la recuperación de residuos. Por último, el uso de WMA, a pesar que sus resultados fueron ligeramente inferior respecto a las otras soluciones estudiadas, logró resultados aceptables para su uso como una capa de subalasto. Además, es una solución que garantiza reducir la contaminación y el consumo de energía gracias a su capacidad de reducir las temperaturas de fabricación y compactación.

Palabras claves: Ferrocarril, Subbalasto bituminoso, Subbalasto granular, Mezcla bituminosa en caliente, Mezcla templada 100% reciclada, Pavimento asfaltico reciclado, Polvo de caucho.

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LIST OF NOTATIONS

γ	Damage parameter
ω_n	Energy dissipation produced in loading cycle number n
ω_{n+1}	Energy dissipation in loading cycle n + 1
A1	Ballastless track system with direct support of the track panel on an asphalt-supporting layer
A3	The multi-layer asphalt base direct support of wide concrete sleepers
AC	Asphalt concrete
B.S	Bituminous sub-ballast
B.S.	Bituminous sub-ballast
B.S.+SM	Bituminous layer under the ballast + a stiff mat under the sub-ballast
C	Ballast coefficient
CO	Carbon monoxide
CO2	Carbon dioxide
CRM	Crumb rubber modified
CWR	Continuous welded rail
DRA	Dry rubberized asphalt
Ed	Elastic modulus
ELT	End of life tyres
ETRMA	European Tyre and Rubber Manufacturers Association
EU	European Union
f	Frequency
G	Track gauge
G.S.	Granular sub-ballast
G.S.+SM	Granular sub-ballast + a stiff under sub-ballast mat
GHG	Greenhouse Gas
Hb	Thickness of the ballast layer (in millimeters);
HBU	Heat build up
HMA	Hot mix asphalt
HS	High speed
Hsb	Thickness of the subballast layer (in millimeters);
HWMA	Half-warm mix asphalt

IDT	Indirect Tension Test
ITS	Indirect tensile strength
ITSd	Indirect tensile strength untreated
ITSM	Indirect tensile stiffness modulus test
ITSR	Tensile strength ratio
ITSw	Indirect tensile strength water
K	Permeability coefficient
k	Static vertical track stiffness
Keq	Stiffness coefficient
kxy	Secant stiffness
L.A.	Los Angeles coefficient
LL	Longitudinal level
Nf	Cycle in which the macro-crack appeared at the bottom
NOx	Nitrous oxides
NR	Natural rubber
P.D.	Permanent deformation
Pa	Sinusoidal axial loading
PAHs	Polycyclic aromatic hydrocarbons
Pc	Confining load
PG	Performance grade
Q	Loads applied on the rail
QS3	Quality of the soil
RAP	Reclaimed asphalt pavement
RDEC	Ratio of dissipated energy change
Rpm	Revolutions for minute
S.C.D.	Slope of creep deformation
Sb	Settlement of the ballast layer (in millimetres);
SBS	Styrene–butadiene–styrene
SCBT	Semi-circular bend fracture test
SM	Stiff mat
Sm	Stiffness modulus
SMA	Stone matrix asphalt

SNCF	FRANCE National Railway
SO_2	Sulfur dioxide
SOUBM	Soft under ballast mat
Ss	Settlement of the track formation (in millimetres);
Ssb	Settlement of the subballast layer (in millimetres);
Strack	Total settlement of the track (in millimetres);
SUBM	Stiff under ballast mat
T	Cumulative traffic (in millions of gross tons);
T	Temperature
t	Time
TGV	Train à Grande Vitesse
U	Track modulus
UBM	Under ballast mat
US	United States
VMA	Void in mineral aggregate
VOC	Volatile organic compounds
W	Optimum moisture
WMA	Warm mix asphalt
WRA	Wet rubberized asphalt
z	Maximum deflection of the track structure
α	Track receptance
γd	Maximum density

COMPENDIUM OF PUBLICATIONS

The following thesis consists of a *"compendium of publications",* according to the University of Granada *("Articulo 18.4 2 Las Normas Reguladoras de las Enseñanzas Oficiales de Doctorado y del Título de Doctor por la Universidad de Granada")* about sustainable railways technologies. In addition, this thesis is a result of the European research project "SUSTAINABLE PAVEMENTS & RAILWAYS INITIAL TRAINING NETWORK (SUP&R ITN)" within the research project ESR-12 "The use of waste materials in railways". Furthermore the present thesis meets the requirements to qualify for the International doctorate according to the Decree 99/2011 of the University of Granada.

The papers presented in this thesis are three in total. The PhD student has contributed substantially in all stages of development of all the articles, from the development of the idea, literature search, completion of experiments, analysis and interpretation of data, drafting and preparation of the manuscript, and monitoring and final correction thereof according to the recommendations of the referees.
This doctoral thesis is composed of the publications summarized below. The full texts are included in Annex A.

- **PAPER 1**: ADVANCED CHARACTERISATION OF BITUMINOUS SUB-BALLAST FOR ITS APPLICATION IN RAILWAY TRACKS: THE INFLUENCE OF TEMPERATURE
  - **Authors:** *Miguel Sol-Sánchez,* ***Luca Pirozzolo,*** *Fernando Moreno-Navarro, Maria del Carmen Rubio-Gámez.*
  - **Reference:** *Construction And Building Materials, Volume 101, Part 1, 30 December 2015, Pages 338–346. ISSN: 0950-0618.*
  - **Quality indicators:** *Impact Factor 2,421; Category Construction & Building Technology 9/61, Q1*
  - **DOI:** *http://dx.doi.org/10.1016/j.conbuildmat.2015.10.102*
  - **Abstract:** *The use of bituminous sub-ballast in railway tracks is regarded as an appropriate solution for improving the strength of the section. However, for its widespread application, more in-depth studies are needed to assess its efficacy with respect to the main requirements that this material must meet under various service conditions. Such conditions include the range of temperatures that can occur during the service life of the railway tracks, which can modify the behaviour of bituminous material. This paper therefore focuses on evaluating the mechanical behaviour of bituminous material (under both routine and adverse temperatures that are expected in railway lines in extreme climates) in comparison to that presented by conventional granular sub-ballast. In particular, performance is*

examined with respect to the main requirements that need to be met by these materials (resistance to plastic and punching deformations, bearing capacity, stress dissipation, cracking resistance, and waterproof properties) for their use in railway tracks. At the same time, their influence on the performance of the global section was assessed for both types of subballast by means of a full-scale test. The results demonstrated that the use of bituminous sub-ballast could improve both the mechanical response of the track and the protection of the remainder of the track bed layers, since this material exhibited higher strength against the loads imposed by passing trains, lower permeability, and a higher capacity to dissipate stresses transmitted by the ballast to the substructure. However, it is also important to consider that temperature plays a fundamental role in the resistance of bituminous sub-ballast to plastic and punching deformations, whilst its resistance to cracking declines sharply at higher temperatures. This could limit its application in railway lines in regions where values of this parameter are expected to be higher than those commonly recorded for this layer.

- **PAPER 2:** A STUDY INTO THE MECHANICAL PERFORMANCE OF DIFFERENT CONFIGURATIONS FOR THE RAILWAY TRACK SECTION: A LABORATORY APPROACH
    - **Authors***: Miguel Sol-Sánchez,* ***Luca Pirozzolo,*** *Fernando Moreno-Navarro, Maria del Carmen Rubio-Gámez.*
    - **Reference:** *Engineering Structures, Volume 119, 15 July 2016, Pages 13–23. ISSN: 0141-0296.*
    - **Quality indicators:** *Impact Factor 1,893; Category Engineering Civil 28/126, Q1.*
    - **DOI:** *http://dx.doi.org/10.1016/j.engstruct.2016.04.008*
    - **Abstract:** *A traditional railway track is composed of rails, sleepers, fastenings (included rail pads), ballast, and a formation layer. More recently, other configurations have been commonly used in the track section in order to improve its quality and durability. However, the use of different configurations can lead to important changes in fundamental parameters such as the global vertical stiffness of the track, as well as its settlement and rolling resistance. This paper therefore focuses on a laboratory study of the mechanical performance of a number of different track sections, assessing the effect of using various types of elastic elements with varying properties, various types of sub-ballast, and different thicknesses of ballast layer. The results showed that reducing track stiffness by modifying the elastic elements over the ballast layer leads to an increase in the capacity of the track to dissipate energy and to reduce its settlement. However, the reduction in stiffness induced by modifying the configuration under the ballast (by, for example, adding elastic mats) causes*

an increase in settlement, the latter exerting the strongest influence (even more so than the change in ballast thickness) on track performance. Furthermore, it was seen that changes in track behaviour are lower (particularly in track stiffness) than those observed in the properties of its components.

- **PAPER 3:** EVALUATION OF BITUMINOUS SUB-BALLAST MANUFACTURED AT LOW TEMPERATURES AS AN ALTERNATIVE FOR THE CONSTRUCTION OF MORE SUSTAINABLE RAILWAY STRUCTURES.
    - **Authors***: **Luca Pirozzolo**, Miguel Sol-Sánchez, Fernando Moreno-Navarro, Germán Martínez Montes, Maria del Carmen Rubio-Gámez.*
    - **Reference:** *Materiales de Construcción. ISSN: 0465-2746.*
    - **Quality indicators:** *Impact Factor 0,960; Category Construction & Building Technology 31/161, Q3.*
    - **DOI:** *2017 IN PRESS*
    - **Abstract:** *Hot bituminous mixtures are becoming widely used in modern railway tracks in the sub-ballast layer. One reason for this is that in comparison with traditional granular sub-ballast (the conventional configuration used in high-speed railways), these materials allow for both an increase in bearing capacity and greater protection of the substructure. Despite these advantages, the fact that these materials are manufactured at a temperature of 160 °C means that their application can incur significant construction costs, along with a rise in pollution and energy consumption. This paper therefore aims to study the possibility of using WMA manufactured at lower temperatures, as bituminous sub-ballast. The use of these materials could save energy and reduce emissions throughout the production process, as well as diminish the global costs of this layer. To this end, this study focuses on a comparison of the mechanical behaviour of warm and hot bituminous mixtures as sub-ballast under various loading conditions. The main failure modes that take place during the service life of sub-ballast were evaluated. The results indicate that WMA offers mechanical behaviour that is comparable to conventional HMA sub-ballast, which makes it a potential alternative for use in construction of this layer, due to its economic and environmental benefits.*

Another two papers are currently under review.

- **PAPER 4:** ANALYSIS OF THE MECHANICAL BEHAVIOUR OF SUSTAINABLE RUBBERIZED BITUMINOUS SUB-BALLAST TO BE USED IN RAILWAYS INFRASTRUCTURES.

- **Authors***: **Luca Pirozzolo**, Miguel Sol-Sánchez, Fernando Moreno-Navarro, Maria del Carmen Rubio-Gámez.*
- **Reference:**
- **Quality indicators:**
- **DOI:** *Under review*
- **Abstract:** *In recent years, in the constructions sector, sustainability has become one of the major priorities for both management and decrease in the use of natural resources and at the same time develop new techniques in order to reuse waste material generated in the environment. Particularly, there are several techniques that have already been adopted in road engineering through various ways such as pavement recycling, use of waste material, low-temperature mixes that reduce emissions and energy consumption etc. Even the railway sector, has been directed towards development through the implementation of sustainable constructive techniques and utilization of waste materials. This paper therefore assesses the possibility of using bituminous sub-ballast, which are becoming widely used in modern railway tracks, under sustainability criteria. To this end, this study focuses on the evaluation of the mechanical behaviour of rubberized bituminous sub-ballast manufactured by both dry and wet process and comparing its performance with that presented by conventional bituminous sub-ballast. In particular, performances are examined with respect to the main requirements that need to be met by these materials for their use in railway tracks. The results showed that both types of rubberized asphalt as sub-ballast offer comparable and in some cases better performances to conventional bituminous sub-ballast***.**

- **PAPER 5:** DEVELOPMENT OF HALF-WARM MIX ASPHALT WITH 100% RECLAIMED ASPHALT PAVEMENT AS SUB-BALLAST FOR RAILWAY FOR AN ENVIRONMENTALLY-FRIENDLY MEANS OF TRANSPORTATION.
  - **Authors***: **Luca Pirozzolo**, Miguel Sol-Sánchez, Fernando Moreno-Navarro, Maria del Carmen Rubio-Gámez.*
  - **Reference:**
  - **Quality indicators:**
  - **DOI:** *Under review*
  - **Abstract:** *In recent years, railway sector has been directed towards more sustainable constructive techniques and more durable solutions such as the inclusion of bituminous sub-ballast in order to reduce track degradation while its quality is improved. However, the use of this material leads to diverse negative economic and environmental effects, which limits its wider application in railway tracks. Nonetheless, several alternative technologies have*

already been adopted in road engineering to reduce these negative issues by reducing manufacturing temperature (and then, decreasing emissions and energy consumption), including waste materials, recycling degraded road pavements, etc. In this context, this paper focuses on the study of the feasibility of using half-warm mix asphalt manufactured with a 100% of RAP (Reclaimed Asphalt Pavements) as sub-ballast in railway track. To this end, the work carried out compares the mechanical behaviour of sub-ballast with RAP and conventional bituminous sub-ballast. In particular, performances are examined according to the main requirements that need to be met by these materials for their use in railway tracks. Results show that half-warm mix asphalt with 100% RAP offers a good performance in comparison to conventional bituminous sub-ballast, and therefore it could be an interesting alternative to be used in railway construction.

Other dissemination of the results obtained has taken place through different international conferences, events, seminars, and workshops such as:

- THE THIRD INTERNATIONAL CONFERENCE ON RAILWAY TECHNOLOGY. CAGLIARI, ITALY 5-8 APRIL 2016: *A Study for the Viability of using Warm Mix Asphalt as Bituminous Sub-Ballast for Railway Track.*

- X JORNADAS INTERNACIONALES "INGENIERÍA PARA ALTA VELOCIDAD". CORDOBA, SPAIN 15-17 JUNE 2016: *Análisis de la respuesta mecánica de subbalasto bituminoso ante sus principales formas de fallo para su aplicación en vías de alta velocidad.*

- WORLD CONGRESS ON RAILWAY RESEARCH WCRR. MILAN, ITALY 29 MAY-2 JUNE 2016: *Study into the viability of using Warm Mix Asphalt as bituminous subballast in railway tracks.*

- X JORNADA NACIONAL DE ASEFMA. ZARAGOZA, 2015. *Caracterización avanzada de la respuesta mecánica de subbalasto bituminoso para su utilización en infraestructuras ferroviarias.*

- XI JORNADA NACIONAL DE ASEFMA. MADRID, 2015. *Desarrollo de sub-balasto bituminoso a partir de mezclas a baja temperatura para su utilización en infraestructuras ferroviarias*.

- 8TH INTERNATIONAL RILEM SYMPOSIUM. ANCONA 2015. *Optimization of bituminous subballast in railways infrastructures under sustainability criteria.*

- X INTERNATIONAL CONFERENCE ON THE BEARING CAPACITY OF ROADS, RAILWAYS AND AIRFIELDS. ATHENS 2017. *Effect of stiffness and bearing capacity of railway components on track behaviour: a laboratory approach for design optimization of railway tracks.*

- XII FORO PTEC INNOVACIÓN EN PROCESOS DE CONSTRUCCIÓN. SEVILLE 2016. *Optimization of bituminous subballast in railways infrastructures under sustainability criteria.*

- SUP&R ITN TRAINING WEEK - BITUMINOUS PRODUCTS FOR SUSTAINABLE ASPHALT TECHNOLOGIES. REPSOL, TECHNOLOGY CENTRE & UNIVERSITY OF HUELVA, PRO2TECS. MADRID – HUELVA 2016. *Optimization of bituminous subballast in railways infrastructures under sustainability criteria.*

- SUP&R ITN TRAINING WEEK - *“*FROM RESEARCH ON SUSTAINABLE PAVEMENT & RAILWAY TO ITS IMPLEMENTATION IN PRATICAL ENGINEERING PROJECTS”, UNIVERSIDAD DE GRANADA, 2016. *Optimization of bituminous subballast in railways infrastructures under sustainability criteria.*

INTRODUCTION

1. INTRODUCTION

1.1. PROBLEM STATEMENT

With the rapid growth and development of countries, it would be mistaken to think that resources are unlimited; the growth of excessive populations with long-term consequences for the environment are all factors arising from our development model that will generate negative effects for future generations.

In reality, resources are limited, the environment is able to absorb a certain amount of waste and eliminate them in a natural way from the environmental system, and the social and economic differences between the developed and developing countries are enormous. As a result, recent years have seen the proposal of a new social and economic development model: Sustainable Development.

However, what does it mean? Sustainability is a very broad concept, and is one that is undoubtedly easier to understand than to define. In any case, there are many definitions with similar principles. One of the most commonly quoted is that issued by the United Nations World Commission on Environment and Development, which states that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations World Commission on Environment and Development (Brundtland Commission) Report – Our Common Future, 1987).

Sustainability is based on the three major factors of economic, social, and environmental sustainability in equal harmony. This can be illustrated with a sustainability Venn diagram, as shown in Figure 1.

Figure 1 Venn diagram of sustainable development: at the confluence of three constituent parts. (RAE, 2005)

- Environmental sustainability: this is the ability to preserve over time the three functions of the environment: the role of the supplier of resources, the waste receptor function, and the direct source of utility. To live in a truly sustainable environment, we must ensure that natural resources are consumed in a sustainable manner. We must take into account that some resources are in abundance in comparison with others, considering the scarcity of material as well as the damage to the environment by extraction of the materials. Environmental sustainability should not be confused with full sustainability, which also needs to balance economic and social factors.

- Economic Sustainability: this requires that a business or country use its resources efficiently and responsibly so that it can operate in a sustainable manner to consistently produce an operational profit. Without an operational profit, a business cannot sustain its activities. Without acting responsibly and using its resources efficiently a company will not be able to sustain its activities in the long term.

- Social sustainability: this is the capacity of society to achieve a good level of social welfare. Achieving social sustainability ensures that social welfare can be maintained in the long term.

At the centre of these definitions lies the concept of sustainability and its applicability to three elements of life: economic or financial considerations, environmental protection and stewardship, and community and individual human welfare. This entails improving the quality of life, whilst trying to limit the impact on the environment.

In reality, however, our life style requires resources and ecosystem services that considerably exceed the rate of resource regeneration; the waste is produced at a speed higher than that which the environment is able to absorb, thus causing changes that are irreversible in some cases. Moreover, the social and economic differences are increasing between developed and undeveloped countries and environmental effects serve to widen this gap even further (Millennium Ecosystem Assessment, 2005). From this point of view, ideal solutions for any type of challenge will generate long-term benefits in all three sectors.

In this context, it is estimated that the construction sector is one of the activities that have the most influence on climate change, since it employs approximately half of the resources that man consumes from nature. It is believed that around 25 - 30% of waste material comes from construction and demolition (European commission), and more than 70% of worldwide energy moves around this sector (Oteiza & Tenorio, 2007; Alarcón, 2005).

However, in recent years, in the construction sector sustainability has become one of the major priorities in order to manage dwindling natural resources and at the same time develop new techniques that allow the reuse of waste material generated in the environment. In particular, these new techniques have already been adopted in road engineering through various methods such as pavement recycling, use of waste material in bituminous mixes, and low-temperature mixes that reduce emissions and energy consumption etc. (Silva et al., 2010; Kim et al., 2011).

Even the railway sector has directed attention towards a commitment to the future through the implementation of sustainable constructive techniques and the utilization of waste materials. The railroad sector could have a key role to play in the sustainability of our country, as it has the potential to reinvigorate our community, to support regeneration, and generate local employment. This sector has already taken steps to become greener, more efficient, and more sustainable. However, it has to do more if it is to fully realise its potential. From this point of view the purpose of this thesis is to develop new materials that are economically and environmentally more competitive and with an adequate mechanical behaviour, as an alternative to conventional materials.

1.2. THESIS OUTLINE

This thesis is divided into eight chapters and one annex. A summary of the remaining chapters is given below.

Chapter 2 focuses on the study of the state of the art in order to review the knowledge related to the railway infrastructure and its response to passing vehicles, as well as the main characteristics, functions, and experiences of the sub-ballast layer. The study was firstly conducted on the sub-ballast made of granular material and then on bituminous sub-ballast. With the aim of optimizing the bituminous layer under the sustainability criteria, this chapter includes a study of the state of knowledge on sustainable technologies already developed in road construction. A depth study was conducted in detail to examine, on the one hand the use of recycled materials, such as crumb soil from scrap tires and reclaimed asphalt pavement (RAP) from road pavement at the end of their service life, and on the other hand the use of technologies capable of reducing the manufacturing temperature such as warm mix asphalt, analysing the main characteristics and experiences in the road sector, and evaluating the feasibility of using them to manufacture sustainable asphalt to be used as sub-ballast in railways tracks.

Chapter 3 presents the main objective pursued in this research, established from the revision of the state of the art. Likewise, several specific objectives were formulated for the achievement of the general aim of this doctoral thesis.

Chapter 4 explains the methodology carried out, with the aim of manufacturing sustainable asphalts to be used as sub-ballast in railway tracks. Therefore, this chapter contains a description of the properties of the raw materials and the testing plan followed during the thesis, for the achievement of the current aims. The testing plan includes a conventional test used for the application of asphalt mixtures in highways, and specific tests for the sub-ballast layer.

Chapter 5 presents the results obtained in accord with the methodology presented in the previous chapter, as well as the discussion of the results with the aim of evaluating the response of several types of sub-ballast under different failure modes that can take place during the real service life of these materials in railway tracks.

Based on the results derived from the study of different types of sub-ballast layer, *Chapter 6* lists the main conclusion extracted during the present study, in line with the objectives set.

Chapter 7 proposes a series of potential future research lines that could be conducted in order to improve the development of the sustainable bituminous sub-ballast.

Finally, *Chapter 8* includes the bibliographic list of the studies cited during the progress of this thesis.

Annex A. According to the regulation quoted above, the last part of the thesis collects published papers that make up this doctoral thesis.

STATE OF THE ART

2. STATE OF THE ART

2.1. RAIL TRACK STRUCTURES

The rail network is one of the most important transportation systems in everyday life. It is designed to provide a safe, efficient, and durable transit route for cargo and passengers. In recent years, the continual competition with road, air, and water transport in terms of speed, carrying capacity and cost has substantially increased the frequency and axle load of the trains with a faster running time. In this context, high quality railway services are needed to withstand the increasing number of passengers and goods as well as to relieve the already congested roads.

There are two types of railroad tracks in use today: slab tracks (also called ballastless), and ballasted tracks. This research will focus on the ballasted track structure.

In the slab track, the ballast layer is replaced by a concrete or asphalt surface which supports the rails above that can be directly attached to concrete sleepers or into a cast embedment of rubber or cork. This structure is made essentially of slabs of precast or cast-in-place concrete with a stiff and brittle behaviour, hence the required elasticity can be obtained by inserting elastic components below the rail or/and below the sleeper (Lichtberger, 2005).

The major advantages of slab track are: low maintenance, high availability, low structural weight and height, and its high resistance against lateral loading.

Furthermore, maintenance costs are relatively low if the structure has sufficient strength and resilience to prevent cracking of the concrete (Esveld, 2001). For this reason, these tracks are more suitable for high-speed transit and high intensity rail lines where shut-down for maintenance would considerably impact the users. In addition, recent life cycle studies have shown that from the cost point of view, slab track might be very competitive.

The slabs tracks are divided into two main categories: discrete rail support systems and continuous rail support systems. These two are further divided into four and two subcategories respectively (Table 1).

SLAB TRACK SYSTEMS					
DISCRETE RAIL SUPPORT				CONTINUOUS RAIL SUPPORT	
With sleepers or blocks encased in concrete	Sleepers on top pf asphalt-concrete roadbed	Prefabricated concrete slabs	Monolithic design	Embedded rail structure (ERS)	Clamped and continuously supported rail

Table 1. Different slab track systems (Bastin, 2005; Esveld, 2001; Miodrag).

Railway ballasted track may be briefly described as an assembly of elements of distinct elasticity which serves to guide trains in their path and to gradually transmit the dynamic loading of the wheels to a flexible subsoil. The chief components of ballasted track structures can be grouped into two main categories: track superstructure and track substructure (Figure 2), both of which are mutually important in ensuring the safety and comfort of passengers and quality of the ride.

The superstructure receives the load stress from the rolling stock and transmits it to the substructure, and includes the rails, fastening system, sleepers, ballast, and thus increasingly common elastic elements such as rail pad. The substructure supports the components of the superstructure and it must be capable of supporting the track structure above it and remaining stable under traffic loads. The substructure is associated with a geotechnical system made up of supporting layers such as sub-ballast, as well as form-layer and subsoil.

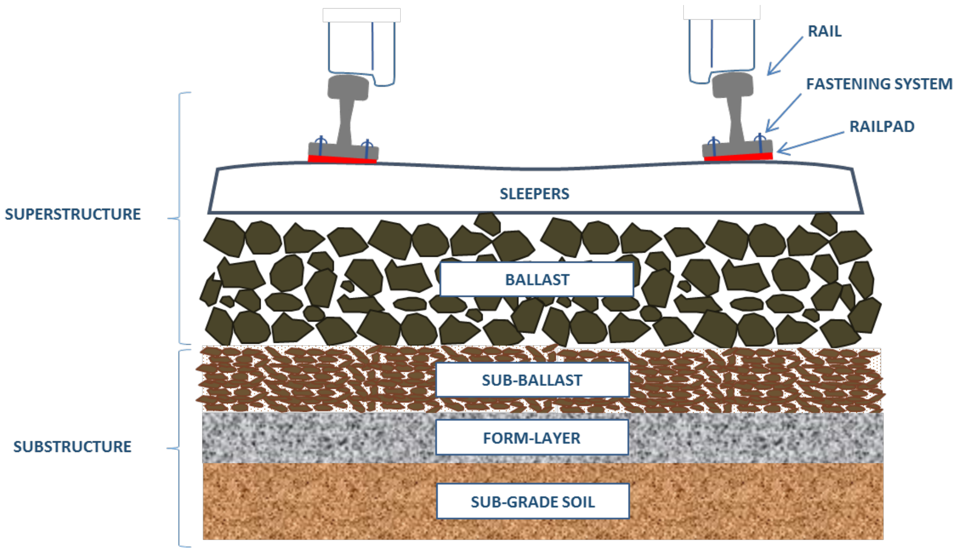

Figure 2. Ballasted track section.

Rails are longitudinal steel members that are placed on spaced sleepers and are in contact with the train wheels. One of their primary functions is to accommodate and transfer the wheel/axle loads to the sleepers, and their strength and stiffness must also be sufficient to maintain a steady shape and smooth track configuration (Selig and Waters, 1994). The rails UIC54 and UIC60 are the most used type in Europe, (the number indicates the weight per longitudinal meter). However, high speed lines adopt the heaviest rail (UIC60 which weighs 60 kg/m), due to the need to increase the inertia, thereby increasing its resistance to bending, to be able to withstand greater stresses without compromising the geometric quality of the track (Ruano Gomez, 2007; Dahlberg, 2010).

Railway sleepers are an important element of railway track structures. Their main functions are to provide supporting and fixing for the rail foot and fastenings, to transfer wheel loads from the rails to the underlying ballast foundation, and to be resistant to mechanical influences and weathering over a long period of time. Currently the most commonly used sleepers in modern European tracks are the concrete sleepers, which are very heavy (200-400 kg), have a long service life, great freedom of design, and are relatively simple to manufacture. They can be categorised into two groups: twin-block sleeper, which consists of two blocks of reinforced concrete connected by a coupling rod or pipe, which are well-defined bearing surfaces and also show high lateral resistance in the ballast bed; and the mono-block sleeper, which is cheaper, heavier and exhibits low susceptibility to cracking (Esveld, 2001).

Fastenings are all the materials whose function is to structurally connect the rail to the sleeper. The fastenings used in concrete sleepers must be resilient, presenting elasticity in both tension and compression, upwards and downwards. They clamp the rail gauge and absorb forces from the rails and transfer them to the sleepers. Fasteners are typically classified into two categories: rigid and elastic (Esveld, 2001; Smutny, 2004). Rigid fasteners that rigidly bolt the rail to the tie were superseded by elastic fasteners, which allow more resilience relative to rigid fasteners. There are many different types and techniques of fastening systems from manufacturers such as: Vossloh (primarily used in Germany and Spain), Nabla (developed and applied in the French railway network, including high-speed lines) and Pandrol (used, for example, in the new high speed LGV-East: Paris-Strasbourg).

The fastening system also includes rail pads, which are placed on the rail seat to filter and transfer the dynamic forces from rails and fasteners to the sleepers. The use of this component improves load distribution, which means a smoother ride and better conservation of the superstructure. Furthermore, rail pads provide electrical insulation (between track rails) and damp the vibrations that the rail transmits to the sleepers. This prevents the concrete from cracking and reduces ballast wear.

The railway ballast layer is a significant part of the railway track system, placed between the substructure and sleepers. The layer is formed by crushed granular material that should be resistant and hard, resistant to weather conditions, to water absorption and to crushing by passing trains whilst being sufficiently elastic with diameters varying between 22,4 to 60,0 mm. It not only provides support but also resists vertical, lateral, and longitudinal forces applied to the sleepers and provides a means of transferring these forces to the substructure. Moreover, the ballast greatly contributes towards the absorption of track vibrations, attenuating an important part of vibrations induced by running trains. To achieve the aforementioned functions, the layer should have an adequate thickness, which is in general between 30 and 35 cm for high-speed lines.

In recent decades, the development of high-speed railway and the increases in train speed as well as the load transported by modern trains produces an increase in the dynamic forces that are transmitted to the track (Lopez Pita, 2006). Because of this, it was necessary to add a much stiffer granular layer under the ballast in order to increase the bearing capacity of high-speed tracks and lengthen the service life of the track, reducing its maintenance costs (Figure 3).

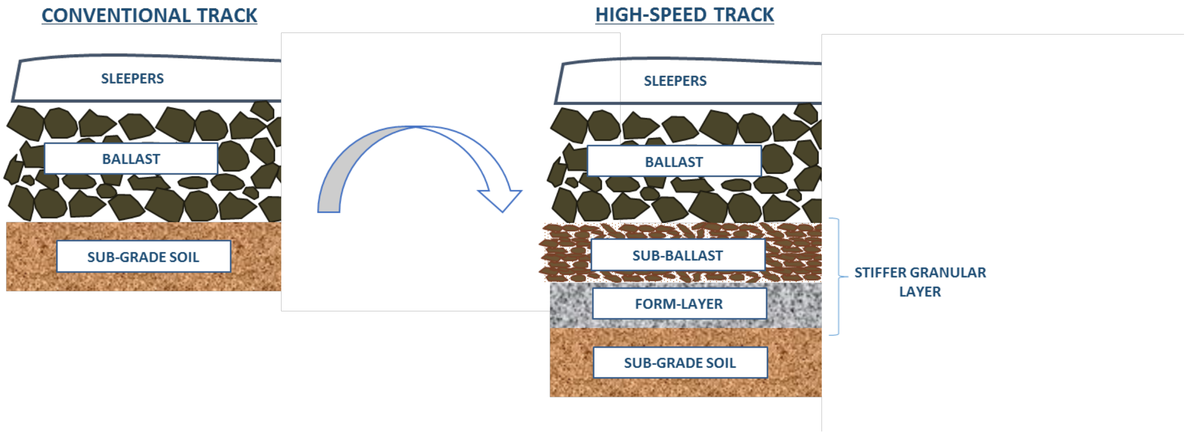

Figure 3. Standard configurations of the layers in conventional and high-speed track (Adapted from Lopez Pita, 2006).

The sub-ballast layer is commonly placed as the top layer of the substructure and consists of gravel and/or well-graded sand, which is a material suitable for carrying out their functions within the track. This is employed in the majority of European high-speed lines with the aim of distributing and reducing the cyclic loads transmitted to the underlying subgrade layer to an acceptable level of stress, and among others, to protect the subgrade from climatic effects (Selig and Waters, 1994; Teixeira et al., 2006). Thus, bearing capacity and impermeability are the principal functions of the sub-ballast layer that must be ensured to lengthen the service life of the infrastructure and reduce its maintenance costs.

The form-layer is placed between the sub-ballast layer and the sub-grade and its function is to help support the weight of tracks and trains without the occurrence of any subsidence.

The sub-grade includes the existing soil and rock, which possess slopes, verges, ditches and other structures or materials within. The subgrade is the last support, which bears and distributes the resultant dynamic loading downward along its infinite depth. This deep layer must have sufficient bearing capacity, provide good drainage, and yield a tolerably smooth settlement in order to prolong track serviceability.

2.1.1. TRACK FORCES

For the study of the behaviour of the various components of the railway infrastructure, it is important to know the transmission of loads from train loading to sub-grade soil. This is accomplished through stress degradation among the different components, which have different materials and geometry. The main forces generated by train vehicles, which must be supported by railway tracks, can be distinguished by forces in the vertical, lateral, and longitudinal directions, as displayed in Figure 4.

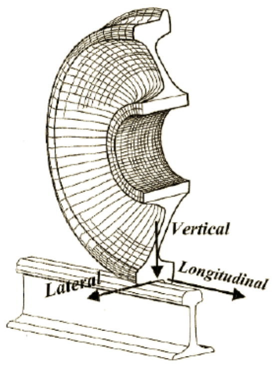

Figure 4. Three main directions of loads acting on track (Selig and Waters, 1994).

The *vertical force* can be subdivided into the downward and upward force. In reaction to the downward force, the upward force is induced by the rail as shown in Figure 5 (Selig and Waters, 1994). The downward force is a combination of a static load and a dynamic component. The static component is the weight of the train, which, in Europe, the part of the static axle load related to the train gravity load is limited to 225 KN. Axle loads normally take values below 150 KN for passenger coaches and between 200 KN to 225 KN for freight wagons and locomotives, including modern locomotives that are able to circulate at speeds up to 200 km/h. However, when circulating at speeds over 250 km/h, the maximum axle loads must be significantly reduced to nearly 170 kN/axle in order to contain track damage. The dynamic component is a function of track conditions, train characteristics, operating conditions, train speed, and environmental conditions. It is the dynamic component that usually causes an adverse effect to the track, as it can be much larger than the static load. According to Selig and Waters (1994), the magnitude of the dynamic component can be up to 2.4 times the static load.

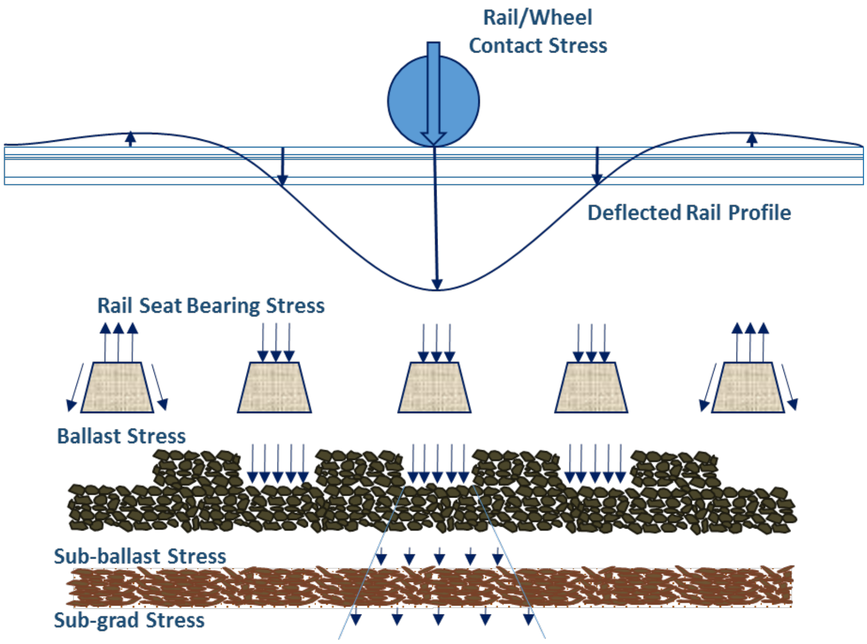

Figure 5. Wheel load distribution into the track structure (Adapted from Selig and Waters, 1994).

Lateral forces act upon the track structure and are introduced by the curving of the freight equipment, the development of lateral instabilities, or the response of the vehicle to lateral track irregularities. During curving, lateral forces can arise due to creep or flanging of the wheel set, generally on the high rail of the curve. Lateral instabilities, most particularly truck hunting, are a function of the vehicle characteristics and speed. Finally, track irregularities can cause lateral loading. The amount of lateral force generated depends on the amplitude and shape of the defect, the speed of the vehicle, and the track and vehicle characteristics

Previous studies have shown that the lateral forces induced within a track are primarily controlled by the track curvature, with mild curves < 10° causing lateral forces 30% – 60% larger in comparison with straight sections (ORE, 1978). If these lateral force values exceed the inherent lateral resistance of the tracks, derailments and track instability can arise. The underlying ballast layer provides the lateral frictional resistance for the train when under any of the previously mentioned loadings (Di Pilato et al., 1983). Thus, good ballast conditions are important to adequately resist and handle any lateral forces induced by the train.

The *longitudinal forces* act in parallel to the long axis of the rail and are caused by four different effects. The first longitudinal force is generated through temperature effects from thermal expansion and the frictional heat of the train wheel contacting the steel rail. The second is from the acceleration and braking of the train along with its cars. The third type of longitudinal force is formed when the rails shrink after continuous welded rail (CWR) installation. The fourth and last form of longitudinal stress is due to track creep of the underlying ballast layer and embankment, compacting and creeping the ballast layer forward from the force (Ionescu, 2004).

Overall, longitudinal forces within the track system create a third axis of ballast loading, creating the possibility of ballast loading in all 3 axes (vertical, lateral, and longitudinal). With three separate loading axes, the ballast-loading environment forms a complex system of interaction. This system of several variable forces on all axes creates a highly dynamic loaded environment that favours abrasion and breakdown of the ballast in all directions (Selig and Waters, 1994).

2.1.2. TRACK GEOMETRIC QUALITY

The European standard EN 13848-1, established five main parameters to evaluate the quality of the track geometry, which are related to vertical and horizontal geometry following a spatial Cartesian coordinate system where the X-axis is parallel to the rolling direction, the Y-axis is horizontally perpendicular to the rails, and the Z-axis is vertically perpendicular to the track grid, (Figure 6).

Figure 6. Adopted spatial Cartesian coordinate system.

The different parameters include track gauge, longitudinal level, horizontal alignment, cross level and twist and are described below (European Committee for Standardization, 2008; International Union of Railways, 2005)

- *Track gauge (G)* is defined as the smallest distance between lines perpendicular to the running surface intersecting each railhead at point P in a range from 0 to z_p, below the running surface, on the Y direction (Figure 7).

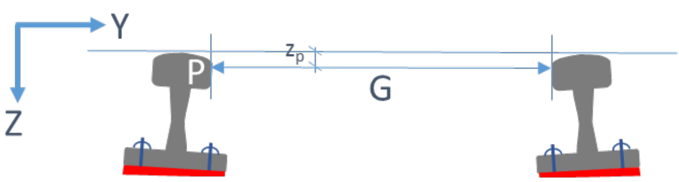

Figure 7. Track gauge (Adapted from EN 13848-1).

The standard nominal track in the majority of European countries is 1435 mm. Nominal track gauges smaller than 1435 mm are called narrow gauge (e.g. 1067 mm in Japan, South Africa and Queensland) and those wider than 1435 mm are called broad gauge (e.g. 1524 mm in Finland and former Soviet Union as well as 1688 mm in Spain and Portugal).

- *Longitudinal level (LL)* is measured for both rails and is defined as vertical deviation of the rail axis (Z-axis) from its theoretical reference line, in millimetres (Figure 8).

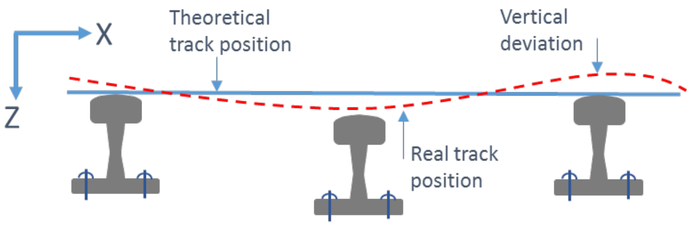

Figure 8. Longitudinal Level (Adapted from Profillidis, 2000).

Longitudinal level defects are considered to be the main factor for maintenance planning purposes, through the analysis of the standard deviation for short wavelength defects (3–25 m) in 200 metre-long track sections and absolute values of local defects.

- *Horizontal alignment* is the lateral deviation of the rail axis with respect to its reference mean location, measured in millimetres (Figure 9). It depends on the transverse effects of the rolling stock upon the track structure.

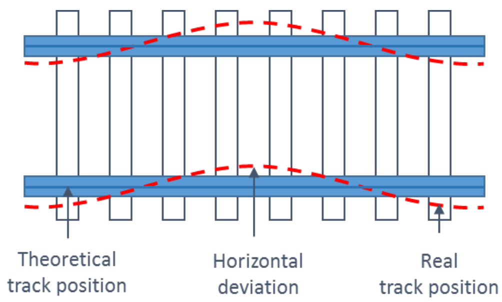

Figure 9. Horizontal alignment (Adapted from Profillidis, 2000).

- *Cross level* is the difference in millimetres between the actual running surface and its horizontal reference plan, or theoretical cant. On straight lines, it may be interpreted as the difference in elevation between both rails (Figure 10).

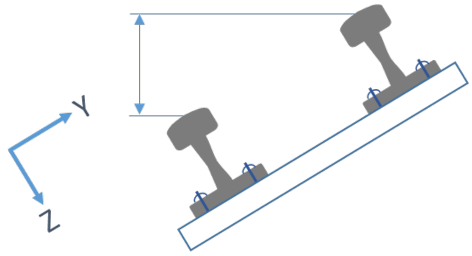

Figure 10. Cross level (EN 13848-1).

- *Track twist* is the deviation between one point of one cross section and the plan defined by the other three points, considering two cross-sections several metres apart (Figure 11). Hence it is directly related to the track cross level. This factor is the most important when considering railway safety as it is considered the primary reason for derailments due to the possibility of causing absence of wheel-rail contact. It is usually measured by millimetres per meter.

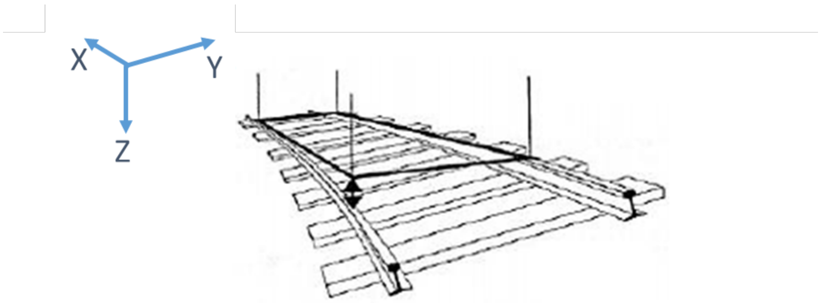

Figure 11. Track twist (Teixeira, 2014).

Track geometry quality decreases as the rolling stock transmits static and dynamic loads into the track structure through wheel-rail contact. Dynamic loads are responsible for increasing geometry deterioration and may cause permanent damage to the track components, leading to the need for its renewal (Jovanovic, 2006; Rhayma et al., 2013; Selig & Waters, 1994). The European standard EN 13848-5:2008 specifies limits for each geometry defects previously defined, expressed in term of quality levels according to those described in Table 2.

AL	If limit value is exceeded at this level, an action that corrects the error has to be done during the next scheduled maintenance
IL	If a limit value is exceeded at this level, an action that corrects the error has to be done before the next inspection
IAL	If a limit is exceeded at this level, an action that lowers the risk of derailment has to be done immediately

Table 2. EN 13848-5 track quality levels.

The same European standard has also regulated the minimum requirements for track quality and specified thresholds for acceptable quality levels of track geometry (European Committee for Standardization, 2008).

- *QN1.* It is the acceptance level above which 50% of the track sections have to be. It means that the condition of these track sections has to be under surveillance or under regularly planned maintenance operations. It can be related to the AL.

- *QN2.* It is the acceptance level above which track sections that are under the values defined for QN1 must be subjected to short-term maintenance action. A minimum of 40% of the total track extension has to be between QN1 and QN2. It can be related to the IL.

- *QN3.* It is the level above which the regular track speed has to be restricted for safety reasons until maintenance action, as the track geometric quality is under usual quality standards. Only 10% of the track sections may be between QN2 and QN3 levels. This is in conditions of immediate action limit (IAL), and if exceeded, immediate measures must be taken to reduce safety risks, by reducing speed, or even by closing the line for immediate correction of track geometry.

2.1.3. TRACK GEOMETRY DETERIORATION

It is recognised that track irregularities are largely caused by uneven track settlement, and uneven track settlement is largely influenced by the bending stiffness of the rail, ballast layer, and subgrade deformation and initial track misalignment. As will be discussed later, vertical track stiffness interacts with the mass, velocity, spring and damping characteristics of the train (Esveld, 2001) which increase the dynamic forces on the wheel-rail interface and downwards to the sleepers and ballast, affecting the condition of the track's components (Berggren, 2009).

The cyclic train loads subject the particles of the ballast layer to considerable stress, crushing them and leading to the decrease of the shear strength of the layer; thus the deterioration process of railway is natural, inevitable, and irreversible (Horvát et al., 2013; Indraratna et al., 2005). Maintenance operations are therefore essential to extend the life cycle of the track itself. Analysing Figure 12, which represents the hypothetical temporal evolution of the decrease in track geometry quality, it can be concluded that there are three main phases in the degradation process (Jovanovic, 2006; Lyngby et al., 2008).

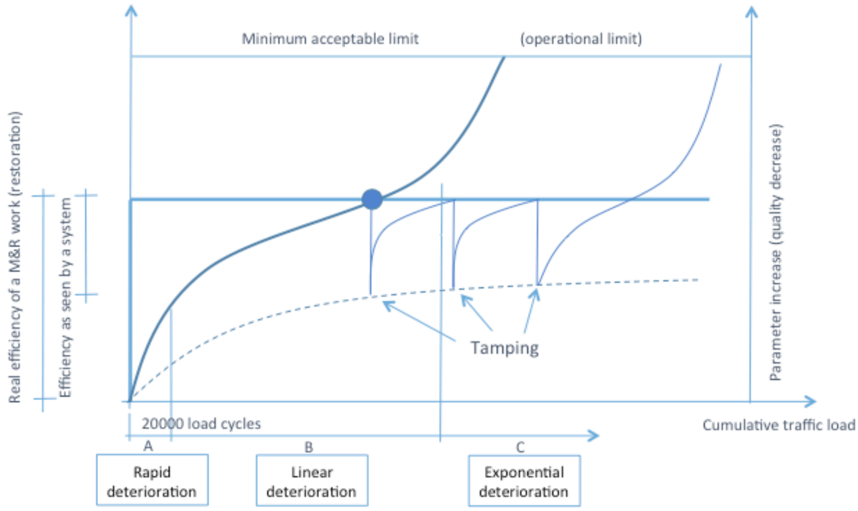

Figure 12. Schematic representation of track geometry deterioration (Adapted from Guler et al., 2011).

- Phase A: This stage is characterised by a fast and considerable deterioration caused by unpredictable settlements of the track during the application of around the first 20000 load cycles (Ionescu et al., 1998; Jeffs and Marich, 1987). This happens immediately after the completion of a track section. Nevertheless, independent of the type of ballast and axle load, the settlement rate stabilizes within around 100000 load cycles (Indraratna et al., 2011; Ionescu, 2004; Jeffs and Marich, 1987).

- Phase B: This stage occurs during the majority of the lifetime of the track and it is characterised by a linear deterioration pattern.

- Phase C: This is a late phase of the track where the deterioration speed increases due to the bad condition of the track's components. Hence maintenance operations such as tamping are required to improve track quality from time to time, delaying the start of the rapid degradation phase. Ultimately, complete renewal of the section is needed in order to restart the cycle and avoid non-safety of traffic.

After a tamping operation, track geometry quality often increases and the deterioration process starts again. However, as time goes by, the efficiency of tamping reduces and material fatigue may increase the deterioration rate leading to shorter maintenance intervals until it reaches the late phase of the track's life cycle where renewal of some of the components is needed (Guler et al., 2011). The available experiences regarding traditional ballasted structure has shown the relationship of mean track settlement with loss of track geometric quality and, thus, track maintenance needs. On tracks with good-quality subgrades (as in the case of high-speed lines), ballast settlements generally represent around 50 to 70% of total track settlement (Selig and Waters, 1994), as shown in Figure 13.

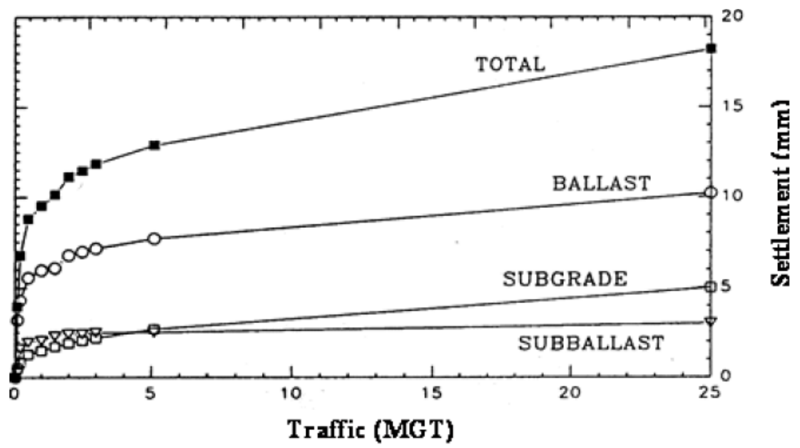

Figure 13. Contributions of different layers to mean track settlement (Selig and Waters, 1994).

The maintenance activity of the granular layer are measures that try to correct the defects caused by the deterioration of the ballast. Thus, there is the need for other preventive solutions that try to increase the durability of the track, reducing the number of maintenance activities. In this context, there are many solutions such as the use of Geogrid to reduce the settlement of the ballast layer (Thom, 2006; Brown, 2007), or the incorporation of elastic elements such as rail pads, under sleeper pads, and under ballast mats to reduce the dynamic overloading.

Another solution could be the use of bituminous sub-ballast for keeping the railroad geometry unaltered thanks to its high stiffness. In this case, the settlement can be considered null, allowing for reductions in the overall mean settlement of the track. Increase in granular sub-ballast height leads to an increase in settlement. Equation 1 quantitatively represents this situation:

$$Strack = Sb + Ssb + Sf \qquad (1)$$

Where

$Strack =$ total settlement of the track (in millimetres);

$Sb =$ settlement of the ballast layer (in millimetres);

$Ssb =$ settlement of the subballast layer (in millimetres);

$Ss =$ settlement of the track formation (in millimetres);

And,

$$Sb = 0.026 \times hb \times T^{0.21} \qquad (2)$$

$$Ssb = 0.017 \times hsb \times T^{0.16} \qquad (3)$$

$$Sf = 1.4 \times T^{0.25} \qquad (4)$$

Where

$hb =$ thickness of the ballast layer (in millimeters);

$hsb =$ thickness of the subballast layer (in millimeters);

$T =$ cumulative traffic (in millions of gross tons);

From Equations 1 and 3, it can be deduced that increases in sub-ballast thickness will increase the settlement. This reasoning is applicable mainly to the initial life period of the track (after this period, on a good-quality track, settlement will be concentrated in the upper part of the ballast). However, track settlement verified on this initial life period (and the corresponding defects corrected by tamping) will continue to have a residual effect on the track geometric deterioration process throughout the track life cycle. From this perspective, it can be inferred that increasing ballast support-bearing capacity by means of stiffer layers without deformities (e.g., bituminous sub-ballast) will result in reduced levels of track settlement.

2.1.4. VERTICAL TRACK STIFFNESS

Winkler (1867) was the first researcher to make a breakthrough on the study of the mechanical behaviour of the railway track. The vertical resistance of the supporting foundation was characterised by a proportionality between pressure and track settlement. This relationship was represented by the ballast coefficient or bed modulus beam. The ballast coefficient (C) was defined as the pressure per unit of length producing unit deflection in the ballast (N/mm3). Talbot (1918) adopted a different approach in comparison with Winkler regarding the behaviour of the track by defining the track modulus (u) for characterising the track support by unit of length of the rail (N/mm2). There was also another approach for the definition of the effect of the vertical support provided by the track structure, which was based on the resulting displacement of the ballast layer due to the load transmitted by the sleeper. The stiffness coefficient (keq) represents the vertical resistance provided by each sleeper (Teixeira, 2003) and it is defined as a “spring coefficient” that embodies the contribution of each layer to the total track stiffness coefficient (kN/mm).
The approach of static vertical stiffness can be considered as a step towards better modelling of the track. Static vertical track stiffness (k → kN/mm), Figure 14 may be defined as the ratio between the concentrated loads applied on the rail (Q → kN) and the maximum deflection of the track structure (z → mm), Equation 5.

$$K = \frac{Q}{Z} \qquad (5)$$

The static vertical stiffness is the easiest parameter to obtain as it only requires the measurement of the maximum deflection due to a wheel load at a given point (Teixeira, 2003).

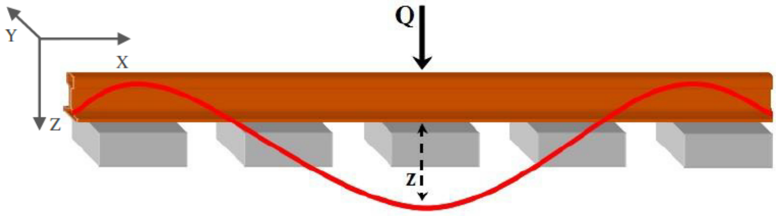

Figure 14. Vertical track stiffness (Adapted from Teixeira 2003).

In any case, when a train starts to move, the load changes immediately from static to dynamic (Berggren et al., 2002). The response given by the track structure to the dynamic vertical movements created by the rolling stock on the rail is the dynamic vertical stiffness and it varies as a function of time (t → s), Equation 6:

$$K(t) = \frac{Q(t)}{Z(t)} \qquad (6)$$

For the purposes of studying dynamic vertical stiffness in the frequency domain (f → Hz), it is preferable to use its inverse, the dynamic vertical flexibility, also known as track receptance (α → m/kN), Equation 7:

$$\alpha(f) = \frac{Z(f)}{Q(f)} \qquad (7)$$

However, the track stiffness and its effect on track performance are difficult parameters to understand because rail deflection is influenced by the combined stiffness of all components of the track. The problem is that those components present a non-linearity stiffness and this fact leads to a non-linear behaviour of the track. The non-linear behaviour can also be explained by the ballast tightening when submitted to load stresses, which increases the contact area between the stones leading to higher stiffness of the layer (Hosseingholian et al., 2009). Thus, the secant stiffness (kxy) may be used to eliminate the effect of the gap between the sleepers and the ballast layer (Equation 8).

$$Kxy = \frac{\Delta Q}{\Delta Z} = \frac{Qy - Qx}{Zy - Zx} \qquad (8)$$

Where:

- Qy and Qx the maximum and the low applied load (KN)

- Zy and Zx initial and final deflection under the load.

2.2. GRANULAR SUB-BALLAST

As mentioned previously, the development of high speed railway and the increase in the loading capacity of trains have led to the need for enhancing the track substructure by adding stiffer granular layers, such as sub-ballast between the subgrade and the ballast.

The materials most commonly available for use as sub-ballast are those aggregates ordinarily specified and used in construction for highway bases and subbases. These include crushed stone, natural or crushed gravels, natural or manufactured sands, crushed slag or a homogeneous mixture of these materials.

Typically, this is a locally available aggregate material that has a smaller top size than ballast and contains considerably more fine-sized particles, graded as to prevent penetration into the subgrade and penetration of track ballast particle into the sub-ballast zone. In addition, it must be compacted to a very low void content with very low permeability (at least 98% of PROCTOR density under laboratory conditions).

It fulfils two functions, which can be broadly grouped as the stress distribution function and hydraulic function. These are broken down into specific purposes such as:

- *Reducing the traffic induced stress at the bottom of the ballast layer to a tolerable level for the top of subgrade* by acting as a structural material layer, performing in a similar way to ballast. As a structural layer, granular material must have a high resilient modulus and must not deform significantly over many load cycles. Figure 15 shows the importance of sub-ballast layer. The thicker the sub-ballast, the larger the area that can be used to withhold the force because the stress is distributed horizontally with depth.

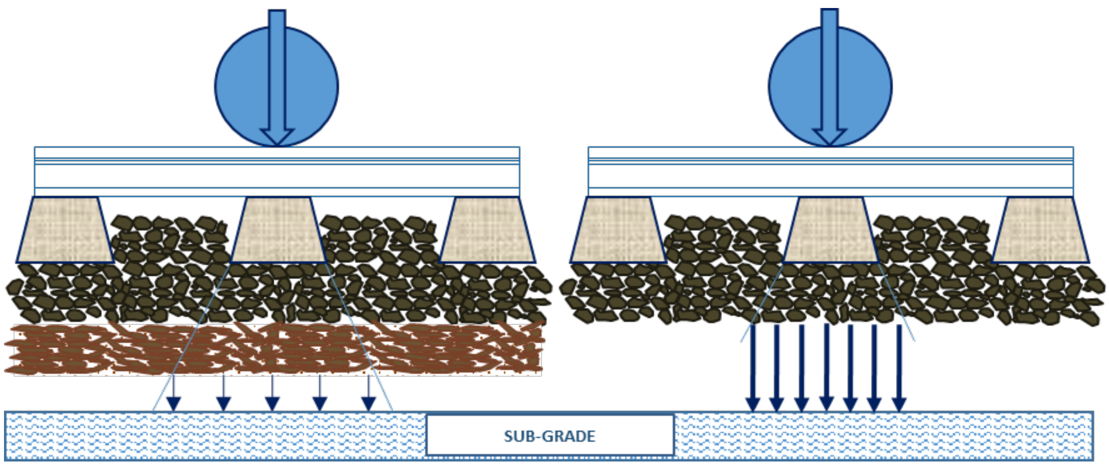

Figure 15. Sub-ballast as a stress reducer (Adapted from Selig and Waters, 1994).

The minimum bearing capacities within a range of 80 to 120 MPa under the ballast layer is usually required (Selig and Waters, 1994).

- *Extending the subgrade frost protection.* Great care must be taken in areas where the soil temperature can fall below freezing to avoid problems associated with the soil freezing. When soil freezes, the pore water is converted to ice, which consequently increases the resilient modulus and decreases the rate of plastic strain accumulation. If soil is not completely saturated, then the expansion of water upon freezing can be accommodated by compressing the air voids, with the result that little soil volume change occurs. If no water migration occurs during the freezing process, then when the soil thaws the moisture content returns to its value prior to freezing, and the unfrozen soil properties will not have been altered significantly by the freeze-thaw cycle.

  When the pore water freezes a deficiency of absorbed water is created around fine-grained soil particles, causing water to flow towards the freezing ice. If the relationship between the rate of freezing and the rate of water movement is in a certain balance, then the ice crystals at the freezing front will grow into lenses of ice, pushing the soil particles apart. This can result in local soil volume change of more than 10% when water turns to ice. This process, called frost heave, can cause significant vertical differential displacement of pavement or track. Then, when the ice melts, an excess of water remains which causes softening and loss of soil strength, all of which is depicted in Figure 16. During this period of thaw softening, severe plastic deformation can occur, resulting in rapid loss of track geometry and accelerated damage to track components (Selig and Waters, 1994).

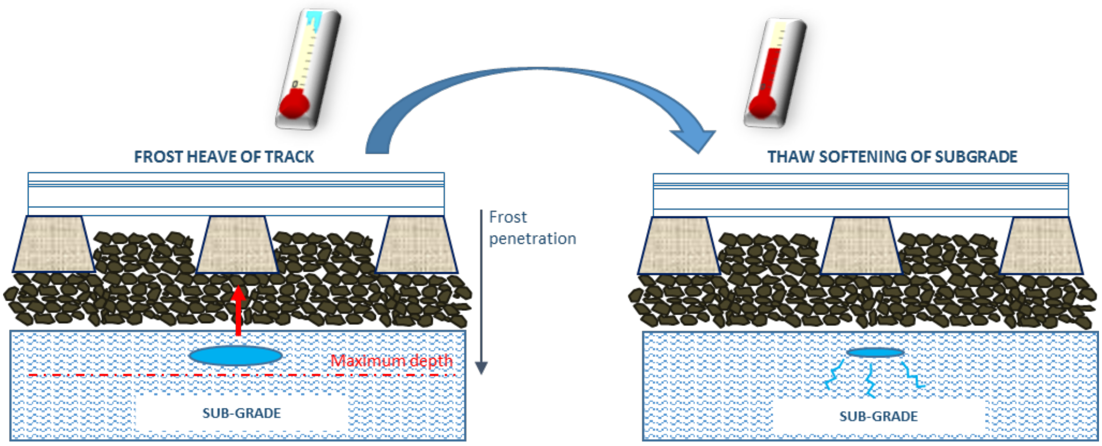

Figure 16. Freezing conditions without an insulating (Adapted from Selig and Waters, 1994).

Good drainage helps to limit the source of water. Insulation of the frost-susceptible soil by a sufficiently thick covering layer of non-frost susceptible soil will prevent freezing temperature. The combined thickness of the ballast and the sub-ballast will serve as insulation for the subgrade. The sub-ballast must not be susceptible to frost; it must, however, be protected by an insulating layer of ballast. Predicting the frost susceptibility of soil is difficult because of the complex thermodynamics and seepage processes involved. General experience shows that soils containing a high percentage of silt particles are the most susceptible and clays are the second most susceptible to frost. Sands and gravels are not frost susceptible; thus when the frost level reaches the sub-ballast, a good rule of thumb is that the sub-ballast must have less than 5% silt and clay size particles (Figure 17).

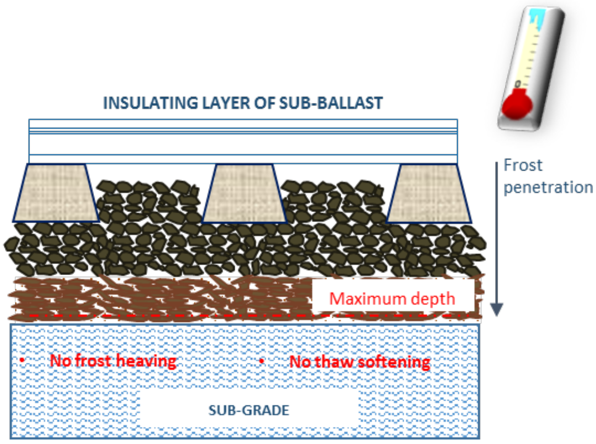

Figure 17. Freezing condition with a sub-ballast insulator (Adapted from Selig and Waters, 1994).

- *Separation function.* This Intermixing results from progressive penetration of the coarse ballast particles into the finer subgrade accompanied by the upward displacement of the subgrade particles into the ballast voids. This process can occur at any subgrade moisture condition; however, it is accentuated by wet conditions. Upward migration of subgrade particles develops from at least three sources:
    - subgrade seepage carrying soil particles;
    - hydraulic pumping of slurry from subgrade attrition;
    - pumping of slurry through opening and closing of subgrade cracks and fissures.

  Prevention of intermixing and migration is achieved by using a proper sub-ballast gradation. The smaller particles of the sub-ballast lower the hydraulic conductivity reducing subgrade infiltration (Selig and Waters, 1994).

- *Shedding water*. The sub-ballast must shed water entering from the surface. The large voids in the ballast make it highly permeable, much more so than the sub-ballast. It then serves as an underlying lower permeability boundary of the ballast to direct the water away from the subgrade (Figure 18).

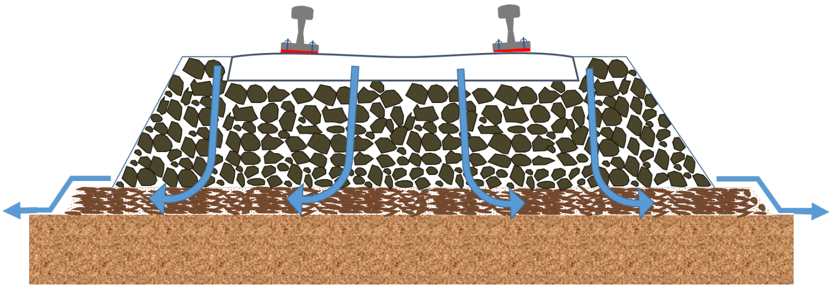

Figure 18. Sub-ballast shedding water from the surface (Adapted from Selig and Waters, 1994).

- *Permits* drainage of water that might be flowing upward from the subgrade, includes draining water weeping up from the subgrade, including that produced by excess pore pressure generated from cyclic stress. Thus, the sub-ballast cannot be impermeable, but rather should have permeability greater than that of the subgrade. The exceptions are when the subgrade is relatively permeable, such as natural sand or sand-gravel layer, or when no upward seepage is expected such as on an embankment (Figure 19).

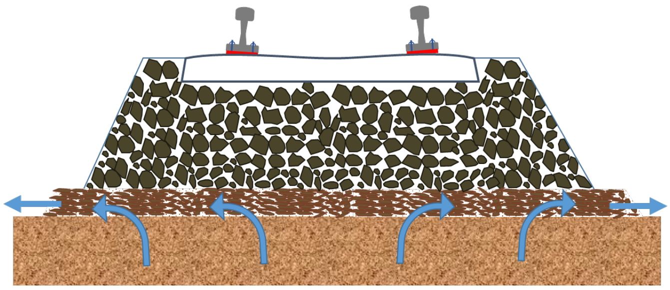

Figure 19. Sub-ballast shedding water from subgrade (Adapted from Selig and Waters, 1994).

Hence, the main functions of the sub-ballast layer can be summarized as *permeability* and *bearing capacity*.

2.2.1. PERMEABILITY

Drainage plays a significant role in the stability and safety of a track substructure. There are three basic sources of the water that enters this substructure (Figure 20). Because the ballast surface is open, precipitation (rain and snow) falling onto the track will enter the ballast rather than run off the surface, as will occur for intact road pavements. Water flowing down adjacent slopes will also enter the ballast underlying layers unless diverted. Finally, in regions with a high groundwater table, water can seep upward from the subsurface and enter the substructure zone. Adequate drainage for these sources of water is of the utmost importance in order to prevent or minimise substructure problems related to excess water (Selig and Waters, 1994).

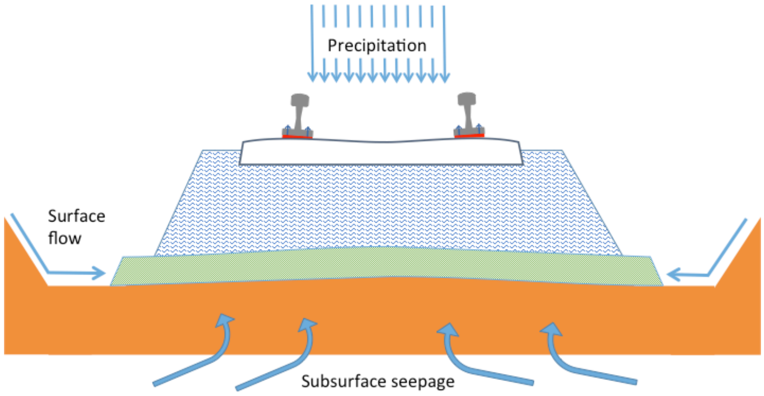

Figure 20. Sources of water into track substructure (Selig and Waters, 1994).

Although at least portions of the ballast sometimes can be dry, generally ballast — and always sub-ballast and sub-grade — contain a certain amount of moisture. In fact, sub-ballast and sub-grade perform best under repeated load when they are in a state that is intermediate to dry and saturated. Excess substructure water, particularly when it creates a saturated state, causes significant increases in track maintenance costs because of problems such as the following:

- *Pore pressure increase under cycling load, which causes increases in plastic strain accumulation, decrease in stiffness, and decrease in strength.*

- *Loss of strength from water content increase.*

  Subgrade deformation. Figure 21 shows how soft subgrade deforming under repeated train loading traps water because the clay subgrade is not permeable. This depression becomes filled with sub-ballast and ballast forming a "ballast pocket". This is also sometimes called a "bathtub effect

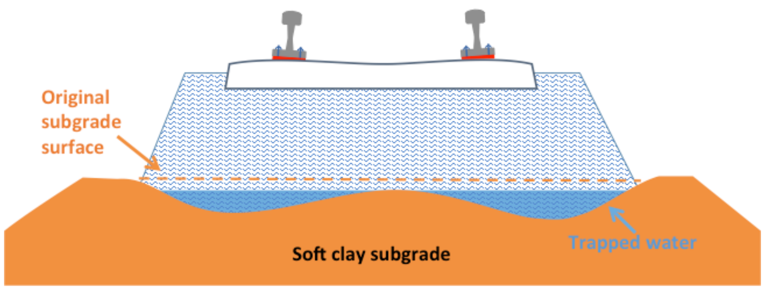

Figure 21. Ballast pockets formed from deformation of the subgrade can inhibit drainage (Selig and Waters, 1994).

- *Hydraulic pumping of fine material* (Figure 22).

Figure 22. Fouled ballast due to subgrade attrition and pumping of fine material.

- *Volume changes from swelling*. This is followed by shrinking in periods of dry weather when the water is removed from the soil by evaporation. Since the volume changes upon swelling and shrinking are uneven, they usually result in substantial deterioration of track geometry. Finally, water trapped in the track is a source of frost heave when the ground freezes in winter.

- *Frost heave/thaw softening.*

- *Ballast degradation from slurry abrasion, chemical action, and freezing of water.* Figure 23 shows ballast filled with slurry, which is often called “mud”

Figure 23. Slurry (mud) filled ballast.

➢ *Sleeper attrition from slurry abrasion.* Figure 24 shows the aggressive effect of pumping slurry, which in this case has worn away a considerable part of the bottom of the concrete sleepers.

Figure 24. Slurry abraded concrete ties.

2.2.2. BEARING CAPACITY AND STRESS REDUCTION

Bearing capacity and stress reduction are generally not economical solutions for providing the entire stress reduction function by ballast alone because of the often-large depth requirements between the sleepers and the subgrade surface. Because a sub-ballast layer is required for other reasons and the nature of the sub-ballast material makes it suitable for the structural function of the subgrade stress reduction, the sub-ballast layer thickness is considered as part of the total depth required between the bottom of the sleeper and the top of the subgrade.

To serve as a structural material, the sub-ballast must have a sufficiently high resilient modulus, and a stable plastic strain accumulation characteristic under repeated wheel load. To achieve these properties the material must be permeable enough to avoid significant positive pore pressure build up under repeated load, must consist of durable particles, and must not be sensitive to moisture content. The durability must be adequate to resist breakdown and abrasion from the cyclic stresses produced by the train loading. Such a material is provided by mixtures of sand and gravel particles composed of crushed and abrasion resistant minerals.

Under dry conditions, the strength and settlement characteristics of the sub-ballast will be governed primarily by the in-place density of the material, provided that durable and angular material is used. The density to which granular material can be compacted is controlled, to a large extent, by the gradation of the material. In general, higher densities are achievable by well-graded gradation as opposed to uniformly graded aggregates. Some fine materials are needed to achieve optimal gradation for high density; however, granular material exhibits decreasing stiffness with increasing fines content, so fines should be kept to a minimum.

The strength of sub-ballast is profoundly affected by the amount of moisture in the aggregate. In an unsaturated condition, water acts to lubricate the particles and increases both elastic and permanent deformation, even without developing pore pressure. A high percentage of fines are undesirable since fines tend to both attract and retain moisture, which causes hydraulic problems due to low permeability and the possibility of retaining water at a high degree of saturation.

Figure 25 illustrates the effects of water on the deformation of granular materials subject to cyclic loading. As the figure shows, settlement of granular material under cyclic loading accumulates more rapidly when water is added. The bottom most curve is a good quality, well-graded crushed rock with no fines and the upper, left most curve is a natural gravel with fines. Note that the clean granular material settles much less when water is added than the granular material with fines.

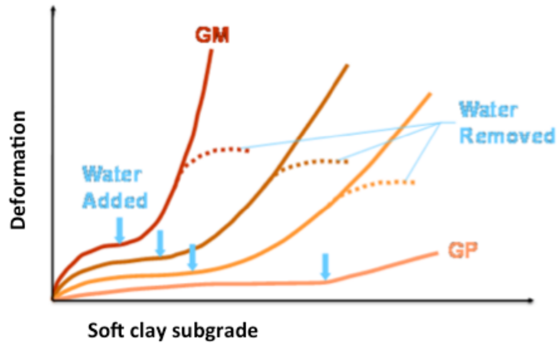

Figure 25. Influence of water on permanent strain development in granular material (Selig and Waters, 1994).

2.2.3. REQUIREMENT AND POSSIBLE SOLUTION

Water from precipitation falling onto the track and entering the ballast must be able to drain out of the substructure. This normally means lateral flow out through the ballast and to some extent through the sub-ballast.

The first requirement to achieve satisfactory track drainage is keeping the ballast clean enough to ensure sufficiently high permeability for quick drainage (Selig and Waters, 1994). Secondly, the surface of the sub-ballast and subgrade should be sloped towards the sides. The third requirement in track drainage is to provide suitable means (channel or conduit) to carry away the water that emanates from the substructure, as shown in Figure 26.

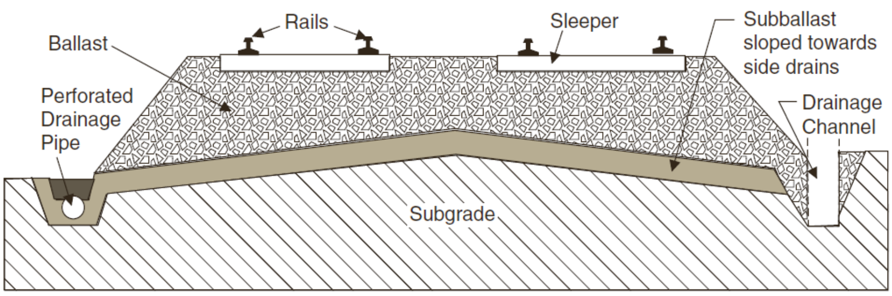

Figure 26. Schematic illustration of track drainage system (Indraratna et al.,2011).

According to Fatahi et al. (2008), the use of Geosynthetics (flexible sheets manufactured from synthetic materials e.g., polyethylene, polypropylene, polyester) is one of the most effective methods for improving the stability and drainage of railway infrastructure. They can be used for different purposes such as to retain fine particles when water passes from fine-grained to coarse-grained layers. But, they can especially be used to provide permanent mechanical and hydraulic filter stability (Fatahi and Khabbaz, 2011).

Another solution is the use of an impermeable membrane that may be placed in the drainage blanket to protect it from the ballast while preventing water from seeping downward to the subgrade surface.

Alternatively, hot mix asphalt can be used as sub-ballast (the focus of this study), which provides an impermeable uniform drainage layer, and reduces the effects of freeze/thaw action and reduced ballast fouling (Rose et al., 2002; Teixeira et al., 2006; Policicchio, 2008; Sol-Sánchez et al., 2015). In this case rain entering the ballast will be diverted by the surface of the asphalt and directed to the side drainage system.

2.2.4. DISADVANTAGES OF GRANULAR SUB-BALLAST

The granular material is employed in the majority of European high-speed lines for the sub-ballast layer with the aim of distributing and reducing the cyclic loads transmitted to the underlying subgrade layer to an acceptable level of stress, and, among others, to protect the subgrade from climatic effects. Nonetheless, the use of this granular configuration may have some drawbacks.

- First of all, it requires an adequate thickness of the layer to ensure an optimal bearing capacity, which involves the consumption of significant natural aggregates, with high costs of transport from the quarry;

- Another problem is related to the lack of quarries able to provide a suitable granular material for the sub-ballast layer, whilst there are high transportation costs from the quarry to the construction site and negative environmental effects;

- Moreover, other research works have shown that the granular material tends to lose its filter properties and "pumps" fine particle to the ballast layer. Excessive fine particles can overfill the voids in the ballast and serve as lubricants, forcing apart the large angular ballast particles. The result is a loss of internal friction, or shear strength, which is the main load distributing mechanism of ballast;

- Another problem is related to the loss of permeability, which has important consequences for the deformation of the tracks (Teixeira et al., 2009; Rose et al., 2011). This is due to the amount of the fine aggregates in the granular material that should be limited by structural requirements; however, the low quantity of fines makes it complicated to reach the mandatory impermeability;

- Furthermore, the granular material is vulnerable to water saturation and vibration. Because of these possible drawbacks, it is important to explore an alternative solution to replace the granular layer that is able to guarantee the required bearing capacity and impermeability, achieving at least an equivalent structural behaviour to the conventional sub-ballast track. In addition, it would be desirable to reduce the costs and to be environmentally friendly.

Over the past 30 or so years different types of sub-ballast layer have been studied, using a wide range of materials. Some of the most important are:

- Granular mix with fly ash and a low percentage of mixed hydrate lime with natural or gap-graded aggregates;

- Granular mix with blast furnace slag and hydraulic binder mostly consisting of calcium sulphate;

- Mixed cement, consisting of natural soft calcareous material or crushed material mixed with a low percentage of cement;

- Bituminous asphalt.

Solutions using blast furnace slag and fly ash are adopted for specific purposes and, sometimes, to restore platforms with stability problems or the floor foundations in goods stations.

Mixed cement sub-ballast undoubtedly provides a number of advantages, such as:

- Low production costs;

- High quality physical and mechanical characteristics (resistance and modules), which tend to increase in time due to the fact that the calcium carbonate in natural aggregates dissolves thereby ensuring that the layer becomes homogenous and stress can consequently be apportioned;

- Waterproof.

However, the mixed cement solution also has some drawbacks, such as:

- Environmental problems involved in finding the necessary natural aggregates;

- Sensitivity to freezing and the fact that work cannot be carried out below certain temperatures;
- Construction vehicles cannot pass along the layer until it is completed;
- The surface of the layer must be protected from bad weather conditions with bituminous sheets or emulsions.

2.3. THE USE OF BITUMINOUS MIXES IN RAILWAY CONSTRUCTION

2.3.1. INTRODUCTION

Bituminous mix consists primarily of mineral aggregates, asphalt binder, and eventually additives. The mechanical properties of a bituminous mixture are dependent on the nature and the amount of the components. It is important to have suitable proportions of asphalt binder and aggregates in bituminous mixes so as to develop mixtures that have desirable properties associated with good performance such as resistance to permanent deformation, fatigue cracking, and low temperature cracking (Kraemer et al., 2004).

The amount of *aggregate* in asphalt concrete mixtures is generally 90 to 95 per cent by weight and 75 to 85 per cent by volume. Aggregates are primarily responsible for the load supporting capacity of a pavement. Aggregates are typically comprised of crushed rock, gravel, sand, or mineral filler. Occasionally, products from other industries, including foundry sand, crumb rubber, blast furnace slag, and glass, may be recycled into asphalt pavement as aggregate. Aggregates are selected and classified according to size and other properties for a specific asphalt mix design and pavement end-use specification.

Bitumen is obtained through distillation of crude oil in an oil refinery. When loaded, the behaviour of bitumen is strongly dependent on the temperature (T) and the loading time (t). At high temperatures and long loading times bitumen behaves as a liquid (viscous) while at low temperatures and short loading times it behaves as a solid material (elastic). In the intermediate area bitumen behaves in a visco-elastic manner.
Figure 27 shows that the elastic behaviour can be modelled with a spring. When a tensile load is applied an instantaneous extension of the spring occurs while the spring immediately returns to its original condition if the load is removed.
The viscous behaviour can be modelled with a dashpot or shock absorber. When the load is applied the deformation gradually increases. The longer the loading time the greater the deformation. If the load is removed the dashpot remains in its deformed condition.

The delayed elastic behaviour can be modelled as a parallel system of a spring and a dashpot. When the load is applied the spring likes to deform immediately but is obstructed by the dashpot. If the load is removed the dashpot likes to maintain its deformed condition but the spring (which favours a return to its original condition immediately) will 'pull back' the dashpot to the original condition; this, however, takes some time.

The total deformation behaviour of bitumen can now be described with a system of springs and dashpots that represent the elastic, delayed elastic, and viscous behaviour respectively (Van Der Poel, 1954).

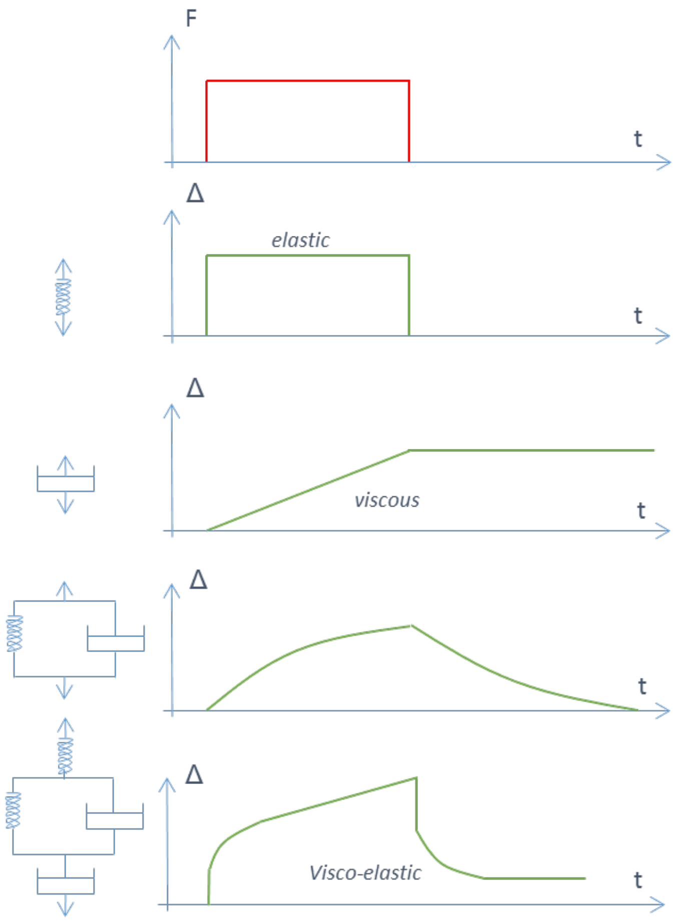

Figure 27. Linear viscoelasticity (Adapted from Van Der Poel, 1954).

All types of bitumen are highly susceptible to temperature, becoming more viscous (harder) as their temperature decrease and less viscous (softer) as their temperature increases. Figure 28 shows the variation in viscosity of a binder at different temperatures, and it is clear that as the temperature increases, the binder becomes less viscous (more fluid). The temperature susceptibility of the binder is very important; it must be fluid enough at elevated temperatures to permit it to coat the aggregate particles during mixing and to allow these particles to move past each other during compaction.

It must then become viscous enough at normal air temperatures to hold the aggregate particles in place in the pavement (Hafeez et al., 2013).

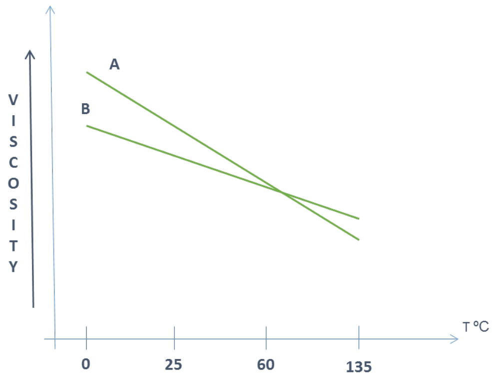

Figure 28. Viscosity Variation of Binders at Different Temperatures (Adapted from Hafeez et al., 2013).

The temperature susceptibility of the binder is very important because it indicates the appropriate mixing and compaction temperatures at which to mix the binder with aggregate, and at which to compact the mixture.

In a number of applications bitumen emulsion is used as binder in the mixture with sand and aggregate. Bitumen emulsions are heterogeneous two-phase systems consisting of bitumen and water. The bitumen is dispersed throughout the continuous water phase in the form of discrete globules, which are held in suspension by electrostatic charges stabilised by an emulsifier. An emulsifier consists of a long hydrocarbon chain that terminates with either a cationic or an anionic functional group. The emulsifier is not only a stabilising agent but also an adhesion promoter. Emulsion based mixtures are referred to as "cold mixes" (EAPA, 2010; Vaitkus et al., 2009).

The asphalt mixes may be classified according to different criteria:

- As a function of the *temperature* of manufacturing it is possible to classify technologies for asphalt materials that are able to consume less energy than traditional hot mix asphalt whilst maintaining the in-service mechanical performance of the material (figure 29).

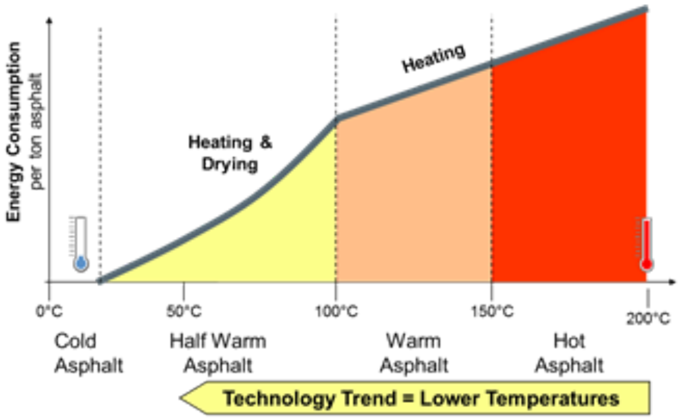

Figure 29 Classification by temperature range (EAPA, 2010).

- Cold mixes: produced with unheated aggregate and bitumen emulsion or foamed bitumen.
- Half Warm Asphalt: produced between approximately 70 °C and roughly 100 °C.
- Warm Mix Asphalt: produced and mixed at temperatures roughly between 100 and 150 °C.
- Hot Mix Asphalt: produced and mixed at temperatures roughly between 120 and 190 °C. The production temperatures of Hot Mix Asphalt depend on the bitumen used.

➢ As a function of the aggregate gradation used in the mix, HMA mixtures are divided into three mixture categories (Bardesi, 2010) (Figure 30):

- **Dense-Graded Mixes:** are a well or continuously graded aggregate (gradation curve does not have any abrupt slope change). The dense-graded mix is relatively impermeable. Dense-graded mixes are generally referred to by their nominal maximum aggregate size and can further be classified as either fine-graded or coarse-graded. Fine-graded mixes have more fine and sand sized particles than coarse-graded mixes.

- **Stone Matrix Asphalt (SMA):** will be missing most intermediate sizes but contains a relatively high proportion of fines. It is a gap-graded HMA originally developed in Europe to maximize rutting resistance and durability. The goal of the mix design is to create stone-on-stone contact within the mixture. Since aggregates do not deform as much as asphalt binder under load, this stone-on-stone contact greatly reduces rutting. Typical SMA composition consists of 70−80% coarse aggregate, 8−12% filler, 6.0−7.0% binder, and 0.3 per cent fibre.

- **Open-Graded Mixes:** are designed to be water permeable formulated to provide large voids (around 20%), which differentiates them from dense-graded and SMA mixtures that are relatively impermeable. Open-graded mixes are produced with relatively uniform-sized aggregate typified by an absence of intermediate-sized particles (the gradation curve has an almost vertical drop in intermediate size range). Because of their open structure, precautions are taken to minimize asphalt drain-down by using modified binders.

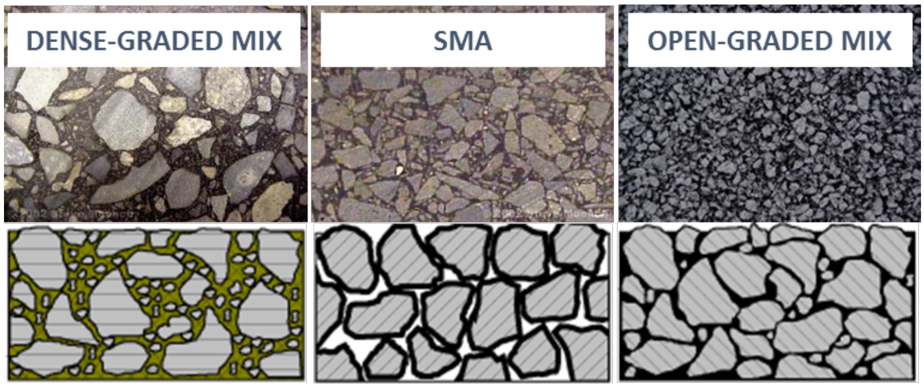

Figure 30. Classification by aggregate gradation.

2.3.2. PROPERTIES OF BITUMINOUS MIXES

To get obtain good asphalt pavement that works well in service, during the design, production, and place phases, various properties must be considered that contribute to the quality of asphalt mixture pavements. They include stability, durability, impermeability, workability, flexibility, and fatigue resistance (Bardesi, 2010).

- **Stability** of an asphalt mixture pavement is the ability of the mixture to resist shoving and rutting under loads (traffic). The stability of a mix depends on internal friction and cohesion. Internal friction among the aggregate particles (inter-particle friction) is related to aggregate characteristics such as shape and surface texture. Cohesion results from the bonding ability of the binder.

- The **durability** of an asphalt mixture pavement is the ability of the asphalt mixture pavement to resist changes in the binder oxidation and disintegration of the aggregate. These factors may be the result of weather, traffic, or a combination of the two.

- **Impermeability** is the resistance of an asphalt mixture pavement to the passage of air and water into or through the mixture. This characteristic is related to the void content of the compacted asphalt mixture.

- **Flexibility** is the ability of an asphalt mixture pavement to adjust to gradual settlements and movements in the subgrade without cracking. An open graded asphalt mixture with high binder content is generally more flexible than dense graded, low binder content asphalt mixtures. Sometimes the need for flexibility conflicts with stability requirements, so that trade-offs are necessary.

- **Workability** describes the ease with which a paving mixture can be placed and compacted. Mixtures with good workability are easy to place and compact; those with poor workability are difficult to place and compact. Workability can be improved by changing mix design parameters, aggregate source, and/or gradation.

- **Fatigue resistance.** HMA should not crack when subjected to repeated loads over time. HMA fatigue cracking is related to asphalt binder content and stiffness. Higher asphalt binder contents will result in a mix that has a greater tendency to deform elastically (or at least deform) rather than fracture under repeated load. The optimum asphalt binder content, as determined by mix design, should be high enough to prevent excessive fatigue cracking. The use of an asphalt binder with a lower stiffness will increase a mixture's fatigue life by providing greater flexibility. However, the potential for rutting must also be considered in the selection of an asphalt binder. Note that fatigue resistance is also highly dependent upon the relationship between structural layer thickness and loading. However, this section only addresses mix design issues

- **Low temperature cracking resistance**. Mix asphalt should not crack when subjected to low ambient temperatures. Low temperature cracking is primarily a function of the asphalt binder low temperature stiffness. Specifying asphalt binder with adequate low temperature properties prevent, or at least limit, low temperature cracking.

2.3.3. DIFFERENT TYPES OF BITUMINOUS LAYER RAILWAY TRACKS

Asphalt mixtures have been shown to provide good technical alternatives for several elements of traditional railway construction, providing a positive contribution to the bearing capacity of the structure, improving both the stability and the durability of the structure, and contributing to the reduction of maintenance activities. In addition, the use of asphalt also helps to reduce vibration and noise (Teixeira et al., 2005; Xiangwu, 2005; Di Mino et el., 2012).

Applications of asphalt in railway construction can be categorised according to their use as sub-ballast layers and use as full depth (asphalt) construction, also called ballast-less track, characterized by the absence of the ballast layer. The first one is similar to the classic All-Granular trackbed but the asphalt layer is used to replay the granular sub-ballast layer, maintaining the ballast downwards at the edges to cover the asphalt and prevent exposure of the asphalt to sunlight (Figure 31). The trackbed can also include both the asphalt layer and the granular sub-ballast layer. The asphalt layer thickness may be lessened somewhat since a relatively thick sub-ballast layer exists below (Figure 32) (Rose et al., 2010).

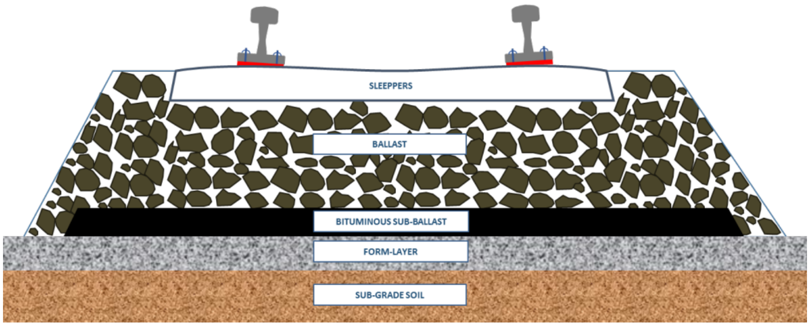

Figure 31. Asphalt Underlayment trackbed without granular sub-ballast layer (Rose et al., 2010).

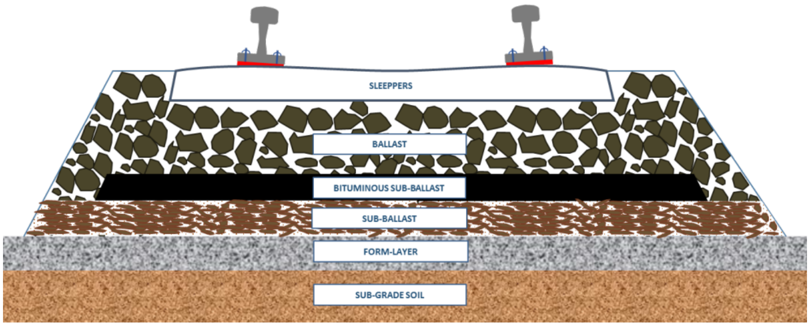

Figure 32. Asphalt Combination trackbed containing both asphalt and sub-ballast layers (Rose et al., 2010).

Less-track is a solution where the track frame of rail and sleepers is placed directly on an asphalt mix (Figure 33) with the aim to have a track structure with a good elasticity, independent of the foundation stiffness. The advantages of these systems are the elasticity of the asphalt layer, especially when polymer modified asphalt is used, and the ease of construction and maintenance. Another important factor in favour of this system is the ability to carry out minor corrections without demolishing and reconstructing the base in comparison with the conventional concrete solution.

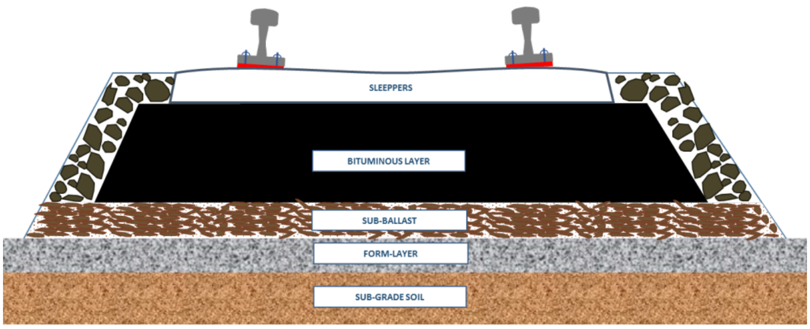

Figure 33. Ballastless trackbed containing thickened asphalt and sub-ballast layers (Rose et al., 2010).

2.3.4. BITUMINOUS SUB-BALLAST

Bituminous asphalt is a solution that has the potential to ensure the required bearing capacity and impermeability, whilst simultaneously reducing the thickness of the layer compared with the conventional granular design. However, before proceeding with the widespread application of this system, studies concerning the short and long-term efficacy of bituminous sub-ballast are needed to confirm that the main requirements of service can be met (mainly impermeability, bearing capacity, stress dissipation and durability) under the various service conditions expected during its application in railway tracks. In addition, it is important to consider that temperature variations cause changes in the performance of asphalt mixtures (more elastic at low temperatures and more viscous at higher temperatures) (Hafeez et al., 2013). Thus, the benefits of using bituminous sub-ballast could depend on the temperature of service, which is subject to considerable variations, particularly in regions with extreme climates such as desert areas.

2.3.5. BITUMINOUS SUB-BALLAST DESIGN

In general, one of the most important requirements for the asphalt is determined by the load type. In the case of the solid railway trackbed, loading frequency is at a lower level than with asphalt roads. In contrast, the axle loads — and consequently the wheel loads — are considerably higher. On roads, the actual distributed load results in a wheel load of 5.75 tons for a truck with an 11.5-ton axle, which works out to around 0.8 MPa for a surface area of around 710 cm². For railways, however, there is a considerable load distribution over the rail and the sleeper. The wheel load of 11.25 tons results in stress on the bottom of the sleeper of around 0.25 MPa, and thus only around one-third of the load experienced on roads.

The asphalt needs to be designed to be permanent, flexible, and dense in order to avoid maintenance work and subsequent improvements, which are practically impossible. The lifetime of the solid railway trackbed has been estimated to be around 60 years.

The type of mixture more commonly used within the track is a dense-graded bituminous mixture. Figure 34 shows an example of extremes of the grain size curve used for bituminous sub-ballast with a maximum aggregate size of 22–25 mm manufactured with characteristics that are suitable for the construction of road pavements (Rose and Bryson, 2009).

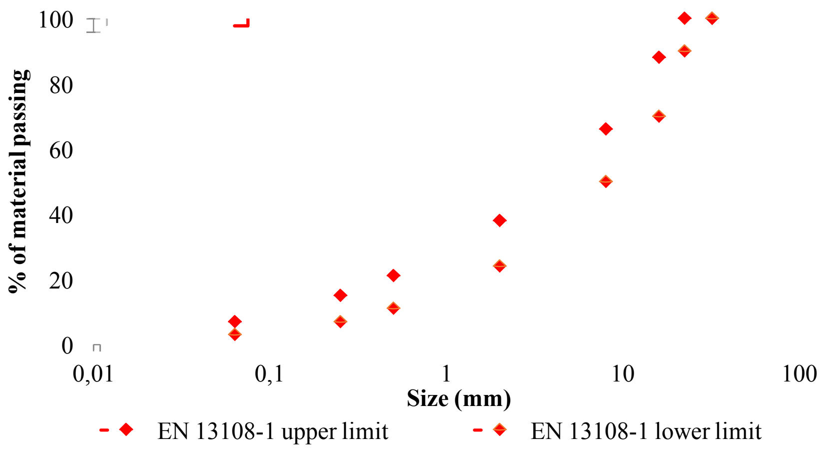

Figure 34. Grading envelope used for bituminous sub-ballast (Spanish Standard for Subballast, 2006).

The asphalt mixture is generally designed with similar characteristics as that used in highways, although for its application as sub-ballast the bitumen content is increased by 0,5% in reference to the optimum for highways. Furthermore, the air void percentage is reduced to 1–3% in order to obtain a mix easier to densify and therefore facilitates adequate strength and an impermeable mat. Rutting of the plastic mix is not a concern in the trackbed since the pressures are applied through the ballast over a wide area. Bleeding and flushing are also of little concern since the wheels do not come in direct contact with the asphalt layer and the temperature extremes are minimized in the insulated trackbed environment.

Table 3 shows the characteristics for aggregates, bitumen, and mixture generally required for their use in railways as bituminous sub-ballast (PF-7, 2006).

AGGREGATES	
Sand equivalent (%)	> 50
Angular particles (%)	> 90
Flakiness index (%)	< 25
Los Angeles test (%)	> 25
BITUMEN	
Type	B50/70 or B70/100
Content (%)	> 4,75
MIXTURE	
Void content (%)	1 - 5
Filler/bitumen	0,9 - 1,2
Water sensitivity (%)	> 85
Dynamic stiffness modulus (20°C) (Mpa)	3700 - 7100

Table 3. Spanish limits for Subballast (Spanish Standard for Subballast, 2006).

2.3.6. INTERNATIONAL ASPHALT TRACKBED APPLICATIONS

Bituminous sub-ballast has been used in a number of railway lines in various countries, although this solution is not very widespread, at least in European countries such as Spain. This part contains the most relevant international experiences regarding the use of the asphalt within the track, mostly in high-speed railways.

The first experimental works were carried out at the end of 1960 in the USA (Huang et al., 1987). However, the use of bituminous sub-ballast layers, instead of crushed stone sub-ballast layers, was developed in 1980, and its use is now widespread due to the demand for reduced maintenance of the rail track (Rose et al., 2000 and 2002).

In Japan, since 1970, the use of bituminous sub-ballast in the rail tracks has been widespread for the construction of both conventional and high-speed rail traffic with the main aim of providing a firm support for the ballast and reducing track irregularities (Momoya et al., 2007).

The performance-based design procedure ranks or classifies three different standard track designs according to performance, but using asphalt just in two of them, which are:

- Performance Rank I: Concrete roadbed or asphalt roadbed for ballastless track;
- Performance Rank II: Asphalt roadbed for ballasted track.

The Performance Rank I track is a ballastless slab track, with a slab width of 222 cm, which has either concrete support with a thickness of 19 cm, or asphalt support with a thickness of 15 cm, both with concrete ties directly fixed to the slab. It is considered the highest quality track. It is checked for track settlement, breakage of concrete reinforcement base, fatigue damage, cracking, contraction, and thermal stresses.

The Performance Rank II design is a ballasted track with a 15-60 cm thick of well graded crushed layer, 50 mm thick asphalt layer and a thickness of ballast beneath tie of 250-300 cm (Figure 35). This design has been used for over 30 years in Japan due to the asphalt‘s ability to distribute loads and facilitate drainage. For performance-based design, the settlement of the track and fatigue damage to the asphalt are the primary considerations.

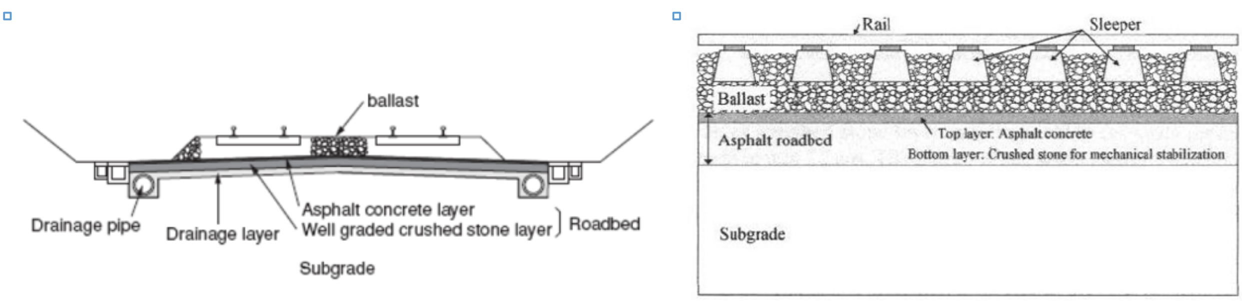

Figure 35. Performance Rank II Cross-sectional profile (Momoya et al., 2007).

In European countries, Italy began to use asphalt mixes in high-speed railway from the early 1970s (Buonanno et al., 2000).

During the construction of the Rome-Florence line, the Italian Railway Company adopted a bituminous layer in order to achieve a minimum bearing capacity of 180 MPa. This layer was also adopted in order to carry out different functions, such as preventing rainwater from infiltrating the layers below the embankment; protecting the upper part of the embankment from freeze/thaw action; and gradually distributing static and dynamic stresses caused by trains and eliminating ballast fouling.

The Italian High-Speed Railway is a multi-layered system, consisting of an embankment, supercompacted sublayer, asphalt sub-ballast, ballast, ties, and rail (Figure 36).

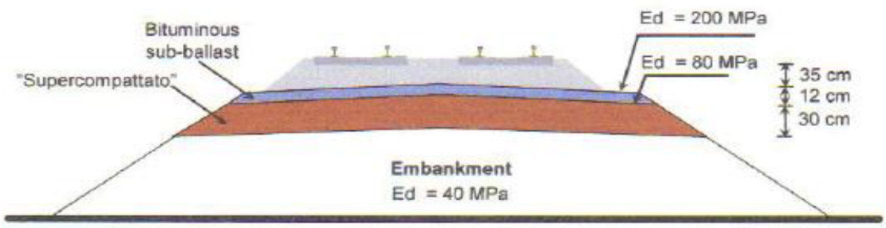

Figure 36. Cross section of Italian trackbed (Buonnano, 2000).

The embankment does not exceed 50 cm in thickness and has a minimum specified bearing capacity of 40 MPa. On top the supercompacted layer is then placed, which consists of sand/gravel mixture and is placed with a cross slope of 3.5%. This layer is able to withstand the loads transmitted by the high-speed trains and at the same time has the ability to serve as an impermeable layer to aid in intercepting and diverting surface water. It is usually applied with a thickness of around 30 cm width and a minimum modulus of 80 MPa. The asphalt sub-ballast layer, placed above the supercompacted layer, consists of an asphalt mixture with a maximum aggregate size of 25 mm and a finished thickness of 12 cm. The asphalt sub-ballast must have a minimum modulus of 200 MPa and compacted to 98% of maximum density (Buonanno et al., 2000; Giavarini et al., 2000).

In Germany, since 1970, bituminous ballast track beds have been used in order to reduce maintenance costs and preserve environmental resources, and since then there have been several other alternatives both for high-speed and conventional tracks, including asphalt ballastless track designs. The German system consists of two different designs, known as A1 and A3.

The A1 system is a ballastless track system with direct support for the track panel on an asphalt supporting layer. The sleepers are made of prestressed-concrete and are installed onto the asphalt supporting layer. The sleepers are interlocked with the asphalt by means of anchor blocks in order to transfer the longitudinal and lateral forces from the rails to the asphalt supporting layer. Installation of the asphalt layers takes place in several layers while the cover layer, consisting of 0/11 asphaltic concrete. The bituminous supporting layer is installed onto a load-bearing ballast layer or hydraulically bonded layer with a modulus greater than or equal to 120 N/mm2 (Figure 37).

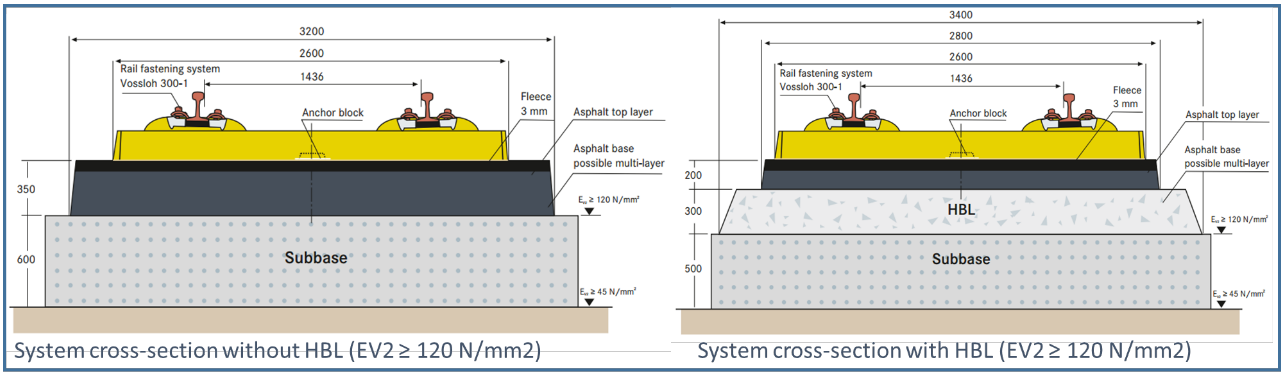

Figure 37. German Getrac A1 Cross Sectional Profile (Frenzel et al., 2000).

In the A3 system, the multi-layer asphalt base provides direct support for the wide concrete sleepers. The secure and permanent position of the track on the asphalt layer is assured by the bond between the individual asphalt layers and by the connection of the pre-stressed concrete sleepers to the top asphalt layer. The horizontal forces are transferred into the asphalt and conduct them away there (Figure 38).

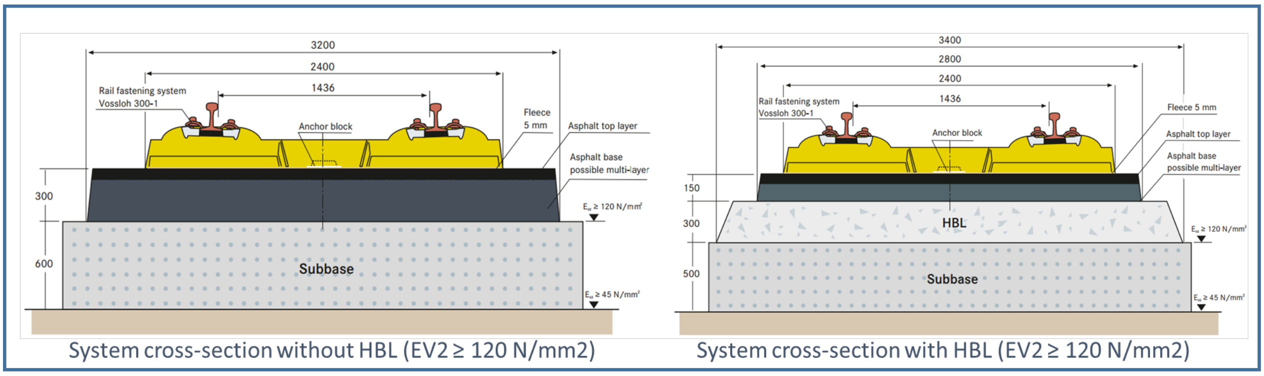

Figure 38. German Getrac A3 Cross Sectional Profile (Frenzel et al., 2000).

Both the A1 and A3 systems possess the same dimensions with the exceptions of the concrete cross tie and asphalt thickness. The system A1 utilizes a 2,6 m long pre-stressed concrete tie that is considered a normal-width tie. The system A3 uses a 2,4 m long pre-stressed tie that is slightly wider (Frenzel et al., 2000).

Moreover, France began to follow this trend, developing a 3 km long test section containing an asphalt sub-ballast layer. Figure 39 shows the comparison of the traditional all-granular profile used in the lines with the experimental asphalt sub-ballast profile adopted in the 3 km test section (Bitume Info, 2005).

The traditional cross section consists of 30 cm of ballast layer resting on 20 cm of sub-ballast layer. The ballast and sub-ballast rest on a 50 cm thick layer of limestone aggregate. The asphalt sub-ballast cross section eliminates the 50 cm layer of limestone and replaces it with 14 cm of asphalt sub-ballast as well as a 20 cm thick adjustment layer. This reduces the overall cross sectional thickness by 36 cm, which reduces the quantity of material by approximately 5000 m^3 per km of track (Bitume Info, 2005). The France National Railway (SNCF) is carrying out several tests regarding the measure of pressure on the subgrade, the deformations of the asphalt layer and the vertical accelerations on the TGV-East line connecting Paris to Strasbourg, to determine if asphalt sub-ballast should be a considered as an alternative material for use in future high speed rail infrastructure projects.

After installation of the asphalt test section the France National Railway (SNCF) conducted various tests for 4 years to evaluate the impact on maintenance and to observe the behaviour during temperature changes. Various sensors were built in to measure the temperature, pressure, acceleration, strains and deformations of the base layer of asphalt, and finally the TGV-East line was opened in June 2007 (Bitume Info, 2005).

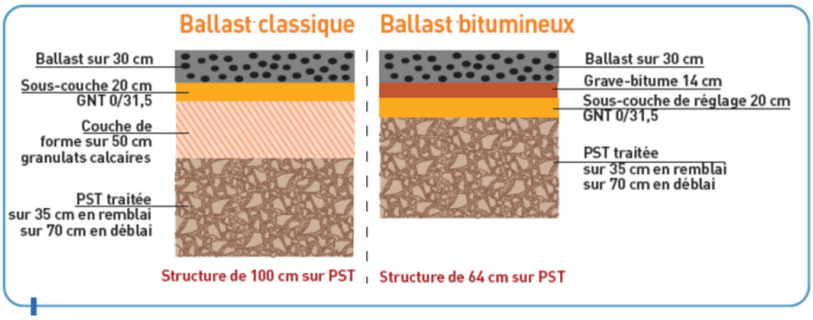

Figure 39. Traditional and bituminous sub-ballast sections (Bitume Info, 2005).

In Spain, many researchers have developed research on this subject in order to better understand the behaviour of bituminous sub-ballast layers compared with crushed stone sub-ballast layers (Teixeira et al., 2006 Teixeira et al., 2009). The Spanish Railway authorities decided to test the use of this solution in trial sections in four sites (Teixeira et al., 2006 Teixeira et al., 2009; Rose et al., 2010):

- Madrid-Valladolid high-speed passenger line (already in commercial operation);
- Sils – Riudellots. (Barcelona – Figueras line) ;
- Villodrigo – Villazopeque. (Valladolid – Burgos line);
- Aspe – El Carrús.(Alicante – Murcia line).

The structural design that supported the construction of these sections consists of a 12 cm to 14 cm layer of a bituminous sub-ballast applied over a form layer with a minimum thickness of 30 cm laying on top of a subgrade with a minimum bearing capacity of 80 MPa, as shown in Figure 40.

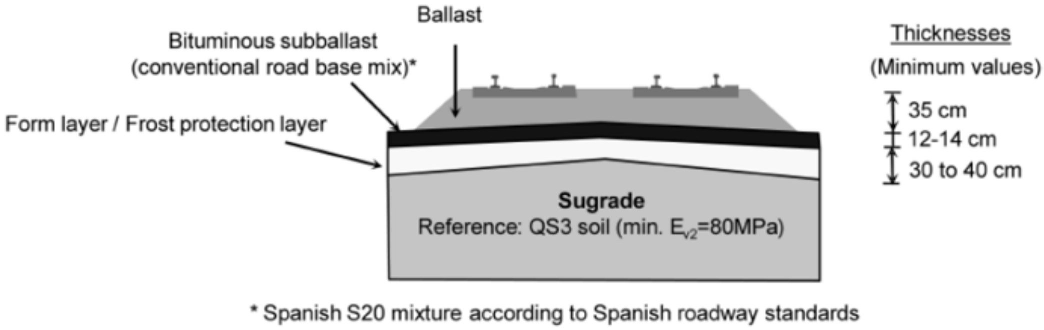

Figure 40. Track design with bituminous sub-ballast for Spanish high-speed lines standards (Teixeira et al., 2006).

In Austria, the asphalt layer consists of an 8 to 12 cm thickness beneath the ballast bed, as shown in Figure 41.

The primary purpose of the asphalt layer is to provide a clear separation between sub- and superstructure (Holzfeind and Hummitzsch, 2008). The main advantages realized are:

- Rain water is prevented from penetrating the substructure (sub-ballast and subgrade);
- Upward pumping of fines is prevented;
- Optimum level of elasticity is obtained;
- Consistent support is provided, homogenizing stresses on the substructure.

Figure 41. Asphalt layer beneath the ballast bed (Holzfeind and Hummitzsch, 2008).

2.3.7. OTHER STUDIES

Several studies and experiences have been reported regarding the use of asphalt mix in railway tracks to replace the conventional granular sub-ballast. The main goal of this part of the thesis is to conduct a review on this topic. In this regard, the bituminous sub-ballast will be compared with the all-granular solution. From the point of view of long-term deterioration of the sub-grade, Rose (2000) found that the bituminous solution offers important comparative advantages. Figure 42 highlights the conclusions of a study where it is shown that, under a bituminous underlayment, the subgrade’s moisture content is kept closer to optimum moisture content. Being almost completely water resistant, the bituminous sub-ballast is able to keep the moisture content unchanged during the whole year and throughout its life cycle, a factor known to have an important influence on the subgrade deformation process.

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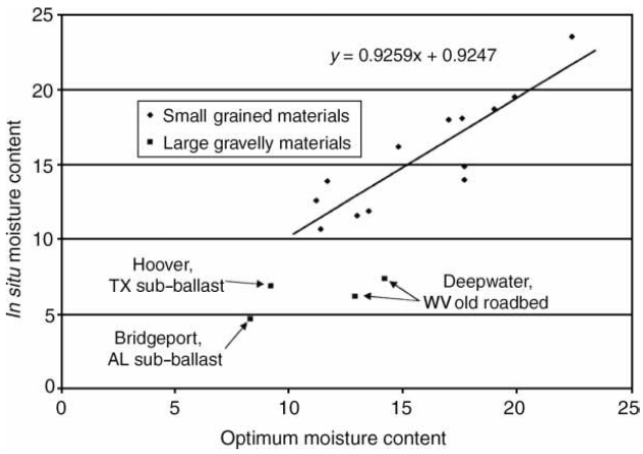

Figure 42. Relationship between in situ subgrade moisture contents and its optimum moisture contents under bituminous sub-ballast, after a 16-year monitoring plan (Rose et al., 2000).

Other advantages of using a bituminous sub-ballast layer are concerned with the differential settlement of the track. A first study carried out by the Centre for Innovation in Transport (CENIT, 2005) in collaboration with the University of Rome, analysed the geometric quality deterioration records on sections with and without bituminous sub-ballast on the Rome–Florence HS line, as an attempt to evaluate the possible benefits of this solution. This study indicates a slight positive effect of using bituminous sub-ballast in the maintenance needs at transition sections (bridge embankment), one of the main problems of deterioration in HS lines (Lopez Pita and Teixeira, 2001, Lopez Pita et al., 2007).

Ferreira et al. (2007) analysed theoretically the performance of bituminous sub-ballast against environmental actions in terms of its seasonal variation as well as the capability of maintaining the moisture content throughout the year, as an alternative to the conventional sub-ballast layers. To reach an equivalent structural behaviour of a granular sub-ballast layer with 30 cm of thickness, the sub-ballast layer was design with 12 cm (as proposed by Teixeira et al., 2006). The comparison was made by recurring to the evolution of liquid saturation, vertical displacements and their amplitude in several points of control. Figure 43 presents the Liquid Saturation inside the embankments for the bituminous and granular cross sections at the end of the 5 years. It is possible to see that the bituminous sub-ballast works as a barrier against water infiltration. In terms of liquid saturation, bituminous sub-ballast helps to maintain low levels of the moisture content throughout the year, as opposed to the granular solution.

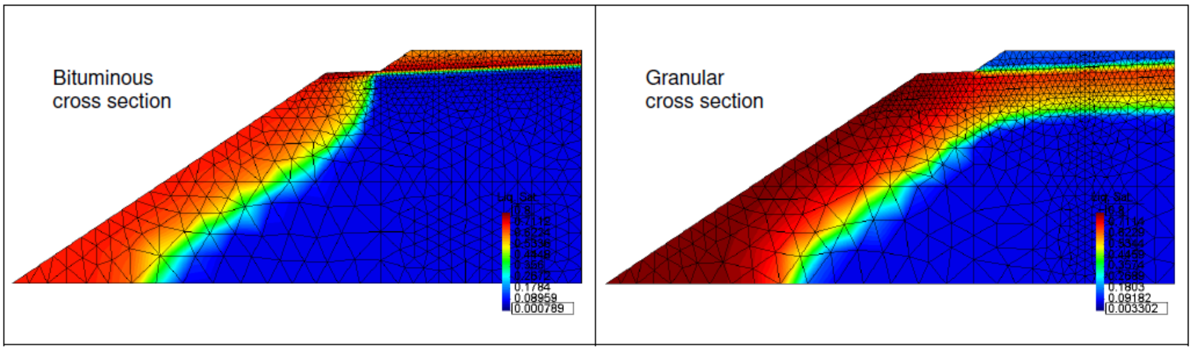

Figure 43. Liquid saturation at the end of 5 years (Ferreira et al., 2007).

Another major factor in track settlements where the bituminous sub-ballast can play an important role is related to the dynamic behaviour of the track at HS and very HS, a key factor in track deterioration (Lopez Pita et al. 2006). To assess this question, displacements and vibration accelerations within the track and sub-track generated by a two-wheel vehicle set travelling at HS (300 and 350 km/h) were calculated using a dynamic finite-element model. Comparisons made for different types of sub-ballast with respect to track dynamic behaviour were performed. Figure 43 shows a preliminary attempt at this comparison, concerning vertical accelerations. As can be seen in Figure 44, the use of bituminous sub-ballast can reduce vibration acceleration levels inside the track for speeds of 300 and 350 km/h, compared to those of a track with an all-granular trackbed. Thus, it seems reasonable to believe that the use of bituminous material in the sub-ballast layer enhances the dynamic performance at HS.

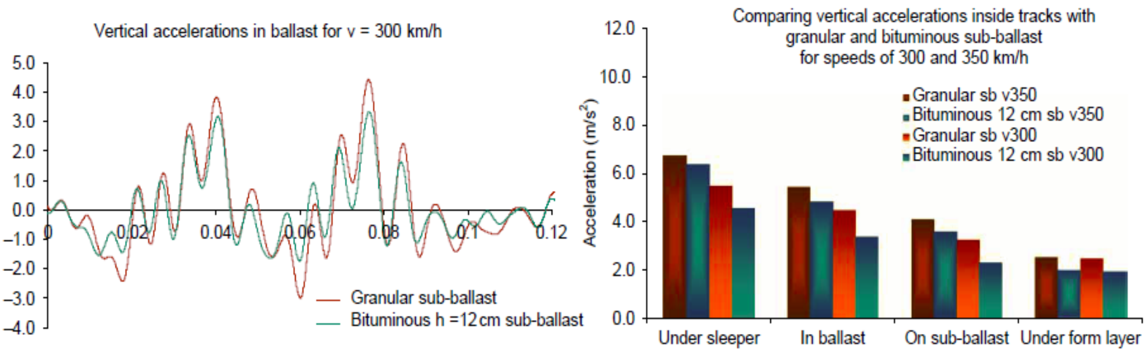

Figure 44. Vertical accelerations: time signals in ballast for v ¼ 300 km/h (left) and maximum values at different levels in the track for speeds of 300 and 350 km/h (right), comparing two identical HS tracks with different sub-ballasts (Ferreira et al., 2007).

Moreover, according to Buonanno and D'andrea (2003), the benefits already attained using an asphalt sub-ballast layer may even be increased by adding rubber granulates into the bituminous mix, as it seems to further improve its tendency to dissipate energy and damp vibrations. Similarly, Zhong et al. (2002) showed that an asphalt mixture with 20% rubber content has an average damping ratio of around 9.5%, whereas without rubber it is approximately 6%, but still greater than normal subgrade soil layers (<3%). These research studies pointed out the great propensity to dissipate energy of this kind of composite material (as the loss factor increases with the increase in rubber content) and, thus, provided evidence of the good dynamic performance of rubber-modified asphalt when applied to sub-ballast layers of HS railway tracks. Furthermore, the authors believe that the use of this waste material, enhancing the track sub-ballast anti-vibrating properties, together with new design and construction methods, may result in an innovative bituminous mixture to be used in railway tracks in the future. However, as mentioned, it still requires further experimental measurements on site in order to obtain more validated conclusions on this matter.

Continuing the discussion on the application of crumb rubber, Lee et al. (2014) evaluated the performance of three asphalt concrete mixtures for railway track using three different asphalt binders, which are PG 64-22, crumb rubber modified (CRM) asphalt binder, and styrene–butadiene–styrene (SBS) modified asphalt binder, investigated in terms of moisture susceptibility, permanent deformation, and fatigue cracking of asphalt concrete mixture. Dynamic modulus and uniaxial creep tests were conducted to characterize the material properties of asphalt mixtures. In terms of resistance to moisture susceptibility, asphalt mixtures with SBS and CRM asphalt binders showed higher resistance than that of the asphalt mixture with PG 64-22 asphalt binder, but all the asphalt mixtures did not meet 80% of minimum TSR value (Figure 45).

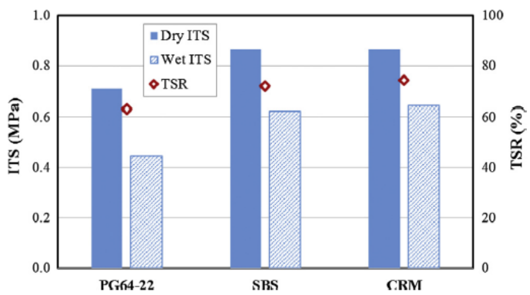

Figure 45. Results of the indirect tensile strength test; indirect tensile strength (ITS) and tensile strength ratio (TSR) (Lee et al., 2014).

In terms of resistance to fatigue cracking, the results of the repeated IDT test under dynamic loading showed that asphalt mixture with CRM asphalt presented the highest fatigue cracking resistance (Figure 46).

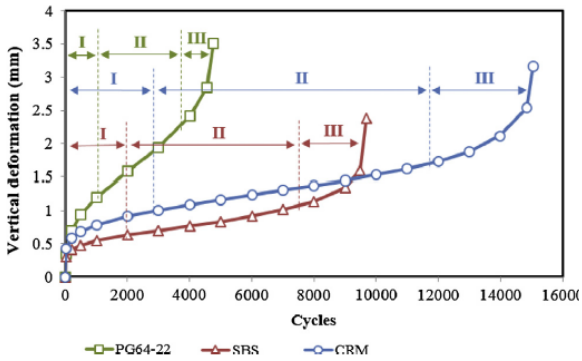

Figure 46. The repeated IDT test results. (Lee et al., 2014).

The results indicate that asphalt mixtures containing crumb rubber and SBS show better performance compared with the PG 64-22 binder.

From an investment/cost viewpoint, it has been demonstrated that the transport distance is a key factor in the cost of the granular sub-ballast. In fact, the cost of granular sub-ballast is highly dependent on the local availability of quarries with materials that are suitable for meeting high-speed track standards. As can be seen from the left of Figure 47, the price of granular layer can double for distances to quarry varying from 20 to 80 km. Regarding the bituminous mix, the bitumen cost is one of the key factors that affect the cost of the bituminous sub-ballast.

Comparing both cost functions obtained, it was found that due to the high sensitivity of granular material cost with distances from quarry, the granular sub-ballast begins to be even to more expensive than the bituminous solution for transport distances above 60 to 80 km. As shown on the right of Figure 47, assuming a variation of 30%, it would suppose a variation in the bituminous sub-ballast cost of around 10%.

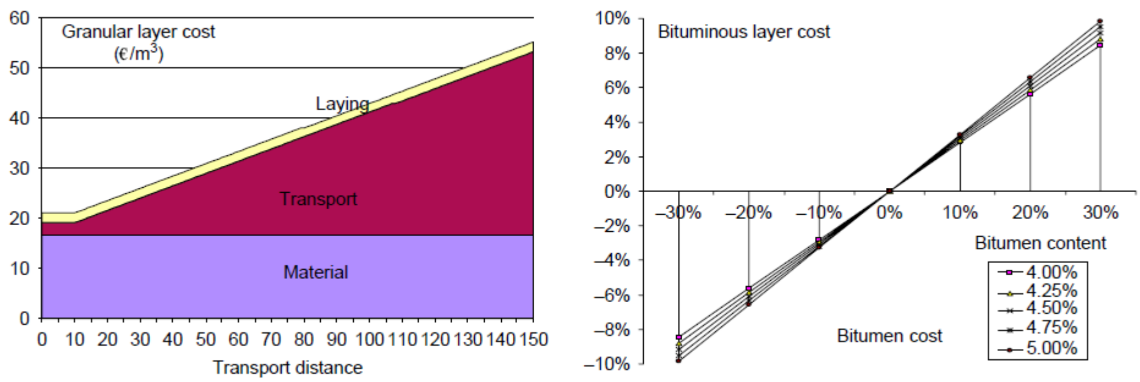

Figure 47. Variability of a granular sub-ballast cost with distance from quarry (left) and sensitivity of bituminous sub-ballast cost to variations in the bitumen price (right) (Teixeira et al., 2009).

Moreover, it has been demonstrated that the use of a bituminous sub-ballast layer can lead to a reduction of around 200 m^3/km/ track in the volume of ballast required for this solution.

This decrease in ballast material needs is due to the waterproof characteristics of bituminous sub-ballast layer, which enables the track lateral slope to be reduced from 5% to almost 3% (as adopted in Italy for bituminous sub-ballast), as evidenced in Figure 48. This saving in ballast material can be equivalent to around 5% of the price of the bituminous sub-ballast layer, considering the average costs of the ballast material suitable for high-speed lines (CENIT, 2005; Teixeira et al., 2009).

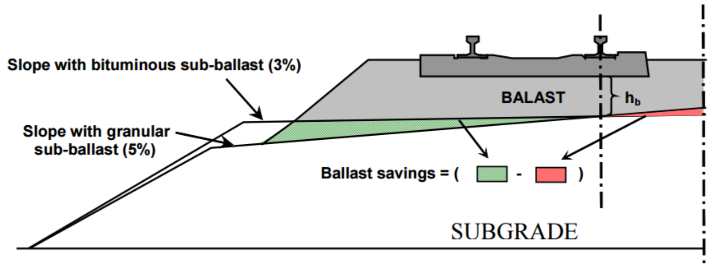

Figure 48. Schematic representation of the savings in ballast material due to the use of a lower lateral slope for the bituminous sub-ballast solution (Teixeira et al., 2009).

2.3.8. ADVANTAGES AND DISADVANTAGES OF BITUMINOUS SUB-BALLAST

From several studies and international experiences discussed above, when compared with all-granular solutions, the use of HMA as sub-ballast can offer important advantages from different points of view.

- *Bearing capacity.* The application of a layer of asphalt as a sub-ballast layer will increase the stiffness of the total structure. The fact that an asphalt layer is also capable of withstanding tensile forces adds an extra positive contribution to this effect.

- *Geometric quality.* The bituminous sub-ballast contributes to keeping the railroad geometry unaltered thanks to its higher stiffness.

- *Resistance to vertical deformation.* The relatively high stiffness of the asphalt layer and its visco-elastic properties make it able to withstand the vertical deformation without losing its integrity.

- *Drainage.* The bituminous sub-ballast is able to offer optimal drainage of the total structure. The impermeable layer can prevent possible contamination of the sub-structure by vertical hydraulic transport of mud and fines. It can also offer important advantages from the point of view of long-term deterioration of the sub-grade.

- *Durability.* The bituminous sub-ballast provides a more rigid foundation, reducing the tension and shearing stress inside the ballast material, with consequently less fatigue and less degradation and wear of the individual aggregate particles.

- *Noise and vibrations.* The mechanical properties of the asphalt material will lead to a reduction in the vibrations and noise produced by passing trains. The use of modified asphalt (polymer modified bitumen, crumb rubber) can further improve the vibration dampening effect of the sub-ballast (Teixeira et al., 2005; Xiangwu, 2005).

- *E*nvironmental benefits. It uses less granular material, allowing material savings of 40% compared to solutions that incorporate cement binders (Buonanno et al., 2000).

- *Less thickness of the layer.*

- *Economic benefits.*

Despite these advantages, the application of hot-mix asphalt can lead to an important increase in construction costs, pollution and energy consumption. Thus, the major disadvantages come from a sustainable point of view, since the production of hot-mix asphalt (HMA) emits pollutant gases and consumes fuel or gas during the manufacturing process. These effects are primarily due to the drying and heating of mineral aggregates and bitumen at temperatures of approximately 160 °C or higher. Thus, in this context, the use of sustainable manufacturing technologies play an important role, particularly those that are capable of consuming less energy than those used in the production of traditional HMA whilst maintaining the in-service mechanical performance of the material.

2.4. SUSTAINABLE BITUMINOUS ASPHALT MIXTURES

2.4.1. INTRODUCTION

Worldwide, the Kyoto Protocol provides the guidelines to follow for the reduction of carbon dioxide (CO_2) and other so-called greenhouse gases. It was adopted by a consensus of the third session of the United Nations Framework Convention on Climatic Change. The Kyoto Protocol is designed to arrest greenhouse gas concentrations that some believe cause global warming.

In the construction sector, sustainability has become one of the major priorities in order to manage dwindling natural resources while at the same time develop new techniques.

Nowadays, in road construction, there are several types of asphalt innovations in favour of sustainability, through methods that minimize energy consumption and encourage recycling of materials or by designs that improve storm-water management.

- Warm mix asphalt: This is able to reduce the viscosity of the binder as well as the mixing and compaction temperatures by 20–40 °C, through the use of organic additives, chemical additives, and water-based or water-containing foaming processes (You et al., 2008; Zaumanis, 2010; Rubio-Gámez et al., 2012).

- Asphalt Reuse/Recycling: This is the part of paving material removed containing bitumen and aggregates. These materials are generated as a result of activities such as reconstruction or resurfacing of the road surface. It is a useful alternative to virgin materials; in fact, it is used to replace mineral aggregates and bitumen in the production of asphalt pavement. The percentage of RAP included in an asphalt mix depends on several factors. Specifications vary in terms of the amount of RAP allowed and the particular pavement application (Pavement Recycling Executive Summary and Report, 1995; Zaumanis et al., 2015).

- Perpetual Pavement: This is a type of pavement designed not to fail, thereby improving its service life. The construction is carried out in successive layers of asphalt pavements that present an adequate level of flexibility and rigidity to avoid cracking and rutting. Perpetual pavements also prevent the inconvenience and environmental impacts of frequent resurfacing. Surface distresses may occur eventually, but they do not penetrate deep into the pavement's structure. Figure 49 shows a typical configuration of perpetual pavement (Perpetual Bituminous Pavements, 2001).

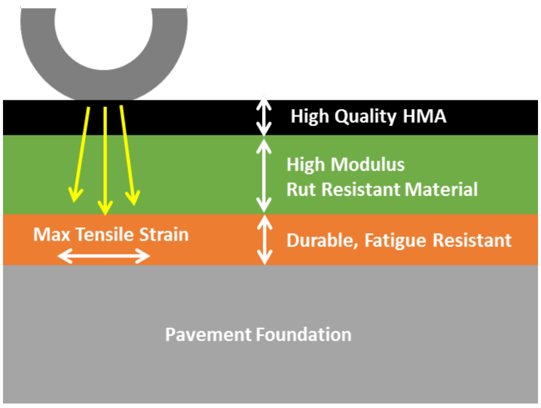

Figure 49. typical configuration of perpetual pavement (Perpetual Bituminous Pavements, 2001).

- Pavement Aggregate Substitutes: Over 95% of the weight of the materials in a bituminous mix comes from aggregates. The asphalt industry annually consumes vast quantities of such materials. This amount is roughly 12,500 tons/km (Zoorob et al., 2000). Since quarries are the source of most aggregate, this has a very negative impact on the environment, and results in important economic and energy losses. To improve this state of affairs as well as to promote sustainability, recycling applications have begun to appear in this sector. Examples of waste materials that have been used in asphalt mixtures are among others: Rubber from old tyres, glass blast furnace slag, steel slag, phosphor slag, bottom ash from incineration of municipal waste, fly ashes from coal powered electricity plants, and plastics. The reuse of local materials derived from industrial waste for road construction is a practice that can bring many economic and environmental benefits.

Warm mix asphalt (WMA) is a technology that is becoming even more used in road construction. This solution could be an appropriate alternative solution through which decreasing the temperature of mixing and paving, lower fume and odour emissions are obtained to create cooler working conditions for the asphalt workers. As a rule of thumb, the release of fume is reduced by around 50% for each 12 °C reduction in temperature (Brandt et al., 1999; Rubio-Gámez et al., 2012). It has also been shown that the performance of these mixtures can be at least equivalent to the performance offered by traditional mixtures. In addition, the concept of sustainable development embraces reduced consumption of raw materials, reduced emissions, and the possibility of increased recycling while still meeting development needs. In this way, the use of crumb rubber from scrap tires, and also the use of reclaimed asphalt pavement (RAP) in bituminous mixes, are sustainable alternatives to improve mix performance whilst at the same time allowing the valorisation of waste products that developed countries generate in vast quantities.

For these reasons, warm mixes asphalt, rubberized asphalt and reclaimed asphalt pavement, also offer great potential for their application as bituminous sub-ballast in railway tracks

2.4.2. WARM MIX ASPHALT (WMA)

In the sector of road pavements, more sustainable bituminous mixtures are required by lowering the manufacturing temperature, but without impoverishing their mechanical performance.
WMA technologies tend to reduce the viscosity of the asphalt and provide complete aggregate coating at lower temperatures. It is produced at temperatures around 20 to 40 °C lower than typical hot-mix asphalt (HMA).

2.4.2.1. TECHNIQUES

Some of the WMA technologies involve a temporary or permanent adjustment of various bitumen properties, such as viscosity, for instance. In a number of technologies, the adhesion between binder and aggregate particles is chemically adjusted to improve the way mineral aggregates are coated by bitumen. When surfactants are also included they will act at the microscopic interface of aggregates and bitumen, reducing friction at that interface, allowing for lower mixing and compaction temperatures. There are also techniques that introduce water into the process with the aim of temporarily improving the workability of the asphalt mixture.

Despite the huge number of reported WMA technologies found in the literature, these can essentially be classified into three main groups (Zaumanis, M., 2010; EAPA, 2010; Rubio-Gámez et al., 2012):

- Organic additives;
- Chemical additives;
- Foaming techniques.

Organic additives

Different organic additives can be used to lower the viscosity of the binder (bitumen) at temperatures above 90 °C. The organic additives, usually waxes or fatty amides, can be added either to the mixture or to the bitumen. When the temperature rises above the melting point of the waxes, there is usually a decrease in viscosity (Zaumanis, M., 2010; EAPA, 2010; Rubio-Gámez et al., 2012). As the mixture cools, these additives solidify into microscopically small and uniformly distributed particles, which increase the stiffness of the binder in the same way as fibre-reinforced materials.

Organic additives typically offer a temperature reduction of between 20 and 30 °C whilst they also improve the deformation resistance of asphalt modified.

Chemical additives

Different types of chemical additives are reported in the literature within WMA technology. In a few cases, additives are formed by a package of products such as emulsification agents, surfactants, polymers, and additives to improve coating, mixture workability, and compaction, as well as adhesion promoters (antistripping agents). Chemical additives are usually added to the binder during the production process, although there are also techniques in which the package of products is used by means of a bituminous emulsion (Button et al., 2007; Zaumanis, 2010).

Chemical additives do not change the bitumen viscosity. As surfactants, they work at the microscopic interface of the aggregates and the bitumen. They regulate and reduce the frictional forces at that interface at a range of temperatures, typically between 85 and 140 °C. It is therefore possible to mix the bitumen and aggregates and to compact the mixture at a lower temperature. The quantity of additives needed and the temperature reduction achieved by this technology depend on the product used but usually they may reduce the mix and compaction temperatures around 20–40 °C.

Foaming techniques

A range of foaming techniques is applied to reduce the viscosity of bitumen. Some of them are employed to introduce small amounts of water into the hot bitumen. The water turns to steam, increases the volume of the bitumen, and reduces its viscosity for a short period. The expansion of the bitumen allows the coating of the aggregates at lower temperatures and the residual moisture supports the compaction of the asphalt on the construction site. Production and paving temperatures can be reduced in parallel.

The amount of expansion depends on a number of factors, including the amount of water added and the temperature of the binder (Jenkins et al., 2000).

Two techniques are commonly used for foaming:

- injection foaming nozzles;
- minerals.

The direct method of foaming is to inject a small controlled amount of water to hot bitumen via a foaming nozzle. This results in a large but temporary increase in the effective volume of the binder, which facilitates coating at lower temperatures. Some vapour remains in the bitumen during compaction reducing effective viscosity and facilitating compaction. On cooling, the binder reverts to normal, as the amount of water is insignificant.

This technique can enable a temperature reduction of the asphalt mix of around 20 to 40 °C. Figure 50 shows examples of foaming nozzles.

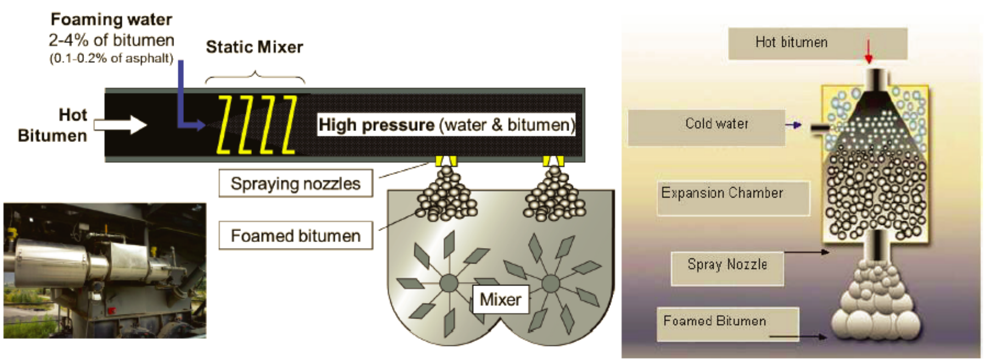

Figure 50. Foaming nozzle (Jenkins et al., 2000).

An indirect foaming technique uses a mineral as the source of foaming water. Hydrophilic minerals from the zeolite family are commonly used. Zeolite is a crystalline hydrated aluminium silicate that contains around 20 per cent of crystalline water, which is released above 100 °C. This release of water creates a controlled foaming effect, which can provide an improved workability for a 6 to 7 hour period, or until the temperature drops below 100 °C.
In this instance, the foaming results in an improved workability of the mix which can subsequently allow a decrease in the mix temperature by approximately 30 °C with equivalent compaction performance.

A second indirect foaming technique uses the moisture on the sand (or RAP) to generate naturally created foam. It is a sequential technique. The coarse aggregate, which represents around 80% of the mix design, is dried/heated to 130–160 °C, it is then coated by the bitumen and thereby creates a thick binder film on the coarse particles. The next stage involves the addition of the cold/wet fraction. The moisture in contact with the hot bitumen causes foaming, which facilitates easy coating of the cold and wet RAP or fine aggregate.
This technique enables the same temperature reduction as the direct foaming through nozzles, around 20 to 40 °C.

Next to the above-mentioned techniques there are also combined products that can be used to produce Warm Mix Asphalt, such as pallets with fibres and zeolite or fibres with organic additives.
As one can see, the gain in temperature reduction is between 20 and 40 °C (more or less) independent from the technique used. One has to keep in mind that this gain also depends on the paving grade of the bitumen used.

2.4.2.2. BENEFITS AND DRAWBACKS OF WMA

Taking into account the lower temperatures applied in WMA technologies, a number of benefits can be expected. Fewer emissions, lower fuel consumption, longer haul distances, and better working conditions are the most significant advantages mentioned. However, because of the relative novelty of these technologies, various concerns have not yet been resolved and need to be further studied.

Benefits

First of all, this technology can create cooler working conditions for the asphalt workers. The release of fume is reduced by around 50% for each 12 °C reduction in temperature. Therefore, a temperature reduction of 25 °C can lead to fume emission reduction of around 75% (Figure 51). This reduction in emissions of fume and odour also minimises inconvenience to the public near work sites.

Figure 51. The fumes noted during the laying of HMA and WMA mixtures.

A significant reduction in pollutant and GHG emissions has been reported. Depending on the WMA technology used, emissions declared in the literature have some variation. Nevertheless, irrespective of the WMA production process, a significant reduction of emissions is observed. European countries (D'Angelo, 2008; EAPA, 2010), for instance, have made clear the decrease in various emissions throughout the production process in plant, as follows: 30–40% for CO_2 (carbon dioxide) and SO_2 (sulfur dioxide), 50% for VOC (volatile organic compounds), 10–30% for CO (carbon monoxide), 60–70% for NOx (nitrous oxides), and 25–55% for dust.

Reductions from 30% to 50% for asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) have also been reported, which have a substantial influence on the exposure of the workers and the surrounding area of construction sites to those products.

Another important benefit is the potentially greater use of Reclaimed Asphalt Pavement (RAP). Because of the increased workability of WMA mixes, it can contain a higher percentage of Reclaimed Asphalt Pavement (RAP) (Bonaquist, 2011). This improved workability leads to a lower production temperature, with less ageing of the binder, thus counteracting the stiffer RAP binder. Certain studies even recorded RAP percentages of over 50% (D'Angelo et al., 2008). This is an interesting result since the properties of properly designed recycled asphalt concrete materials have been proven to be comparable to new asphalt concrete pavements.

Paving benefits are related to the fact that WMA technologies modify mix viscosity, which enhances the workability and compaction of the mix. Research data shows that these technologies act as compaction aids and reduce the compactive effort required (Al-Rawashdeh, 2008).

Still another benefit is the possibility of cold weather paving, stemming from the fact that mix temperature is closer to ambient temperature. This means that the drop-in mix heat is thus less dramatic. This proximity of temperatures extends the paving season since there is more time for paving and compacting. Because of this advantage, it is also feasible to haul longer distances. Furthermore, this reduced temperature difference makes road construction and road opening times shorter. This is especially desirable in certain contexts (e.g. airport rehabilitations, high traffic city roads, etc., see Vaitkus et al., 2009).

From an economic point of view, the benefits depend on the type of energy used in the production process, its cost, and pollution potential. The economical benefit from energy saving should be discussed together with the cost and type of energy used, since higher energy prices promise greater savings.
Yet again, the savings depend on the production technique as some WMA technologies require only initial investment for plant modification, some require continuous additional cost for the additives, and others require both forms of additional cost.
Economical benefits should be evaluated together with environmental benefits. If stricter emission standards are implemented, there may be higher economic potential for WMA. In this case the potential benefits may not be completely economically quantifiable and should be evaluated together with environmental regulations.

Drawbacks

Even though the lower temperatures in WMA are initially a very promising aspect of this technology, they are also a source of concern (Vaitkus et al., 2009) regarding the specifications and quality control. Potential drawbacks should be considered in context with the specific technology as different methods have particular defects, but to generalize, there are some concerns about the performance and implementation of WMA. They are listed below:

- *Rutting.* The lower temperature of manufacturing as well as moisture susceptibility of WMA mixes could cause premature rutting of the pavement surface due to less ageing of the binder. (Zaumanis, 2010).

- *Moisture susceptibility.* Foaming and some of the chemical WMA technologies are somewhat connected with the introduction of water in the initial mixing process. Because of possible incomplete vaporization of water during the mixing and laying process, residual water in the mixtures may cause problems of premature rutting and stripping of pavements. Therefore special attention must be paid to the evaluation of potential moisture damage in the laboratory. This is especially important with any foaming technologies, and although most of them use chemical antistripping additives to improve coating and adhesion, different initial material moisture content together with poor water resistant mix formula may cause some coating problems.

- *Cost.* The unfavourable cost of the asphalt using warm mix asphalt technology because of the additional additive price or asphalt plant modification

2.4.2.3. CONCLUSIONS

Warm-mix asphalt is an opportunity for the asphalt industry to improve its product performance, construction efficiency, and environmental stewardship. Studies have shown that the performance characteristics of WMA mixes can be at least equivalent to conventional mixes, and its application offers several benefits. However, it was also noted that the application of this technology is not exempt from certain drawbacks. In any case, it must be considered that the disadvantages mentioned above refer to the road sector and, at least from a theoretical point of view, in the railway sector, the temperatures are not sufficiently high to promote rutting, unless operated under conditions of totally extreme temperatures such as desert climates. Conversely, the temperatures are not sufficiently low to promote low temperature cracking and decreased fatigue life. The asphalt binder does not weather or harden excessively in the insulated trackbed environment, which would have further negative influence on cracking and fatigue life. Clearly, the tendency to strip/ravel is essentially eliminated in the trackbed environment since there is no rubber pressure action. In addition, the moisture contents of the underlying subgrade/roadbed support materials are maintained at or near optimum for maximum density and support strength. Is possible to conclude that warm-mix asphalt presents great potential for application as bituminous sub-ballast in railway tracks.

2.4.3. RUBBERIZED ASPHALT

2.4.3.1. INTRODUCTION

End of life tyres are among the largest and most problematic sources of waste, due to the large volume produced, their durability, and the fact they contain a number of components that are ecologically problematic. Nonetheless, the same characteristics that make waste tires problematic, their availability, bulk, and resilience, also make them attractive targets for recycling. Thus, material recovered from waste tires, known as "crumb rubber", is being used in new tyres, in tyre-derived fuel, in moulded rubber products, in agricultural uses, and in recreational and sports applications.

In this regard, end-of-life tires, have found great use in diverse applications in civil engineering (Moreno et al., 2011; Corinaldesi et al., 2011; Sol-Sánchez, 2014), particularly in the road and rail sector. For example, they constitute one of the most successful elastic wastes in railway pad manufacturing (Sol-Sánchez, 2014), and are suitable in bituminous mixes, as a modifier of their mechanical properties.

For this reason, this section of this doctoral thesis presents a brief description about the problem of using end-of-life-tyres, as well as their properties and their applications in bituminous mixtures in the railway sector.

2.4.3.2. END-OF-LIFE-TIRES, FROM ENVIRONMENTAL PROBLEM TO ENGINEERING RESOURCE

Both in industrialized and developing countries, the increasing number of vehicles generates millions of used tires every year. It is estimated that worldwide, every year, around 1.5 billion tires are sold and subsequently, at the end of their useful life, fall into the category of end of life tyres (ELTs) (Figure 52) (ETRMA ELTs, 2015). Over the last 18 years, recovery rates for ELT have dramatically increased in Europe, Japan, Korea and the US. At the same time, the cost of recycling to the consumer has decreased due to both increased efficiency in management structures and new recovery routes.

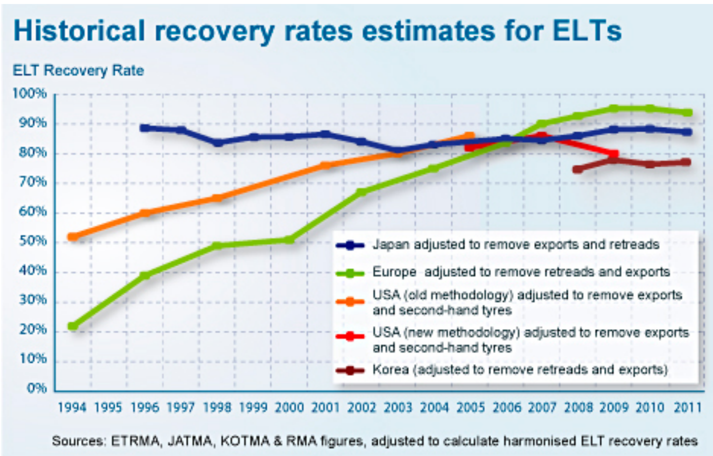

Figure 52. Evolution of ELTs recovery rates in major tyre markets, adapted from (ETRMA ELTs, 2015).

To be more specific in Europe 355 million tires are produced each year, a number that represents around 24% of world production. In addition, a serious problem is that the EU has millions of used tyres that have been illegally dumped or stockpiled. It is estimated that 2 to 3 billion scrap tires are stockpiled illegally or abandoned.

Most countries, both in Europe and worldwide, have relied on land filling to dispose of used tyres, but the limited space and their potential for reuse has led to many countries imposing a ban on this practice. The current estimate for these historic stockpiles throughout the EU stands at 5.5 million tonnes (1.73 times the 2009 annual used tyres and rising) and the estimated annual cost for the management of ELTs is estimated at € 600 million (ETRMA ELTs, 2015). With landfills minimising their acceptance of whole tyres and the health and environmental risks of stockpiling tyres, many new markets have been created for scrap tyres. Production in Europe was set up under the strategic guidance of the European Tyre and Rubber Manufacturers Association (ETRMA).

Recovery rates demonstrate that ELT management in Europe is allowing the progressive elimination of land filling and raises the availability of Recycled Tyre Rubber to be recycled for other purposes. In fact, the same characteristics that make waste tyres such a problem also make them one of the most re-used waste materials, as Recycled Tyre Rubber is very resilient and can be reutilised in other products. One of the most effective recycling options for scrap tires is their use (in the form of ground-crumb rubber) in hot mix asphalt pavements (EPA, 2010). Literature has shown that rubberized asphalt increases resistance against aging, reflective cracking, stripping and rutting. Moreover, rubberized asphalt typically creates more flexible and durable pavement (Fontes et al., 2006).

2.4.3.3. FROM END-OF-LIFE TYRES TO CRUMB RUBBER MODIFIER

From the material point of view, the tyre is made up of four main components: (i) rubber, (ii) carbon black, (iii) metal and (iv) steel. The remaining materials are additives, which facilitate compounding and vulcanisation. Table 4 is a summarised version of general tyre composition in cars and truck tyres in the EU (Shulman, 2000).

Material	Car	Truck
Rubber/Elastomers	48%	45%
Carbon Black	22%	22%
Metal	15%	25%
Textile	5%	-
Zinc oxide	1%	2%
Sulphur	1%	1%
Additives	8%	5%

Table 4. Comparison of passenger car and truck tyres in the EV (Rahman, 2004).

In general, tyres are composed of natural and synthetic rubber. The proportion varies according to the size and use of the tyre. The generally accepted rule of thumb is that the larger the tyre and the more rugged its intended use, the greater will be the ratio of natural to synthetic rubber. Engineering process is necessary to transform natural rubber into a product that is able to ensure performance, durability and safety. In fact, natural rubber is sticky in nature and can easily deform when heated up and it is brittle when cooled down. In this state, it cannot be used to make products with a good level of elasticity.

The second most important component of a tyre is carbon black. This is not a generic product, which means that wide ranges of specific grades of carbon black are used depending upon the compounding formula used by the individual manufacturer. Carbon black is mainly used to enhance rigidity in tyre treads to improve traction, control abrasion and reduce aquaplaning; and in sidewalls to add flexibility and to reduce heat build-up (HBU) (Shulman, 2000). The particle size of the carbon black, as defined by its specific surface area and structure, impacts upon its integration and utilisation in compounding.

The third largest component is steel, mainly high grade steel. This provides rigidity and strength as well as flexibility to the casing. New, higher strength metals are being tested by tyre manufacturers, some of which are said to resist rusting as well as deterioration, which could impact upon the way that the tyre is recycled.

The most common traditional textiles used in rubber are nylon, rayon and polyester. In recent years, a range of new textiles, primarily aramid, which is an ultra-light weight material, have been substituted for more traditional materials, primarily in the more expensive tyres.

Figure 53 shows a simplified version of the life cycle of the tire. This can be summarized in five steps: Extraction, consumption, collection, landfilling, and recovery.

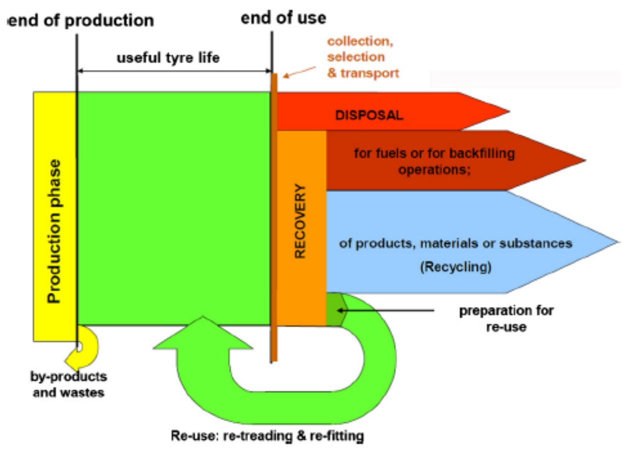

Figure 53. Life cycle of end of life tires (Rimondi, 2009).

The process of recovery includes different options:

- Energy recovery, where the end-life-tires are used as an alternative to fossil fuels since they have a calorific value equivalent to that of good quality coal;

- Chemical process, such as pyrolysis, thermolysis and gasification, (the economic viability of these options has yet to be proved);

- Granulate recovery, which involves tyre shredding and chipping processes which is carried out by using large machinery that cuts up tyres into small pieces of different sizes (called Crumb Rubber Modifier). In this process, the steel is removed by magnet and the fibre is removed by aspiration. After this the crumb rubber can be used. The size may range from as large as 460 mm to as small as 25 mm, with most particles within the 100 mm to 200 mm range, while the tyre chips range from 76 mm down to approximately 13 mm. By further reducing the size of shreds and chips, it is possible to produce Ground and Crumb Rubber, also known as size-reduced rubber, which is suitable for re-use in the asphalt industry.

2.4.3.4. USE OF CRUMB RUBBER IN ASPHALT MATERIALS

There are two processes for incorporating crumb rubber into bituminous mixtures: wet process or dry process (Heitzman, 1992). In the wet process, the crumb rubber is added to hot Bitumen prior to mixing it with the aggregates, modifying its properties. It is then added to the mix as a modifier binder. In the dry process the particles of crumb rubber are added directly to the aggregates prior to the addition of the bitumen as though it was another type of aggregate, thus directly modifying the properties of the mix. The dry process is normally used only with hot bituminous mixtures, whereas the wet process has been applied in crack sealants, surface treatments, and hot bituminous mixtures.

.

Wet process

Asphalt rubber, "wet process", was developed by Charles McDonald in the 1960's and refers to the modification of bitumen with 5-25% by mass of fine tyre crumb at an elevated temperature. The wet process includes the blending of crumb rubber with bitumen at high temperatures and produces a viscous fluid through rubber bitumen interaction. This reaction depends on temperature, size and type of crumb rubber, and aromatic type of asphalt binder (Heitzman, 1992).

The mixing and laying temperatures are slightly higher due to increased bitumen viscosity. It should be noted that the blend of bitumen-rubber must be kept stirred or agitated to prevent stratification or separation of the crumb rubber modifier (Epps, 1994). The mixing temperatures range from 175-205 °C and the modified binder is then transferred to a heated reaction tank for 30-60 minutes at a temperature of 165-190 °C (Figure 54).

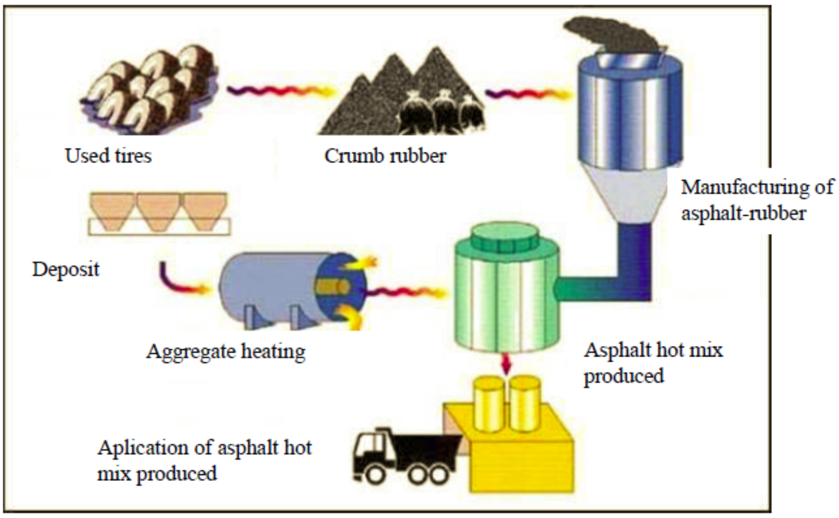

Figure 54. Steps of the wet process (Epps, 1994).

Dry process

This process was first developed in Sweden in the 1960s and is widely known in Europe under the name "Rubit". It was then patented in the USA under the name "PlusRide" in 1978 (Heitzman, 1992). Dry process is a process where rubber particles are added to pre-heated aggregates prior to binder mixing (Crockford, 1995). In this process, CR is added as a replacement for fine aggregate up to 5% of the total weight of the mixture.

Wet process can accommodate dense, gap, and open graded mix design. However, dry process offers the best performance with gap-graded mixes. Gap graded mixes do not only provide space for binder but also increase the resistance against fatigue cracking since more binder is introduced into the aggregate skeleton (Fontes et. al, 2006). Even though anti-oxidants are not completely mixed with binder, dry process provides good skid resistance and dicing properties. More crumb rubber particles are utilized in this process in comparison with the wet process (Figure 55).

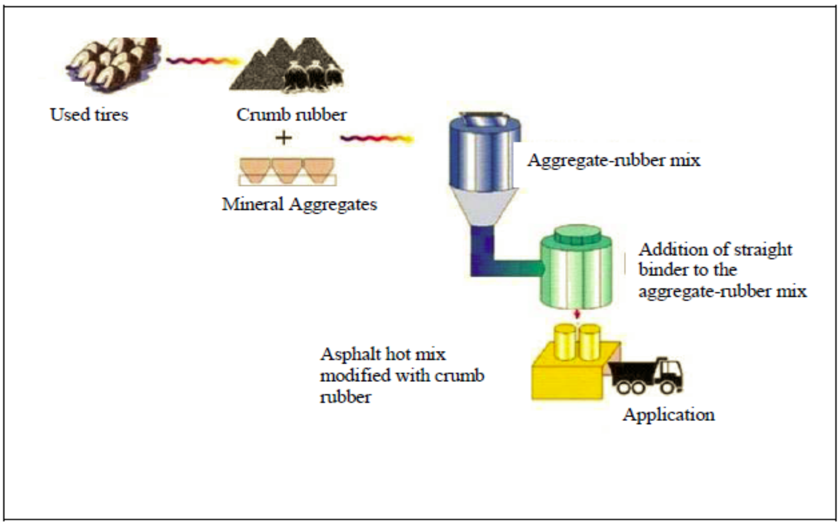

Figure 55. Steps of the dry process (Epps, 1994).

2.4.3.5. OTHER APPLICATIONS OF END-OF-LIFE-TIRES IN RAILWAY TRACK

In recent years, there have been several applications of crumb rubber (from end of life tyres) within the railway structure. Thanks to its capacity for deformation and attenuation of the loads and its ability to withstand external environmental agents, this material has been used in the construction and rehabilitation of both superstructure and infrastructure, covering various tasks such as providing the structure with greater elasticity, reducing problems related to vibration, or absorbing loads, among others.

Starting from the superstructure, crumb rubber was used as the elastic element to mitigate the loads and reduce the stiffness of the track slab. Figure 56 shows an embedded rail system in a mixture of crumb rubber and polymeric matrix resin. This system emphasizes its high level of vibration attenuation, an important parameter in urban road systems due to the presence of nearby buildings.

Figure 56. Embedded rail system (Sistema MLG).

Staying on the theme of development of elastic elements in the superstructure, crumb rubber has been used by various researchers to develop elastic elements such as rail pads, under sleeper pads, and under ballast mats (Carrascal, 2014; Sistema MLG; Sol-Sánchez et Al., 2014; Sol-Sánchez, 2014). Figure 57 shows elastic elements developed by Sol-Sanchez et al. (2014) for high-speed railway from the outer layer (tread layer) of deconstructed end-of-life tires (without grinding up the material), in order to improve track mechanical performance, reducing construction costs, as well as reducing landfill disposal. This application allows for reducing construction costs as well as reusing an abundant waste. Results indicate the ability of tire pads to manufacture elastic elements (rail pads, under sleeper pads and under ballast mats) to be used in high-speed tracks.

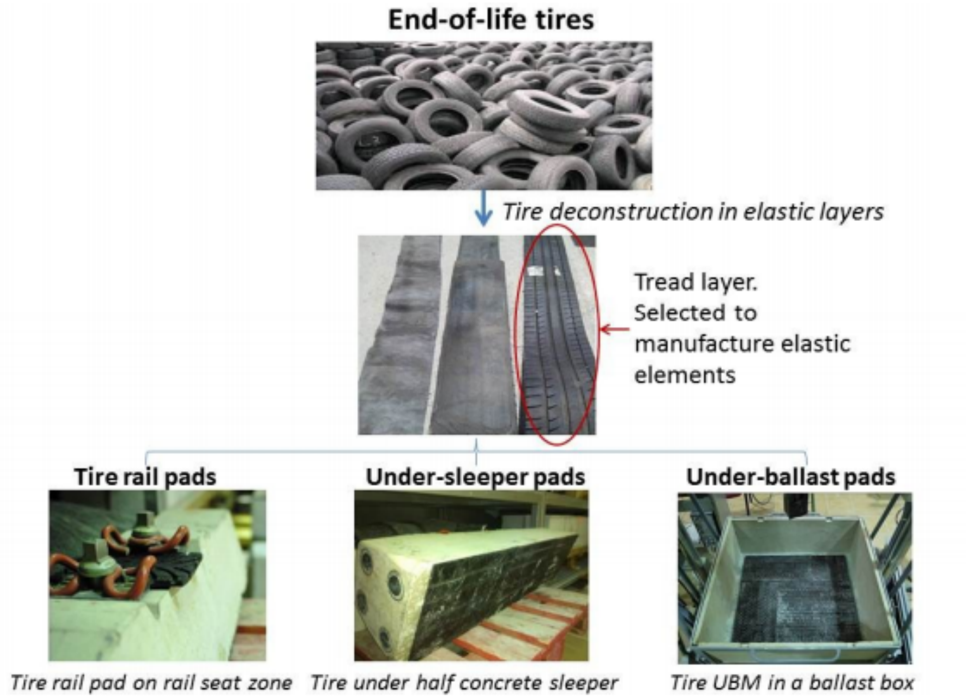

Figure 57. Elastic elements for railway high-speed from deconstructed end-of-life tires (without grinding up the material) (Sol-Sanchez et al., 2014).

Another elastic element under development comes from the RECYTRACK project, coordinated by ACCIONA Infrastructures. During this project, an elastomeric eco-friendly material made of end-of-life tires with resin for railway applications was developed. In detail, they are studying two types of mats: a "New Isolated Block System for slab track" (Figure 58 left) and an "Elastomeric mat for ballast conventional system and slab track" (Figure 58 right)". The overall objective of the project is to demonstrate the technical feasibility and environmental benefits of the implementation of an elastomeric eco-friendly material made of end-of-life tires with resin for railway applications.

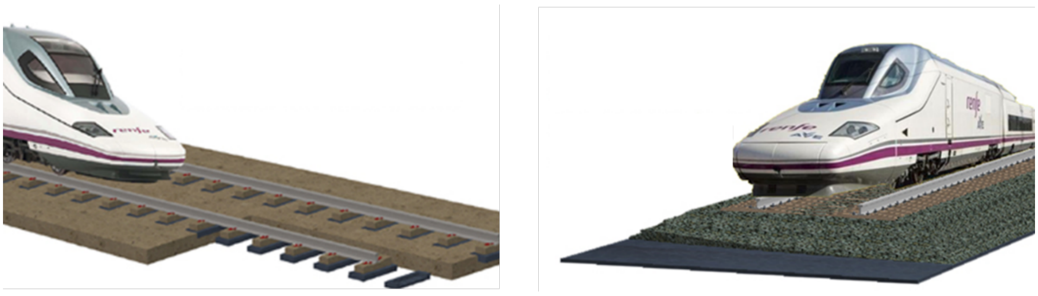

Figure 58. New Isolated Block System for slab track, left - Elastomeric mat for ballast conventional system and slab track, right.

A US company, TieTek LLC of Houston, Texas (Evans A. and Evans, R., 2006) has developed a railroad sleeper made of a rubber-plastic composite (Figure 59). They are composed of a mixture of plastics, rubber from whole end-life-tires, rubber buffings from retreaters, and other waste materials. They are lighter, impervious to insect and moisture damage, resistant to fungus, electrically non-conducive, resistant to chemical damage, and reduce the vibrations that can shorten the life span of other track materials. However, their size and weight are similar to wooden sleepers, so their use is limited to conventional track, since the high-speed lines require heavier sleepers to increase the stability of the track.

Figure 59. Railroad sleeper made of a rubber-plastic composite (Evans and Evans, 2006).

Another study of the superstructure concerns the ballast layer, with the aim of increasing the service life of the track (Sol Sanchez et al., 2015). The latter authors used crumb rubber as elastic aggregates mixed with ballast particles, which could reduce ballast degradation and consumption (Figure 60). Results show that the use of 10% of crumb rubber (by volume) could reduce ballast degradation whilst at the same time increasing the capacity of the ballast layer to dissipate energy and reducing its stiffness. Additionally, based on the present laboratory study, the track settlement could be reduced with 10% rubber particles used as elastic aggregates.

Figure 60. Visual appearance of the ballast and crumb rubber used as well as the mix of both materials (Sol Sanchez et al., 2015).

Stjepan Lakušić et al. (2011), from the Faculty of Civil Engineering at the University of Zagreb developed a new approach for forming the absorbing layer. Instead of using natural resources, whose usage degrades the environment and natural balance, it incorporates rubber granules - a product of end-of-life tyre recycling (Rubberized Concrete Noise Barriers or RUCONBAR). Namely, concrete can incorporate rubber granules from recycled tyres to form a porous noise-absorptive layer. The functionality aspect clearly demonstrates that RUCONBAR rubber concrete, expanded clay concrete, and wood fibre concrete can be considered equal in terms of functionality (Figure 61). They share similar acoustic properties, the same durability and maintenance requirements, and excellent static stability.

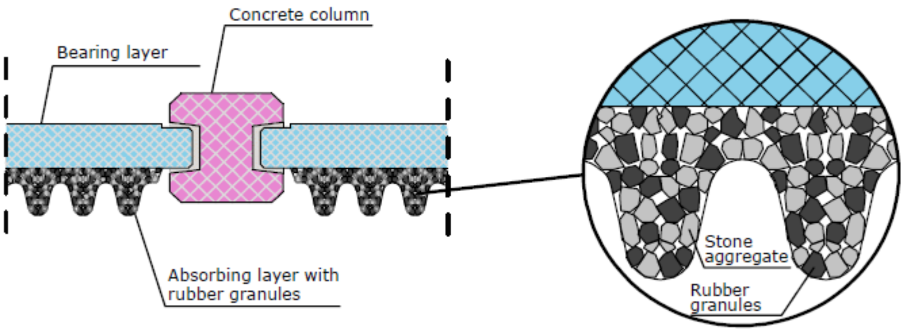

Figure 61. Rubberized Concrete Noise Barriers or RUCONBAR (Lakušić et al., 2011).

In the infrastructure, the crumb rubber was also used for bituminous sub-ballast by different authors that have found that this solution could improve the behaviour of the track in terms of bearing capacity, permeability, and vibrations, among others (See the previous section *"Bituminous sub-ballast"*).

2.4.3.6. CONCLUSIONS

In an attempt to address the problem of the disposal of used tires, during recent years there have been several applications in civil engineering, especially in the road and rail sector. In this context, in the rail sector, different studies have been carried out in order to assess the feasibility of using a new hot mix asphalt (HMA), containing crumb rubber as sub-ballast layer in railway track.
In particular, the majority of the studies assess the capacity of this material in vibration damping of the dynamic loading and noise due to the transit of the trains, since previous studies and field measurements on highways have shown that rubber-modified asphalt can significantly reduce noise pollution.
The results obtained and the comparison with conventional bituminous sub-ballast has shown that this new bituminous mixture could be particularly effective in damping vibrations and noise.
As shown previously, other studies have been carried out in terms of moisture susceptibility, fatigue cracking, stiffness etc. but they have not been investigated in enough detail, and there is a need for further research, especially in terms of permanent deformation, bearing capacity and permeability under more realistic load conditions and taking into account both standard temperatures of service and adverse climate conditions that are expected in railway tracks.

2.4.4. RECLAIMED ASPHALT PAVEMENT (RAP)

2.4.4.1. INTRODUCTION

Asphalt pavements, in the road construction sector, are manufactured by the use of natural resources such as aggregates and binders. However, given that these resources are limited, the recycling of asphalt after the service-life is important for sustainable development. In some cases, the asphalt pavements fail prematurely due to heavy traffic loads and environmental conditions that have not been taken into account during the design phase (Martinez-Echevarria, 2012). Therefore, the overlap or replacement of the asphalt pavements becomes a necessity. However, the problem of overlapping a pavement (a process in which a new layer is added on top of the existing one) is that with time, the new pavement tends to take the shape of the old damaged pavement (Figure 62).

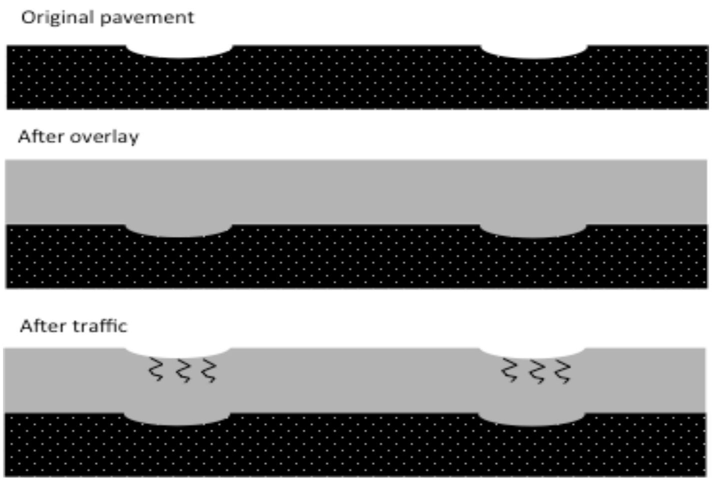

Figure 62. Overlaying over Distressed Asphalt Pavement (Brock and Richmond, 2006).

Thus, the best solution is to remove the old pavement surface through milling (Okafor, 2010).

From here, the possibilities are to dump the removed material, or evaluate the possibility of reusing them as new construction materials.

In this regard, in recent years RAP (Recycled asphalt pavement) has passed from being considered an environmental problem to an important engineering resource for producing new asphalt. RAP in hot mix asphalt has been shown to have the same quality as hot mix asphalt without RAP in terms of rutting, ravelling, and weathering and fatigue cracking. This recycled pavement has also been shown to age slower and is more resistant to water than normal hot mix asphalt.

However, the production of HMA requires a high level of energy consumption that inevitably leads to a high level of greenhouse gases emissions. Therefore, in this context it is particularly interesting to study the possibility of lowering the temperature of manufacturing of a mixture produced with high levels of reclaimed asphalt pavement.

The temperature reduction in turn reduces emissions, energy consumption, extends paving seasons, and improves workability at lower temperatures. There are several new techniques that are becoming increasingly frequent to replace the hot mix asphalt, such as, for example half warm mix techniques (HWMA), where the mixing temperatures are below 100 °C.

This section of this doctoral thesis presents a brief description of the Recycled asphalt pavements, about their properties, and their applications in bituminous mixtures.

2.4.4.2. RAP SOURCE

The reclaimed asphalt pavements (RAP) can be obtained from several sources (Copeland, 2011) such as:

- Milling operations;

- Full-depth pavement demolition;
- Asphalt plant waste.

- *Milling operation* (also known as cold planing), is the most commonly used method to obtain RAP (Figure 63). There are several advantages of milling, including the following:

  • Removes distressed pavement layers,

  • Maintains clearances under bridges and avoids build-up of pavement weight on bridge decks,

  • Avoids filling up curbs and avoids drop-offs at drainage inlets and pavement edges,

  • Restores pavement grades and profiles, which are important for smoothness,

  • Leaves a rough texture on the remaining surface that creates a very good bond with an overlay, and

  • Is an efficient removal process that can be done within a short lane closure with the paving operations.

Figure 63. Milling machine removes asphalt pavement layers as part of pavement rehabilitation.

Key in the milling process is the selection of the milling depth. Often the milling depth selection is based on visual examinations of cores to detect the depth of surface cracks and/or the location of weak layers or interfaces. Cores should be taken in areas where the pavement is distressed and not distressed with at least one core every lane mile on highways and one per lane per block on city streets. The cores should be carefully inspected for crack depths, weak interfaces, and layers damaged by stripping. The milling processes must be carefully examined to ensure that the milled material is not contaminated with soil, base, geotextiles or other debris. Milled materials that become contaminated should be used only as shoulder material and should be stockpiled separately from RAP to be used in asphalt mix. A recommended maximum limit of 1% deleterious material should be used to evaluate RAP contamination.

- *Full-depth pavement demolition;* Pavement Demolition RAP may also be obtained from complete demolition of an existing pavement using a bulldozer or backhoe (Figure 64). This process is typically limited to small areas of pavement. It is slow and results in large chunks of pavement that may be more challenging to process into a useable recycled material. When pavement rubble is contaminated with underlying layers and soil, it is better for this material to be crushed and used as a shoulder or base material than used in an asphalt mixture.

Figure 64. Full-depth pavement demolition.

- *Asphalt plant waste* (Figure 65). All asphalt plant operations generate some waste during plant start-up, transition between mixes, and clean-out. Generally, start-up and shut-down plant wastes have very low asphalt contents. Another form of waste is the mix rejected from a project due to incomplete coating or due to the mix temperature being too high or too low for the job. Other situations that may result in wasted mix include trucks loaded with too much mix to finish the job or mix that could not be placed due to inclement weather. These waste materials are often stockpiled for later processing into a recyclable material. Since these waste mixes have not been subjected to environmental aging from years of service, the asphalt binder is less aged than RAP recovered from a road. Waste materials also have fewer fines than other sources of RAP since they was not milled or broken up during demolition. However, waste materials must be thoroughly mixed and processed to make them into uniform, recyclable materials.

Figure 65. Asphalt plant waste.

2.4.4.3. RECYCLING OF ASPHALT PAVEMENTS

The recycling processes can be divided into two major methods: hot or cold techniques. These can be further sub-divided into central plant or in-situ recycling.

- *Hot recycling* is a process for rehabilitating the surface of the distressed asphalt pavement by softening the existing surface through a source of heat, after which the surface is removed through a mechanical removal, is mixed with a modifier agent, adding new asphalt or aggregate if required, and replacing it on the pavement (Button and Estakhri, 1994). The in-plant process usually uses a quantity of recycled pavement up to 30% from any layer. For hot in-place recycling, the process normally treats existing pavement to a depth of about 25 – 50 mm, but can be up to 80 mm. The hot in-place recycling process is suitable for highways with slight to moderate non-structural surface distresses.

- *Cold recycling* is a process that allows for combining without heating the existing pavement, stabilising agents, and virgin aggregates (if required) to produce new asphalt that is expected to satisfy the specification for its use. Cold recycled materials are most commonly used for road base although they can also be employed as subbase and surface courses (Epps, 1990). In cold plant recycling, the new binder consists of bitumen emulsion. In most cases, water is added and in some cases 10-20% aggregate. Different variants of the mixing procedure have been developed in order for the asphalt to be as homogeneous as possible and for the particles to have a good degree of coating. This process generally uses 100% Reclaimed Asphalt Pavement (RAP) mixed with a new binder which may be either emulsion or foamed asphalt cement. The cold nature of the process reduces the impact on the environment and preserves energy due to the absence of heat application (Martinez-Echevarria, 2012).

2.4.4.4. STABILISING AGENTS

Nowadays, stabilising agents are used in pavement construction worldwide to overcome the shortage of natural resources. By adding a small amount of stabilising agent at a relatively low cost, the required strength can be obtained from a local marginal material (Williams, 1986). Stabilising agents are often able to improve durability as well as the water resistance of the pavement (Mallick et al., 2002; Tarefder et al., 2005). Similarly, stabilising agent can be utilised to improve the materials recovered from existing pavements. Therefore, in many cases there is no need to import new materials to produce stronger layers in the rehabilitated pavement structure.

Stabilisation agent can be divided into two groups – chemical, and bituminous (Kearnet and Huffman, 1999). Chemical stabilisation uses additives such as Portland cement, fly ash or hydrated lime as stabilising agents. In the case of bituminous stabilisation, foam bitumen and asphalt emulsion are usually used.

A wide range of stabilising agents is available with different advantages and disadvantages. However, all stabilising agents have the same objectives of binding material particles together and increasing strength and/or improving durability.

Cement, lime, and a combination of these materials with fly ash, ground granulated blast furnace slag and other such materials are the most common cementitious stabilised materials.

Regarding bituminous stabilising, this can be applied in the form of emulsion or foam. Bitumen emulsion is sprayed into the mixing chamber where it is blended with the milled materials. An emulsion stabilised base course is flexible, fatigue resistant, and not likely to crack (Mallick et al., 2002). When in-place moisture content is high, addition of asphalt emulsion can increase moisture content above optimum resulting in reduced layer strength (Kearnet and Huffman, 1999).

Foamed bitumen is produced by injecting air and water droplets under high pressure (5 bar) into hot (160 – 180 °C) liquid bitumen, resulting in bitumen taking the form of foam.

Bituminous and cementitious stabilising agent can be also used together in order to be more effective (Tarefder et al., 2005; Mallick et al., 2002).

Although adding a small percentage of cementitious agent results in being more expensive, the use of both the agents presents several benefits. It can improve the adhesion between bitumen and aggregate as well as the strength of the RAP (Cross and Fager, 1995), and it also improves the resistance to deformation, rutting and moisture (Cross and Fager, 1995; Mallick et al., 2002; Tarefder et al., 2005).

Table 5 summarizes the advantages and disadvantages of the three most commonly used stabilising agents.

Cement	
Advantages	Disadvantages
• Cheaper then bitumen; • Available; • Cab be spread by hand; • Improves strength; • Improves resistance to water damage-	• Increase in rigidity but decrease in fatigue resistance; • Requires curing time.
Bitumen emulsion	
Advantages	Disadvantages
• Increases the fatigue characteristic; • Can be applied through a special spray bar after coupling the bulk tanker; • Well known in the construction sector.	• Is not normally produced on site; • Moisture content of material in existing pavement is sometimes too high and becomes saturated when emulsion is added; • Curing can take a long time.
Foamed bitumen	
Advantages	Disadvantages
• Can be applied through a special spray bar after coupling the bulk tanker; • Good resistance to fatigue; • Construction cost can be reduced since foamed bitumen allows reuse of waste; • Binder can be applied in relatively low amounts	• Requires heating of the bitumen and safety precautions; • The quality of the stabilised material depends on the foaming characteristic, which depends on the quality of the bitumen; • Saturated material cannot be treated with foamed bitumen.

Table 5. Advantages and disadvantages of three types of stabilising agent (Jitareekul, 2009).

2.4.4.5. LIMITATIONS OF HIGH CONTENT RECLAIMED ASPHALT PAVEMENT

When talking about RAP, there are many questions to which many studies have tried or still trying to answer. How can the addition of RAP affect the performance of the asphalt mix? But particularly, what is the optimal amount of RAP to be used? RAP is essentially aged asphalt mix, which is stiffer and less ductile, giving the combined mix more strength but less flexibility, which may cause cracks to appear quicker than when using a conventional mix.

Depending on the countries and type of RAP, high RAP content can be considered for wearing courses, these mixtures containing a quantity of RAP more than 30% by weight (Austroads, 2015).

Generally, the main limitations of a high RAP content mix design are (Newcomb et al. 2007, Howard et al. 2009, Copeland 2011):

- The properties of the aged binder;

- The degree of blending and diffusion that occurs between the virgin and RAP binder and;
- The RAP aggregate properties.

- *RAP BINDER PROPERTIES.* In general, the asphalt is subject to two phases of aging: short and long term.

  Short-term aging occurs during the construction phase, where the binder is exposed to very high temperatures (150-165 °C) with a consequent increase in viscosity and consequent change of its rheological and physiochemical properties.

  Long-term aging occurs during service, where asphalt binder also progressively ages and hardens through various mechanisms.

  Aging during the construction and service phases was associated with six main mechanisms (Roberts et al. 1996; Karlsson and Isacsson 2006):

- Oxidation through diffusive reaction between the binder and oxygen in the air;
- Volatilization through evaporation of the lighter components, especially during construction;
- Polymerization through chemical reaction of molecular components;
- Thixotropy due to the formation of a structure within the asphalt binder over a long period of time;
- Syneresis due to the exudation of thin oily components; and
- Separation through the removal of oily constituents, resins, and asphaltenes by absorptive aggregates.

The level of aging of the binder also depends on the voids content in the mixture) and by the level of damage to the recycled pavement (Smiljanic et al., 1993).

The properties of aged binder are also affected by the level of moisture damage on the existing pavement prior to recycling. In principle, stripped HMA should not be recycled due to the probability of reoccurrence of this distress in the new HMA (Karlsson and Isacsson, 2006). However, when a small percentage of RAP is used (15 to 20%) together with an anti-strip agent, samples with moisture-damaged HMA provided a comparable strength and moisture resistance to samples made with virgin materials (Amirkhanian and Williams, 1993). Other researchers have reported that RAP materials might in fact provide stronger moisture resistance than virgin HMA since the aggregates are already covered and protected with binder (Karlsson and Isacsson, 2006).

- *BITUMEN BLENDING AND DIFFUSION.* In the production process, during the short mixing time, the aged asphalt reaches necessary viscosity, blends with binder, and mobilises so that RAP and virgin aggregates receive a homogeneous film thickness. At the same time, to restore its properties to the required level, there must be sufficient diffusion of the added binder into the aged asphalt (Zaumanis and Mallick, 2013).

The blending and diffusion between the RAP and neat binder depends on several factors such as source, production temperature, mixing time, storage and transportation time as well as plant type (Bennert and Dongre, 2010; Mogawer et al., 2011). Moreover, inaccurate assumption of blending can create problems both in mix design and in pavement performance.

- *RAP AGGREGATE QUALITY.* The basic principle for ensuring good performing high RAP asphalt pavement is to apply the same requirements to the RAP fractions as those that are specified for virgin aggregates (Willis et al., 2012). This may potentially limit the amount of RAP, especially because of the fines content (Newcomb et al., 2007). Excessive fines can be generated by milling and crushing operations and may not allow to meet the aggregate size distribution requirements, dust to binder ratio, air voids and voids in mineral aggregate (VMA) (Copeland, 2011). The inhomogeneity of RAP has been reported as a problem, but a recent survey of RAP variability by West (2013) shows that RAP gradation is generally more consistent than that of virgin aggregates.

2.4.4.6. LITERATURE REVIEW

Different studies have been carried out in order to increase the RAP percentages in wearing courses (Sabouri et al., 2015; Doyle and Howard, 2010; Bressi et al., 2012). This section lists a number of studies and the results obtained for the performance of high RAP content mixtures with an emphasis on the potential failures.

- *CRACKING.* The cracking starts at the bottom of the asphalt layer where tensile stress and strain is very high due to repeated loads and it propagates on the surface layer as one or a series of longitudinal parallel cracks. The distress in high RAP mixtures is associated with the aged binder where its stiffness and less elasticity could increase fatigue damage (West et al., 2011) and low temperature brittleness (West et al., 2011; Terrel et al., 1992). For example, Tabakovic´ et al. (2010) determined an improvement in all mechanical properties during laboratory tests on asphalt mix with different content of RAP. The results showed that mix with 30% RAP performed better than conventional mixes in terms of improving fatigue resistance.

  Pradyumna et al. (2013) observed an improvement in the fatigue life with increase of RAP content in an asphalt mix. It was found that by adding 20% RAP, fatigue life increased by 67.2% compared to a virgin mix.

NCHRP 9-46 study by West et al. (2013) evaluated the use of 55% RAP mixes and showed that stiffness as measured by dynamic modulus at different temperatures and frequencies increased by 25–60% compared with virgin mixtures. The research also concluded that fracture energy, which is an indicator of fatigue cracking, was better for virgin mixes compared with high RAP mixtures.

Results of the Austroads report (2015), as well as Sabouri et al. (2015) show how an increase in the content of the RAP leads to an increase in the stiffness with a consequent reduction in fatigue life. Furthermore, It was observed that for mixes with hard RAP, incorporating content below 30%, the performance properties are very similar, but differ significantly from mixes with 60% of RAP and those containing only virgin binder (0% RAP) (Austroads, 2015). Instead, when RAP mixtures were manufactured with even 40% of soft RAP, results of performance-related tests provided evidence of little impact of the RAP.

In the same vein, Sunil et al. (2014) have carried out a study on the fatigue life of mixtures with different content of RAP (600%, 70%, 80%), and they have confirmed that increasing the RAP content produces a decrease in fatigue resistance. Figure 66 shows that the number of cycles to failure reduced with an increase of the percentages of RAP whilst still meeting the design requirements.

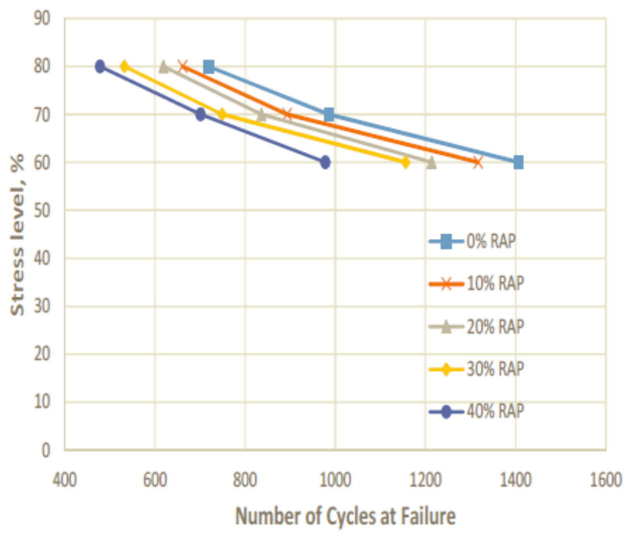

Figure 66. Fatigue Cycle Test Results for Different Percentages of RAP (Sunil et al., 2014).

- *PLASTIC DEFORMATION.* A study by Pradyumna et al. (2013), using a Wheel Tracking Device (WTD), evaluated plastic deformation on mixes with 20% RAP applying 20,000 passes of the rolling wheel at 45 °C. Mixes with RAP showed better resistance than conventional mixes. Thus, since mixes with RAP become stronger and stiffer when compared to virgin mixes, the addition of RAP improved the rutting resistance of an asphalt mix.

West et al. (2012) tested mixes with 45% of RAP at NCAT test track. The results showed excellent rutting performance, even when a bumped down binder grade was used and evaluation of plant produced 40% mixtures. A study by Mogawer et al. (2012) has also showed excellent rutting resistance.

Hussain and Yanjun (2012) conducted a study with the Marshall Method, confirming an increase of the Marshall Stability with the increase of RAP reaching twice the stability for mixes with 100% RAP when compared to the control mix. Furthermore, they argued that using RAP in design even up to 30% will help in preserving natural resources, reduction in costs, and performance improvement.

A study conducted by Abu El-Maaty and El-Moher (2015) demonstrated that mixes with RAP showed improvement in the indirect tensile strength where the highest value was achieved at 50% RAP content, and exhibited a 106% increase when compared to control mixes. Additionally, the increase in RAP content enhanced the resilient modulus, absorbed energy, and rutting (Figure 67) by around 216%, 194% and 70% respectively.

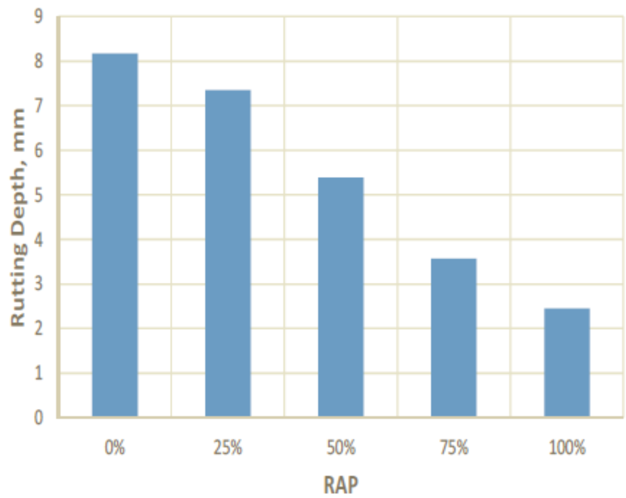

Figure 67. Rutting Depths of Mixes with Different RAP Percentages (Abu El-Maaty and El-Moher, 2015).

- *WATER SUSCEPTIBILITY.* Since the RAP aggregates are already covered with asphalt, there is less chance of water penetration in the particles. Therefore, generally high recycled asphalt mixtures are expected to have similar or better moisture susceptibility compared to conventional asphalt (Mogawer et al., 2012; Karlsson and Isacsson, 2006; Tran et al., 2012). If the milled pavement had stripping problems, adhesion additive should be used.

  Mogawer et al. (2012) through the Hamburg wheel-tracking test, showed that the moisture susceptibility of 40% mixtures was equal or better than that of virgin mixtures, in accordance with other studies (Al-Qadi et al. 2012). The authors also noted that moisture damage resistance improved as the percent of RAP in the mixtures increased.

- *THERMAL CRACKING.*

  Thermal cracking is defined as an isolated crack perpendicular to the traffic that occurs due to a high load at low temperatures in which the asphalt pavement becomes very hard and brittle. Several tests were conducted at low temperatures of mixtures containing RAP up to 55%. The results show that creep stiffness measured through Indirect Tensile Test IDT increases with the increasing RAP content with a consequent reduction in crack resistance. Further, the increase of RAP in mixes lowered the fracture energy measured by the Semi-Circular Bend Fracture Test (SCBT). Thus, the increase in RAP content led to a drop in fracture resistance at cold temperatures (Johnson et al., 2013).

  In a similar study, Solanki et al. (2015) argued that mixes with RAP showed a slight increase in IDT strengths but were not enough to cause larger increases in thermal stress. Results from SCBT Tests showed that with the increase of RAP, the fracture energy decreased and the fracture toughness increased in these mixes, as illustrated in Figure 68. Furthermore, all tested mixes did not meet the minimum recommended levels of fracture toughness or energy.

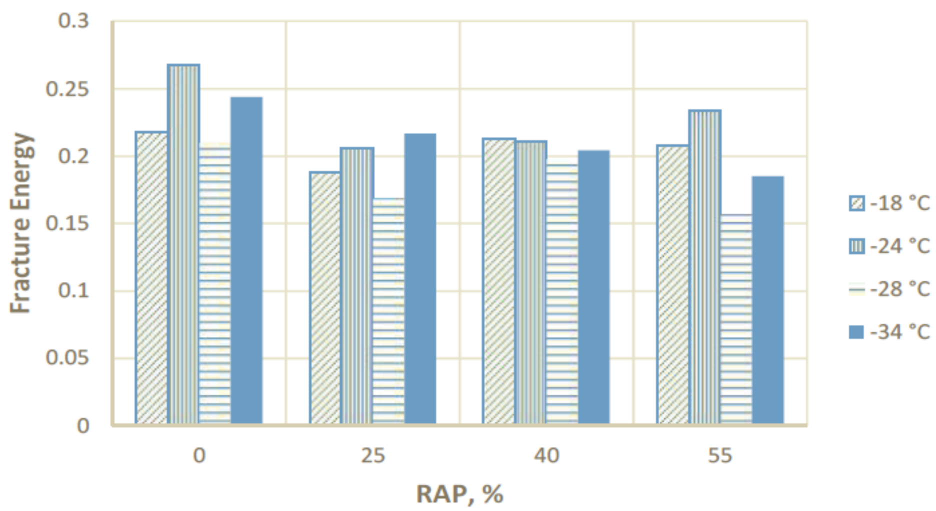

Figure 68. SCBT Test Results for Different Percentages of RAP (Solanki et al., 2015).

2.4.4.7. HALF WARM MIX ASPHALT WITH HIGH RATES OF RECLAIMED ASPHALT PAVEMENT

There are several new techniques that are becoming increasingly frequent to replace the hot mix asphalt, such as, for example, half warm mix techniques (HWMA), where the mixing temperatures are below 100 °C. One of the main problems in using HWMA techniques could be that the aggregates still contain considerable amounts of moisture (Jenkins et al. 2002; Xiao et al. 2011; Van De Ven 2007). One of the main problems in using HWMA techniques with high rates of reclaimed asphalt pavement could be that the aggregates still contain considerable amounts of moisture at the mixing temperature of 90–100 °C and this fact can hinder the bonding between the binder and aggregates, which can lead to moisture damage of mixtures and pavement failure (Soenen et al. 2010; Bennert et al. 2011). However, some studies have shown that the mechanical behaviour of HWMA is compatible with that offered by HMA. Soenen et al. studied the half-warm techniques producing mixtures using foamed bitumen and wet aggregates at 90 °C. They analysed the effect of the moisture content of the aggregates, time lag between mixing, and compaction of the asphalt, influence of filler, and effect of foaming the binder versus just adding hot bitumen to the mixture on the properties of the final mixture. Similarly, Van de Ven et al. researched the application of half-warm foamed bitumen mixtures compacted from 90 °C to 100 °C for their application on binder and base layers. They showed that the compaction of this kind of mixture could be managed. Punith et al. (2013) showed that the addition of RAP materials did not affect the performance of the mixes, even though they were compacted at 85 °C. However, on the contrary, the results showed an improvement in wet toughness values for mixtures containing moist aggregates, and it also had no influence on rutting resistance. More recently, Botella et al, (2016) studied the behaviour of mix asphalt with high rates of reclaimed asphalt pavement, from 50% to 100%, for surface layers of low-speed roads. Results indicated that their mechanical properties, cracking resistance and fatigue resistance were close to those expected from regular hot-mix asphalt mixtures.

2.4.4.8. CONCLUSION

With the increase in costs of pavement materials and the need to preserve natural resources, more agencies are incorporating reclaimed asphalt pavement materials (RAP) in new pavement designs.

Permanent deformation (rutting), fatigue cracks, and thermal cracks are the main distresses that affect the performance of asphalt mixes. In this regard, several studies have been conducted to evaluate the effect of RAP on the performance of asphalt pavements and showed that RAP increases the stiffness of asphalt mixes, due to the aged asphalt binder resulting in an improvement of rutting resistance and better performance at high temperatures. On the other hand, results were not consistent with regard to fatigue and thermal cracking. However, once again, these problems are related to the road sector, whilst in the railway sector the temperatures should not be sufficiently high to promote rutting, and at the same time the temperatures should not be sufficiently low to promote low temperature cracking and decreased fatigue life. This is considered to be primarily due to the insulation effects of the overlying ballast, which protects the asphalt from excessive temperature extremes and oxidation and hardening of the asphalt binder.

For the reasons mentioned, the sub-ballast with high content of reclaimed asphalt pavement present great potential for application in modern railway tracks.

2.5. CONCLUSIONS OF THE STATE OF THE ART AND MOTIVATIONS OF THESIS

The development of high speed railway and the increase in the loading capacity of trains have led to the need to improve the track by adding stiffer granular layers (one of them being known as sub-ballast) between the subgrade and the ballast, where its principal functions can be summarized in bearing capacity impermeability and, among others, protection of the subgrade from atmospheric actions. However, the granular configuration presents some problems; the main problem is the lack of quarries able to provide a material with appropriate characteristics for this layer. This results in high transport costs from the quarry to the construction site with negative consequences on the environment. Another problem is that to achieve the requested bearing capacity a high layer thickness is needed, with consequent use of a high amount of raw material.

Other limitations are related to the waterproofing ability, which could be resolved through the presence of fine aggregates in the granular material. However, the fine aggregate is limited by structural requirements, which makes it complicated to reach the mandatory impermeability. Moreover, the granular material is vulnerable to water saturation and vibration. However, some innovative solutions, such as the adoption of bituminous layers, may bring important benefits to subgrade protection and railroad track performance.

The use of asphalt mixtures in place of granular sub-ballast is a solution that must ensure the required conditions of bearing capacity and impermeability, achieving at least an equivalent structural behaviour to that presented by the conventional sub-ballast, whilst at the same time producing environmental benefits. The first results obtained with this material in other studies and experiences found in the literature show that it is worthwhile to conduct further research on this topic, as it is necessary to optimize this solution, implementing new technologies already developed in road construction. Moreover, the solution of asphalt as sub-ballast used so far, could be much improved compared to the asphalt used in road sector; the design can be improved and new material could be used in order to obtain new solutions for the best performance. Furthermore, it is of great interest to study the feasibility of using crumb rubber from scrap tires and HWMA with 100% of reclaimed asphalt pavement using cement as stabilizing agent and bitumen emulsion, to manufacture sustainable asphalt to be used as sub-ballast. Therefore, the manufacture of bituminous mixture by means of techniques at low temperature (warm mixture asphalt and half-warm mix asphalt) is a solution able to offer several benefits compared to HMA, trying if it possible, to improve the mechanical performance of the bituminous sub-ballast, improve its economic competitiveness, and promote sustainable development. All of this justifies the present research project.

In addition, this thesis is a result of the European research project “SUSTAINABLE PAVEMENTS & RAILWAYS INITIAL TRAINING NETWORK (SUP&R ITN) section "WP2 Railway's technologies" within the research project ERS12 "The use of waste materials in railways" which justifies its development.

RESEARCH OBJECTIVES

3. RESEARCH OBJECTIVES

From the conclusions drawn from the state of the art review, it was possible to understand that the adoption of bituminous layers may bring important benefits for subgrade protection and railroad track performance, compared to those offered by the granular layer. This alternative solution could be capable of improve the bearing capacity and impermeability whilst reducing the thickness of the layer. From an investment/cost viewpoint, it has been demonstrated that the use of bituminous sub-ballast is more appropriate than granular material when transport distances from the quarry are higher than 60 km, and it could also allow for a substantial attenuation of vibration and noise.

Nevertheless, despite its advantages, the application of hot mix asphalt as sub-ballast can lead to an important increase in construction costs, pollution, and energy consumption, which are mainly associated with the process of manufacturing at 160 °C, among other factors.

In this context, **the main aim** of the present thesis is the optimization of bituminous sub-ballast in railway infrastructure under sustainability criteria through the reuse of waste, reducing energy consumption and gas emissions. Therefore, the purpose is to obtain a new solution that is economically and environmentally more competitive and with an adequate mechanical behaviour that is at least equivalent to that presented by the granular configuration.

The following **specific objectives** have been set:

- Optimization of bituminous sub-ballast, determining the optimal design of bituminous mixtures to be used as sub-ballast in railway tracks.

- To study the viability of using bituminous mixtures manufactured by low temperature technology as sub-ballast in railway tracks (in this thesis warm mix asphalt WMA will be studied). So construction techniques that carefully consider the environment and climate change will be used, given that lower energy consumption and lower emission rates would occur.

- To study the viability of using bituminous mixtures manufactured with recycled materials such as crumb rubber and 100% reclaimed asphalt pavement as sub-ballast in railway tracks in order to obtain a sustainable and environmentally friendly alternative to traditional asphalt products.

METHODOLOGY

4. METHODOLOGY

4.1. INTRODUCTION

The methodology outlined in this chapter defines the different phases followed to achieve the aims of this doctoral thesis (Figure 69); describing on the one hand the materials used, and on the other hand, the work plan and the various phases carried out to evaluate the mechanical performance of different types of sub-ballast.

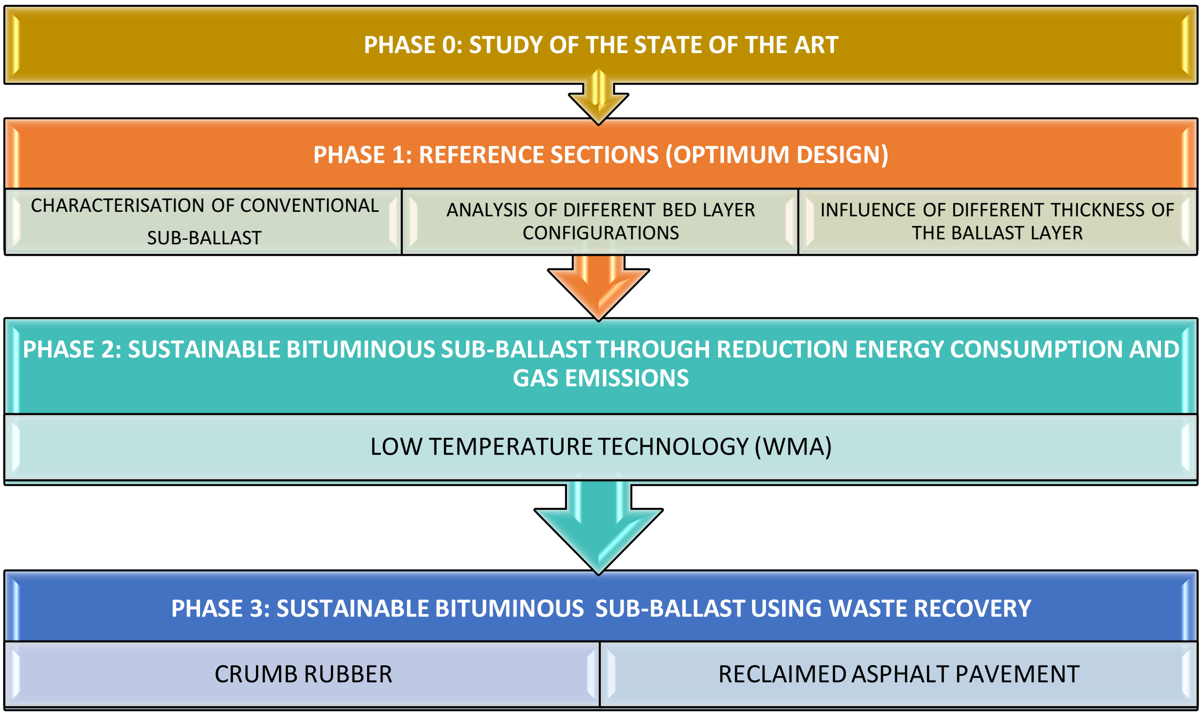

Figure 69. Work plan.

The methodology can be divided into four phases including a previous phase (phase 0) about the problem statement with a subsequent literature review:

- ***Phase 0:*** From the results of the literature review and considering the problem statement, it was decided to adopt, as reference section, granular sub-ballast made of granular material with a thickness of around 22 cm from which the materials will be modified and the change of properties will be investigated and compared to the reference section (Figure 70). In detail, the new section to study will be conventional bituminous sub-ballast and sustainable bituminous sub-ballast such as warm mix asphalt, rubberized asphalt, and 100% half-warm reclaimed asphalt pavement as sub-ballast.

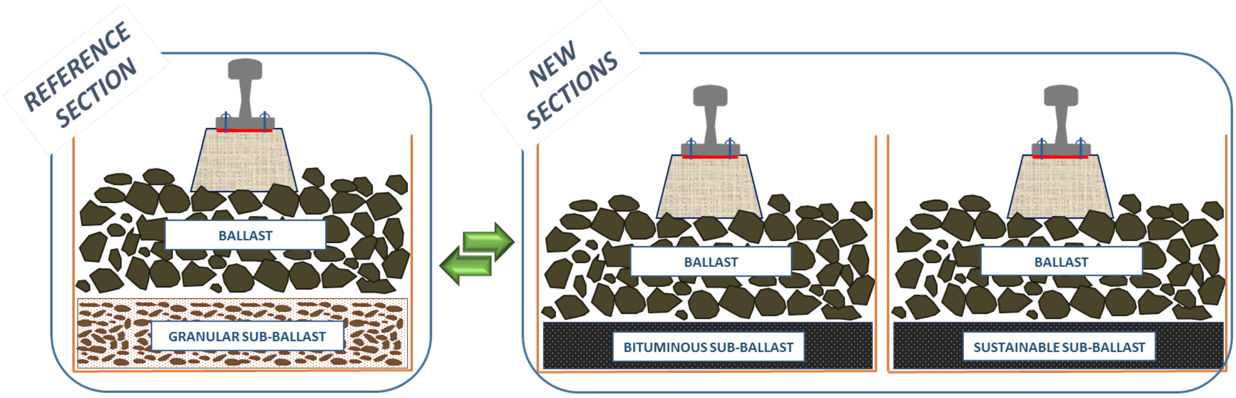

Figure 70. Different types of section.

- ***Phase 1:*** Phase 1 can be divided into three sub-phases; (1.1) *characterisation of conventional sub-ballast* (the granular one, which is the conventional section in high-speed railways in various countries such as Spain; and the conventional bituminous sub-ballast which is becoming widely used in modern railway tracks); (1.2) *analysis of different bed layer configuration* (focused on examining the effect of varying the configuration of track section under the ballast layer and analysing various types of sub-ballast as well as the use of different elastic mats); (1.3) *influence of different thickness of the ballast layer* (with the aim of evaluating the influence of varying the thickness of the ballast layer).

- ***Phase 2:*** The aim of this phase is to design the warm mix asphalt (WMA) as sub-ballast and to compare its mechanical performance with that of the conventional hot mix asphalt (HMA) as sub-ballast, in order to save energy and reduce emissions throughout the production process, as well as diminish the global costs of this layer. This type of asphalt is becoming more popular in road construction while it also presents great potential for its application as bituminous sub-ballast in railway tracks.

- **Phase *3:*** Phase 3 aims to evaluate the feasibility of using bituminous sub-ballast containing waste materials such as crumb rubber, manufactured by both wet process and dry process and 100% RAP (Reclaimed asphalt pavement) in accord with the half-warm mix asphalt technique, and then comparing their response with that of the conventional bituminous sub-ballast.

4.2. MATERIALS

In this study, different materials have been employed in order to be able to design and study the different types of sub-ballast. Figure 71 lists the materials and their respective properties evaluated for their characterization.

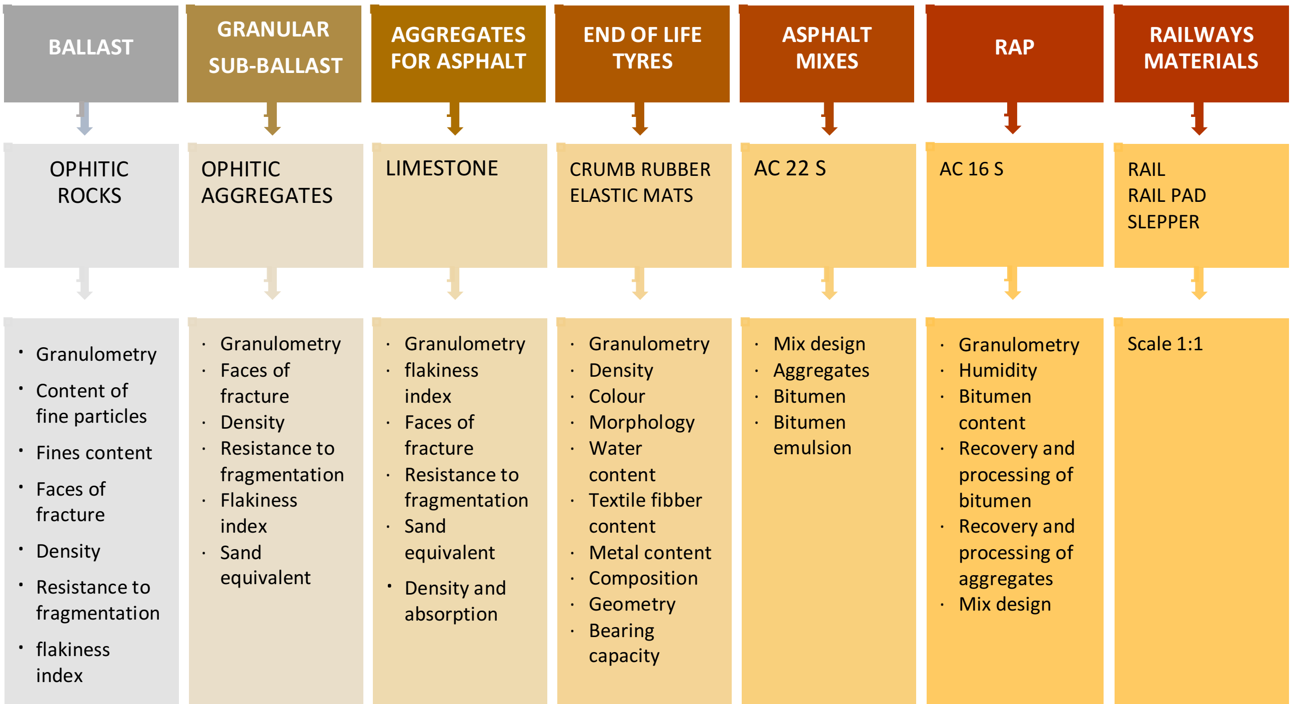

Figure 71 Materials used.

4.2.1. BALLAST

The ballast used in this study was sourced from ophitic rocks at the Cerro Sillado quarry, in Guadix, Spain (Figure 72), and this material presented appropriate characteristics (Table 6 and 7) to be used in high-speed lines according to the Standard EN 13450:2003.

Figure 72. Ballast used.

Granulometry EN 933-1:12				
Sieve (mm)	Standard limits 31,5 mm a 50 mm			% passing
	A	B	C	
80	100	100	100	100
63	100	97 a 100	95 a 100	100
50	70 a 99	70 a 99	70 a 99	85
40	30 a 65	30 a 70	25 a 75	37
31,5	1 a 25	1 a 25	1 a 25	8
22,4	0 a 3	0 a 3	0 a 3	0

Table 6. Results of the ballast Granulometry tests.

Properties	Standard	Results	Standard limits
Content of fine particles (<0.5 mm) (%)	EN 933-1:12	0,08	≤1
Fines content (<0.063 mm) (%)	EN 933-1:12	0,03	≤ 0,5
Faces of fracture (%)	EN 933-5:99	100	100
Density (Mg/m^3)	EN 1097-6:14	3,24	-
Resistance to fragmentation (L.A.) (%)	EN 1097-2:10	5	≤14
Determination of particle shape - Flakiness index (%)	EN 933-3:12	6	≤15

Table 7. Results of the ballast characterization tests.

4.2.2. GRANULAR SUB-BALLAST

The granular sub-ballast analysed was sourced from Cerro Sillado quarry, in Guadix, Spain (Figure 73). This type of sub-ballast was composed of ophitic aggregates with a continuous granulometry from 40 mm to 0,063 mm, as shown in Table 8. In addition, the granular material presented appropriate physical and mechanical properties for its utilisation as sub-ballast according to the Spanish Standard (PF-7, 2006). Moreover, its maximum density and optimal moisture were determined by using the proctor test (EN 103-500) in order to obtain an adequate compaction of this material for its application in railway tracks. The properties are listed in Table 9.

Figure 73. Sub-ballast used.

Granulometry EN 933-1:12		
Sieve (mm)	Standard limits	% passing
63	100	100
50	100	100
40	100	100
31.5	90-100	100
16	85-95	85
8	65-80	66
4	45-65	50
2	30-50	30
0,5	10-40	17
0,2	5-25	14
0,063	3-9	4,2

Table 8. Results of the sub-ballast granulometry tests.

Properties	Standard	Results	Standard limits
Faces of fracture (%)	EN 933-5:99	100	100
Density (Mg/m^3)	EN 1097-6:01	3,24	-
Resistance to fragmentation (L.A.) (%)	EN 1097-2:10	14	≤28
Determination of particle shape - Flakiness index (%)	EN 933-3:12	10	≤28
Sand equivalent (%)	EN 933-8:12	61	>45
Proctor	EN 103-500	γd=2,73 g/cm^3	-
		W=5,28%	-

Table 9. Results of the sub-ballast characterization tests.

4.2.3. AGGREGATES FOR ASPHALT MIXTURES

The aggregates employed to manufacture the mixes used as sub-ballast were the limestone type for the different fractions 0/6, 6/12, 12/18 and 18/25 mm (Figure 74), presenting appropriate properties for their use in asphalt mixes in accordance with Spanish PG-3 (2004) regulations.

Figure 74. Different fractions of aggregates for asphalt mix.

The characteristics of the aggregates are shown in Table 10.

Properties	Standard	Results				Standard limits
		18/25	12/18	6/12	0/6	
Coarse aggregate shape. Flakiness index	EN 933-3:99	8	12	10	-	<25
Percentage of fractured face (UNE-EN 933-5)	EN 933-5:99	99	99	98	-	>90
Resistance to fragmentation (Los Angeles coefficient) (<25)	EN 1097-2	23	23	23	-	<25
Cleaning (organic impurity content) (<0,5%)	EN 146130	0,2	0,4	0,4	-	<0,5
Sand equivalent (>50)	EN 933-8	-	-	-	77	>50
Relative density and absorption:	EN 1097-6:01					
-Apparent density (Mg/m^3)		2,86	2,85	2,86	3,01	-
-ADSS (Mg/m^3)		2,83	2,81	2,81	2,96	-
-Density after drying (Mg/m^3)		2,84	2,83	2,83	2,97	-
-Water absorption after immersion (%)		0,39	0,49	0,62	0,56	-

Table 10. Results of the aggregates characterization tests.

The filler used was Portland cement, CEM II/B-L 32,5 N (EN 197-1:2011). 95% of this filler has a particle size smaller than 0,063 mm with an apparent density (EN 1097-3:1999) of 0,7 Mg/m^3 (Figure 75).

Figure 75. Portland cement.

4.2.4. END-OF-LIFE TIRE

4.2.4.1. CRUMB RUBBER

The crumb rubber used to manufacture the mix in the dry-process was obtained by a mechanical trituration process and presented a particle size of 0,6 mm (Figure 76).

Figure 76. Crumb rubber.

The remainder of its properties are listed in Table 11.

Properties	Sieve (mm)	% passing
Granulometry EN 933-1:12	0,6	100
	0,5	49
	0,25	3
	0,125	1
	0,063	0,6
Density (g/cm3)	1,15	
Colour	Black	
Particle morphology	Irregular	
Water content (%)	<0,75	
Textile fibber content (% in weight)	<0,5	
Metal content (% of the rubber weight)	<0,1	
Composition	**Min. (%)**	**Max. (%)**
Acetone extract	7,5	17,5
Natural rubber (NR)	21	42
Polymers (NR/SBR)	50	55
Sulfur	-	5
Carbon black	20	38
Ash	-	18,5

Table 11. Results of the crumb rubber characterization tests. (Own elaboration)

4.2.4.2. ELASTIC MATS

Other elastics elements whose influence was analysed in this study were a soft (SOUBM) and a stiff (SUBM) under ballast mat (UBM), selected to modify the stiffness of the substructure of the railway track. These mats were also manufactured from end-of-life tire tread layers and their horizontal dimensions were similar to those of the bottom surface of the ballast box. The thickness of the soft element was 21 mm and its dynamic bending modulus at 5 Hz was close to 0,20 N/mm^3 (DBS, 2010), which is appropriate for being used in railway tracks to reduce its deterioration (International Union of Railways, 2005) whilst the stiff mat had a thickness of 9 mm and 0,30 N/mm^3 of dynamic modulus. Figure 77 displays the soft mat at the bottom of the ballast.

In addition, the effect of a very stiff mat (SM) was analysed when it was used as under-sub-ballast mat. This element was also obtained from tire layers, but in this case the inner layer of the end-of-life tire was used, resulting in a thickness of 5 mm and a dynamic modulus close to 0,32 N/mm^3. Figure 77 shows this elastic element, which was placed at the bottom of the box before introducing the sub-ballast layer (any typology selected) and the remainder of the components (ballast, sleeper, fastenings, stiff rail pad, and rail).

Figure 77. Elastic pads used during the study.

4.2.5. RECLAIMED ASPHALT PAVEMENT (RAP)

The origin of the RAP is a mixture AC 16 which came from provided in two fractions: 0/6 mm and 6/25 mm (Figure 78).

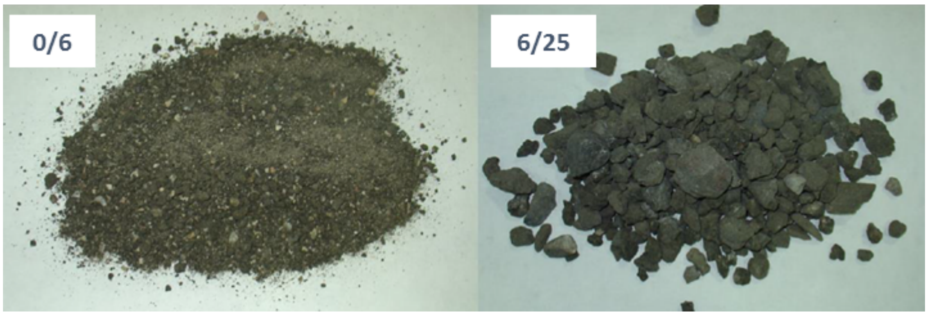

Figure 78. Different fractions of RAP.

With the aim of analysing the properties of the RAP, a series of laboratory characterization tests were carried out for this material: (i) granulometry (in black) (UNE-EN 933-1); (ii) natural humidity content; (ii) bitumen content; (iv) penetration tests (UNE-EN 1426) and different softening point (UNE-EN 1427) of the recovered bitumen; (v) granulometry of the white aggregates after extraction (UNE-EN 933-1); (vi) characterization of the aggregates.

Table 12 shows the results obtained from the *granulometry* (in black) of different samples of each one of the received fractions.

Granulometry EN 933-1:12						
Sieve (mm)	Sample 1 0/6mm	Sample 2 0/6mm	Avarage	Sample 1 6/25mm	Sample 2 6/25mm	Avarage
31.5	100	100	**100**	100	100	**100**
22.4	100	100	**100**	100	100	**100**
16	100	100	**100**	92	85	**88.5**
8	100	100	**100**	30	21	**25.5**
4	86	78	**82**	3	2	**2.5**
2	62	50	**56**	2	1	**1.5**
0.5	24	16	**20**	2	1	**1.5**
0.25	15	9	**12**	1	1	**1**
0.063	2	1.4	**1.7**	0.4	0.5	**0.45**

Table 12. Results of RAP of granulometry tests.

The *natural humidity* contained in the RAP was determined, as well as its ability to lose moisture over time. To achieve this, samples of both RAP fractions were oven dried at 100 °C, and the evolution of weight loss was monitored as a function of time (every 10 minutes). Figure 79 shows the results obtained.

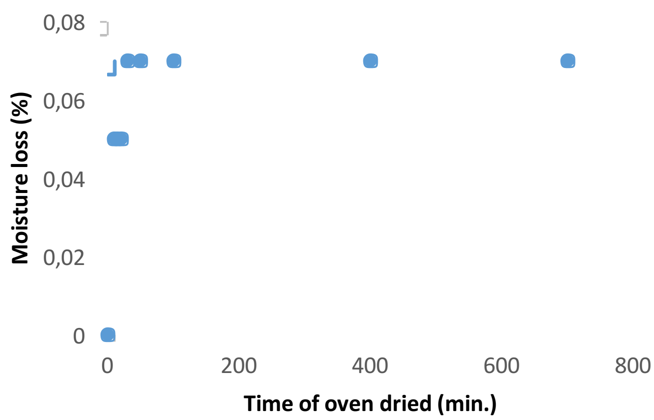

Figure 79. Evolution of weight loss.

The *bitumen content* was determined by two methods: extraction with centrifuge and with ignition furnace (Figure 80).

Figure 80. Centrifuge and with ignition furnace.

Table 13 shows the results obtained for each of the granulometries studied with both methods.

	0/6 mm RAP (centrifuge)	0/6 mm RAP (ignition)	6/25 mm RAP (centrifuge)	06/25 mm RAP (ignition)
BITUMEN s/m %	5,49	6,7	1,95	3,2
BITUMEN s/m %	5,81		1,99	

Table 13. Bitumen content.

Subsequently, in the case of centrifugal extraction, the sample of "solvent + binder" obtained was separated by a rotary evaporation process in order to recover the aged bitumen contained in the RAP (Figure 81).

Figure 81. Extraction of bitumen.

The recovered bitumen was characterized by penetration tests (EN 1426) at 25 °C and softening point (EN 1427) (Figure 82). The values were compared with those obtained by the reference binder B 50/70.

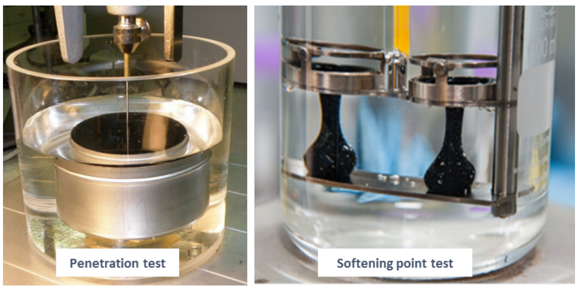

Figure 82. Penetration tests (EN 1426) at 25 ° C and softening point (EN 1427).

The results obtained in the penetration tests (in dmm) and different softening point tests (°C) on different binder samples recovered from the RAP are given in Table 14.

Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Avarage
Penetration (dmm)	15	10	15	13	17	17	17	**14.9**
Softening point (°C)	70	71.2	79.8	73	73	71	72	**73**

Table 14. Results obtained in the penetration tests (dmm) and different softening point (°C).

After the extraction of the bitumen (by the centrifugal and ignition method), the physical and mechanical properties of the aggregates (white) were characterized (Table 15).

Properties	Standard	Results
Determination of particle shape - Flakiness index (%)	EN 933-3:12	9,5
Sand equivalent (%)	EN 933-8:12	89

Table 15. Results of the RAP characterization tests.

The table 16 shows the results obtained in the granulometry of the natural aggregates (white) of each of the RAP fractions after extraction of bitumen.

Granulometry EN 933-1:12						
Sieve (mm)	Sample 1 0/6mm	Sample 2 0/6mm	Avarage	Sample 1 6/25mm	Sample 2 6/25mm	Avarage
31.5	100	100	**100**	100	100	**100**
22.4	100	100	**100**	100	100	**100**
16	100	100	**100**	92	96	**94**
8	100	100	**100**	36	53	**44.5**
4	85	91	**88**	14	25	**19.5**
2	61	75	**68**	9	19	**14**
0.5	32	41	**36.5**	5	13	**9**
0.25	23	30	**26.5**	4	10	**7**
0.063	5.3	11.6	**8.45**	1.2	4.2	**2.7**

Table 16. Results of granulometry of the natural aggregates (white) of each RAP fractions after extraction of bitumen.

Finally, Figure 83 shows the average particle size curves of the "white" and “black” aggregates of each of the RAP fractions studied.

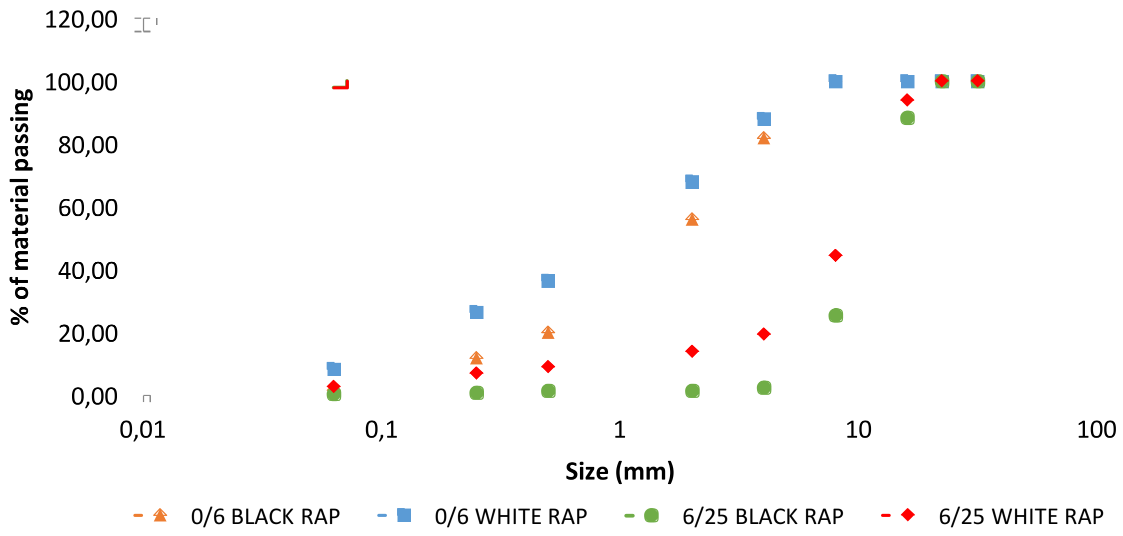

Figure 83. Average particle size curves of the "white" and "black" aggregates.

4.2.6. ASPHALT MIXES

In this research, five types of bituminous mixtures were used as sub-ballast layer:

- Four of these, in detail (i) hot mix asphalt (HMA), (ii) warm mix asphalt (WMA), (iii) rubberized asphalt manufactured by wet process (WRA), and (iv) rubberized asphalt manufactured by dry process (DRA) were a dense-graded mix type AC 22 S (EN 13108-1) with a maximum size of aggregates equal to 22 mm, manufactured with the same mineral skeleton (Figure 84) and bitumen type 50/70.

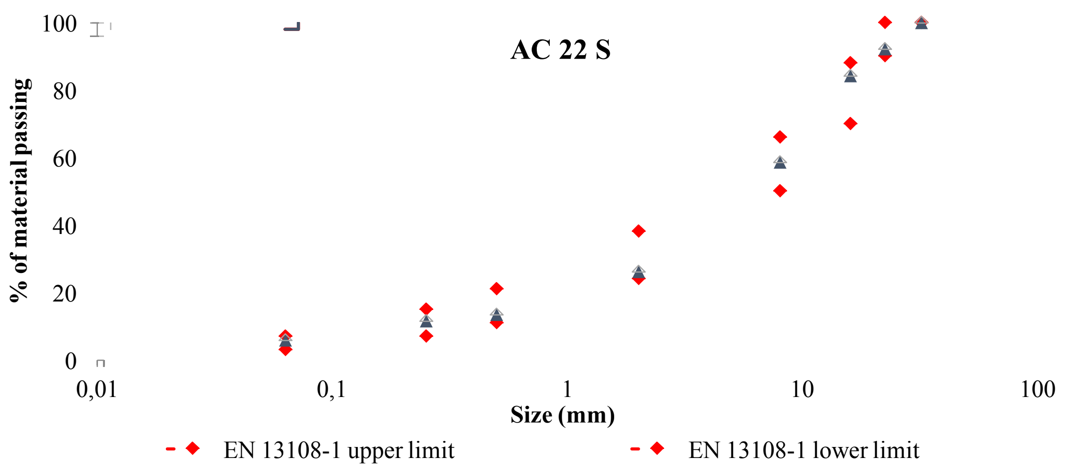

Figure 84. Mineral skeleton of the mixes AC 22 S.

- The last one, (v) HWMA with 100% RAP (reclaimed asphalt pavement) was a dense-graded mix type AC 16 S with a continuous grain size and maximum size of aggregates equal to 16 mm (Figure 85).

For this type of mix, a slow-breaking cationic emulsion and 2% of cement Portland as stabilising agent were used.

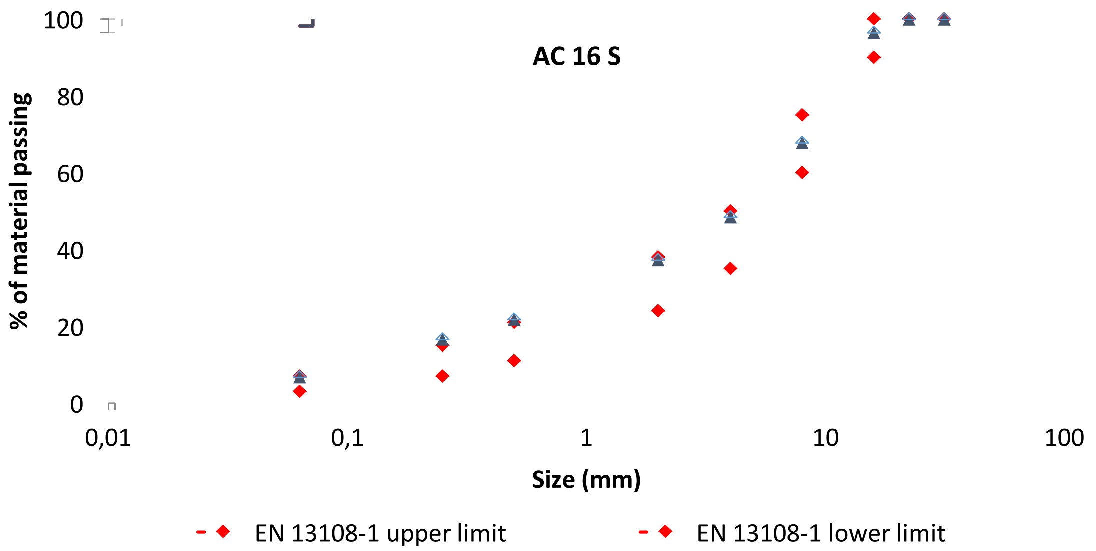

Figure 85. Mineral skeleton of the mixes AC 16 S.

The *WMA* was manufactured at 135 °C and compacted at 125 °C, using a surfactant chemical additive that reduces the surface tension of asphalt binder and improves the moisture resistance of pavements by serving as an antistrip (Rohith et al., 2013). The additive was introduced at 0,5% by weight (additive density: 1,01 gm/cc) and it had previously been mixed with the bitumen at a temperature of 160 °C by using a conventional blender, set at a speed of 350 rpm for a period of 10 minutes, in accord with Pérez-Lepe et al., (2003).

In the *DRA* (dry rubberized asphalt) the particles of crumb rubber were added directly to the aggregates; the quantity added to the mix was 1% and the digestion time before the compaction was 45 minutes in an oven at a compaction temperature of 150 – 160 °C. These values can be considered optimal mix values, since a previous study showed that increasing the crumb rubber content above 1% caused a considerable reduction in the density of the mixes and a substantial loss of cohesion (Moreno et al., 2012). In addition, the temperature of the mix was increased by 10 °C more than that of the reference mix to facilitate the interaction between the rubber and the bitumen in order to improve the cohesion of the mastic. In contrast, the *WRA* (wet rubberized asphalt) was manufactured with BC 50/70 rubber-modified bitumen where the crumb rubber was added to hot binder prior to mixing it with the aggregates.

To manufacture the *HWMA with 100% RAP,* different considerations about the manufacturing/compaction temperature, mixing time, moisture content and compaction process should be taken into account.

Regarding the manufacture/compaction temperatures, the RAP was preheated at 100±5 °C while the bitumen emulsion was heated between 50-60 °C, in order to manufacture the mixture at 100 °C and to ensure a compaction temperature around 90 °C. The process and mixing time of the components must ensure a homogeneous and complete wrap of the mix. The maximum mixing time should not exceed 3 minutes. The compaction of the mixture was conducted using a gyratory compactor (applying 65 gyros and avoiding compacting at below of 90 °C).

After the manufacturing process and before proceeding with the tests, the specimens were subjected to a curing period of three days at 50 °C in a forced convection oven.

The characteristics of the different types of bitumen are shown in Table 17.

Bitumen	BC 50/70	B 50/70	Recovered	Emulsion
Penetration (EN 1426) (dmm)	50 - 70	54	14.9	15.0
Softening point (EN 1427) (°C)	53	54,4	73	
Fragility temperature (Fraas method) (EN 12593) (°C)	-8	-8	-	
Residual bitumen content (%)	-	-	-	60

Table 17. Properties of different bitumen used.

4.2.7. RAILWAY MATERIALS

A full-scale box was utilised with the aim of analysing the effect of the bituminous sub-ballast layers on the mechanical performance of railway track sections. This box, shown in Figure 86, was 440 mm in width, 750 mm in length, and 500 mm in height, allowing for the simulation of the railway track section under the rail seat area (with a sleeper spacing near to 500 mm), where the highest levels of stress over ballast are expected. The testing box includes a piece of concrete sleeper (250 mm in width and 357 mm in length) with a tension clamp fastening type VM (composed mainly of a metallic clip type SKL-1, screw spike type VAPE, and an elastic pad) commonly used in Spanish railway tracks, whilst the rail used was a type UIC-54 with a length of 250 mm.

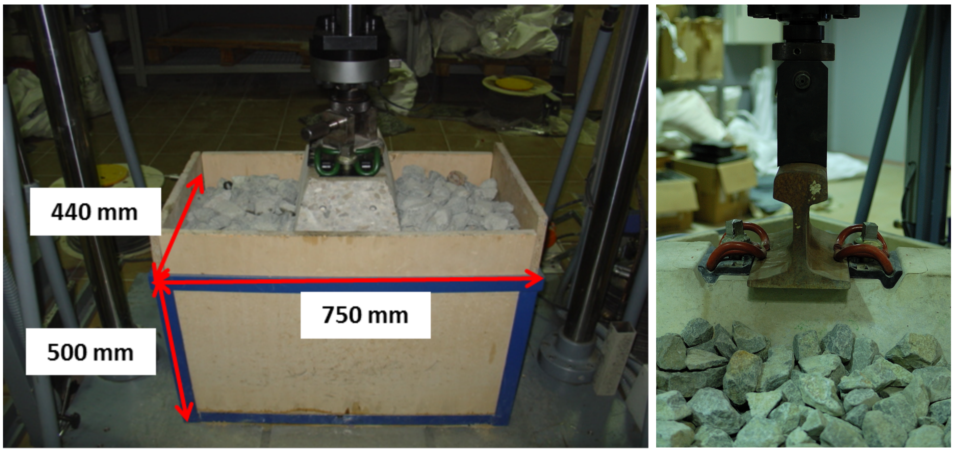

Figure 86. Visual appearance of the full-scale test developed in a laboratory box.

4.3. METHODS

This section describes the methodology followed in the development of the research, explaining in detail the four phases previously described, as well as the tests carried out to achieve the objectives set. The phases of the research are structured and ordered in a chronological way, coinciding with the objectives set out in the previous chapter.

The present thesis therefore focuses on the analysis of the mechanical behaviour of different bituminous sub-ballasts under various conditions that are expected to produce failure of the material, whilst also examining the influence of the temperature on its performance. As a reference to evaluate the response of the bituminous materials, the behaviour of conventional granular sub-ballast commonly used in railway tracks was also analysed.

The first step, common to each of the 4 phases, was to design the mixtures by Marshall Method (NLT-159/00), with the exception of the HWMA 100% reclaimed asphalt pavement (RAP), which was designed with gyratory method since from the literature (Holl, 1991) it is known that the Marshall compactor is not well suited to the compaction of specimens containing larger amounts of water. If the volume of water is higher than the volume of air voids in the aggregate structure, the specimen is oversaturated and water has to be squeezed out to obtain good compaction. However, with an impact compactor such as a Marshall hammer, the water, due to its incompressibility, acts like an elastic spring. The impact hammer bounces back and the water has no time to flow out of the mould unless it is specially prepared to facilitate drainage of excessive water.

In addition, conventional tests used for the application of asphalt mixtures in highways were employed to assess both the resistance against water action (EN 12697-12:2009) and the stiffness modulus (EN 12697-26:2012 Annex C).

An in-depth study was then conducted in order to examine the feasibility of using sustainable bituminous sub-ballast under a range of conditions of service (including adverse climate conditions) in reference to both conventional bituminous sub-ballast and to the more traditional granular material. First, conventional granular and conventional bituminous sub-ballast were characterized under the main failure modes that occur during the service life of this layer, particularly resistance to plastic and punching deformations, bearing capacity, stress dissipation, and waterproofing properties. In addition, resistance to cracking was measured for the bituminous material, since this characteristic is fundamental in ensuring its durability. At the same time, their influence on the performance of the global section was assessed for both types of sub-ballast by means of a full-scale test. In addition, always in the ballast box and in order to optimize the reference section, the behaviour of a track section 1:1 was analysed, changing some variables in the vertical configuration such as two kinds of under-ballast mat (soft and stiff) incorporating a stiff elastic mat under each type of sub-ballast and modifying the thickness of the ballast layer. The parameters used to evaluate the performance of each configuration were global vertical stiffness and settlement of the section (associated with maintenance costs), as well as dissipated energy (related to service costs).

The various sustainable bituminous sub-ballasts (WMA, DRA, WRA and HWMA 100% RAP), have been characterized in reference only to the main properties required by the sub-ballast layer (plastic and punching deformations, bearing capacity, stress dissipation, and waterproofing properties). Table 18 summarises the properties investigated for each configuration.

<table>
<tr><th rowspan="2"></th><th colspan="2">CONVENTIONAL CONFIGURATIONS</th><th colspan="4">SUSTAINABLE CONFIGURATIONS</th></tr>
<tr><th>GRANULAR SUB-BALLAST</th><th>BITUMINOUS SU-BALLAST</th><th>WARM MIX ASPHALT</th><th>DRAY RUBBERIZED ASPHALT SUB-BALLAST</th><th>WET RUBBERIZED ASPHALT SUB-BALLAST</th><th>HWMA 100% RAP SUB-BALLAST</th></tr>
<tr><td>Characterization of the mixtures</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Plastic-punching deformations</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Bearing capacity-stress distribution</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Permeability</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Crack resistance</td><td></td><td>■</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Full scale assessment</td><td>■</td><td>■</td><td></td><td></td><td></td><td></td></tr>
</table>

Table 18. properties investigated for each configuration.

4.3.1. CHARACTERIZATION OF THE MIXTURES

Marshall test (EN 12697-34:06), gyratory compactor mix design (EN 12697-31:08) (just for RAP), water sensitivity test (EN 12697-12:2009) and indirect tensile stiffness modulus test (EN 12697-26:2012, Annex C) were applied to characterize all types of bituminous sub-ballast.

Marshall Test mix design

Marshall method uses several trial aggregate-asphalt binder blends, each with different bitumen content. Then, by evaluating the performance of each trial blend, an optimum asphalt binder content can be selected.

The specimens were prepared in accordance with the Spanish standard NLT-159/00, placed in a preheated mould and compacted with 75 blows on each side by a Marshall hammer (Figure 87 left) in order to obtain specimens of approximately 60 mm in height and 101,6 mm in diameter. The specimens were then immersed in water at a temperature of 60 °C for 50±5 min. The Marshall test was also conducted to determine the percentage of voids in the mixes, along with the bulk density, deformation, and stability of the mixtures in accordance with the European Standard EN 12697-34:06. Marshall stability of a test specimen is the maximum load required to produce failure when the specimen is preheated to a prescribed temperature placed in a special test head (Figure 87 right) and the load is applied at a constant strain. The Marshall flow value is the deformations measured at the failure point.

Figure 87. Marshall hammer – Marshall press.

Gyratory compactor mix design

With the use of the gyratory compactor (Figure 88) (that was to be used only to design the HWMA with 100% RAP), the mixture was designed, manufacturing specimens with three different percentages (2%, 2,5% and 3%) of emulsion. The specimens were manufactured, and subjected to a compaction energy of 210 turns, with consolidation pressure of 600 kPa, an angle of gyration of 0,82° and with speed of gyration/rotation of 31 rpm. Based on the obtained curve, the number of rotations needed to reach an air-voids content between 1–3% was determined. Afterwards, the specimens manufactured (9 in total, 3 for each emulsion percentage) were subjected to stiffness modulus tests and Water Sensitivity Test. Before carrying out the tests, the specimens were cured for 3 days in an oven at 50 °C. Finally, the optimum emulsion content was determined taking into account, on the one hand, the results obtained during the stiffness test and Water Sensitivity Test, and on the other hand the bitumen content of each element of the mixture (quantity of bitumen provided by the RAP as well as the bitumen in the bitumen emulsion).

Figure 88. Gyratory compactor.

Water Sensitivity Test

The evaluation of water sensitivity is important, because this property is directly related to the performance and durability of mixtures during the life of the layer. The characterization of water sensitivity of bituminous mixtures was performed according to standard EN 12697-12:2009. For this test, six cylindrical specimens of the Marshall type were manufactured and compacted with 50 blows on each side by a Marshall hammer. Then the specimens were divided into two groups of three and conditioned. One subset of specimens was saturated (wet specimens) and sorted for 67-72 h of immersion in a thermostatic bath at 40 °C (Figure 89 left), and a second set was maintained dry (dry specimens) at a test temperature of 15 °C (Figure 89 centre).

However, the standard indicates that the specimens are previously subjected to vacuum in water at 20 °C and kept for 30 minutes under an absolute pressure of 6,7 KPa (Figure 89, right).

Figure 89. Thermostatic bath – Chamber – Vacuum.

The two groups of specimens were then tested for indirect traction (Figure 90).

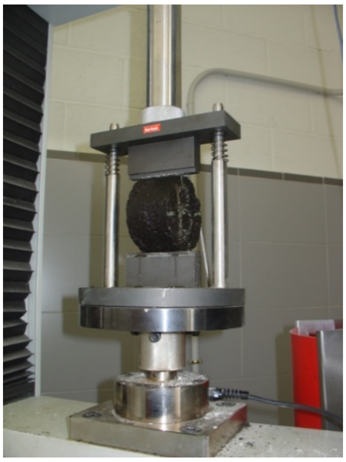

Figure 90. Water Sensitivity Test.

The damage caused by the immersion in water is expressed by the tensile strength ratio (ITSR), according to the formula:

$$ITSR = 100 \times \frac{ITSw}{ITSd}$$

Where:

ITSw and ITSd represent the indirect tensile strength (MPa) of the specimens treated in water and untreated, respectively. The indirect tensile strength was determined using the equation:

$$ITS = \frac{2F}{\pi DH}$$

Where:

F represents the breaking load (N) of the specimens under diametral compression;

D is the average values of the diameter (mm);

H is the average values of the height of the specimen (mm).

Stiffness Modulus Test

Knowledge of the ‘‘stiffness’’ of bituminous mixtures is a key element for the analysis and design of bituminous mixtures, as it is directly linked to the capacity of the material to distribute loads. Moreover, the stiffness can be considered as a synthetic indicator of the structural properties of the mixes. To determine the stiffness modulus of the mixes, the indirect tensile stiffness modulus test (ITSM) was conducted in accord with EN 12697-26, Annex C. The test temperature was 25 °C for two cylindrical specimens compacted with 75 blows on each side by a Marshall hammer. During the test, 15 semi-sinusoidal test pulses were applied along the vertical diameter of the specimens with a total duration of 3±1 s, consisting of a rise time of 124±4 ms in a regime of deformation control (5 µm). The test procedure was repeated in a perpendicular diameter. The stiffness modulus of the mixtures was recorded by taking the average stiffness of the five pulses registered in the two diameters (Figure 91).

Figure 91. Stiffness Modulus Test.

According to the Annex C of the European standard, for each diameter the Modulus is determined with the equation:

$$Sm = \frac{F(v + 0{,}27)}{x \times h}$$

Where:

Sm is the Stiffness Modulus (MPa);

F represents the peak value of the applied vertical load (N);

z the amplitude of the horizontal deformation obtained during the load cycle (mm);

h the mean thickness of the cylindrical specimen (mm) and;

m the Poisson’s ratio (–).

4.3.2. PLASTIC-PUNCHING DEFORMATIONS

To assess the plastic deformations of the different type of sub-ballast, the triaxial and punching tests were conducted under the expected temperature (25 °C) as well as unfavourable (40°C) and extreme (60°C) temperature for sub-ballast layer at which plastic deformations are more likely to develop in asphalt mixtures.

Cyclic Triaxial Test

The cyclic triaxial test (Figure 92), which is considered appropriate for the evaluation of plastic deformations in bituminous materials (Christensen et al., 2002; Huschek, 1985), was conducted for two cylindrical test specimens manufactured by an impact compactor (75 blows per side) (EN 12697-30:2013) with a height of approximately 60 mm and a diameter of 101.6 mm of each material, and was tested under the different temperature conditions analysed in the case of the bituminous sub-ballast. A conditioning period of 2 h was implemented before beginning the test. This test was carried out according to the Standard EN 12695-25:2006 (Method B), applying a cyclic sinusoidal axial loading of 200 kPa (Pa) and a confining load of 80 kPa (Pc) at a frequency of 3 Hz for 10,000 load cycles. The maximum stress was fixed at 200 kPa in order to study the resistance of the material under unfavourable loading conditions (since a normal value for sub-ballast is around 100–120 kPa) that could take place for sub-ballast in railway tracks (Rose et al., 2002). The parameters of creep modulus, creep slope at the final 5000 loading cycles, and permanent deformation were calculated for each pair of specimens.

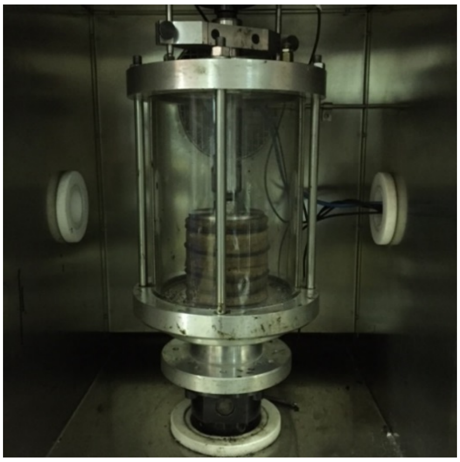

Figure 92. Triaxial test.

Punching Tests

Another method used to assess the resistance to permanent deformations was the punching test (Figure 93 a) which is able to simulate the contact between the ballast and the asphalt layer (Figure 93 b). The test was conducted for two squared (300 mm x 300 mm) specimens for each case studied (granular sub-ballast, and bituminous sub-ballast at different temperatures). The specimens had a height of 220 mm in the case of granular sub-ballast, and 120 mm for the bituminous sub-ballast, since these are common values found for the thickness of these layers in railway tracks. The test consisted of applying a stress of 200 kPa (regarded as an unfavourable loading condition that can occur over the sub-ballast layer) (Rose et al., 2002) by means of a ballast plate with dimensions of 150 mm x 150 mm (Figure 93 c) on the top of the sub-ballast specimen. The calculated parameter represents the evolution of the permanent deformation caused by the punching of ballast particles.

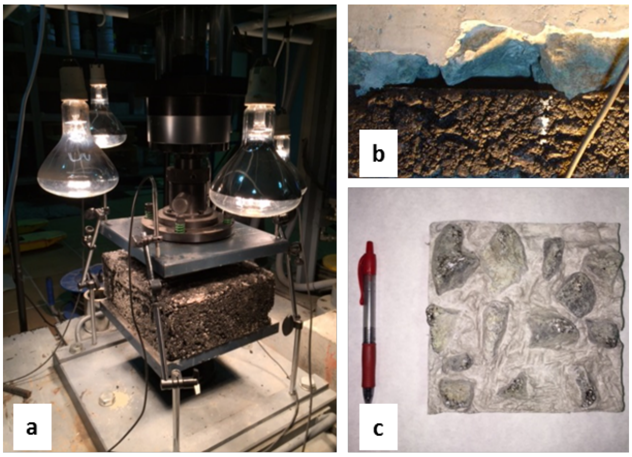

Figure 93. a) punching test, b) contact ballast sub-ballast, c) ballast plate.

4.3.3. BEARING CAPACITY-STRESS DISTRIBUTION

Plate-bearing test

The plate-bearing test was conducted in the laboratory following the loading conditions established in the EN 103808:2006 to measure the bearing capacity of the sub-ballast. This test was carried out under static (at various stress levels: 20, 50, 150 and 250 kPa) and dynamic (at a frequency of 4 Hz) loads. For this test, prismatic samples (512 mm x 408 mm and 120 mm of height) were placed at the bottom of a box in the case of bituminous sub-ballast (Figure 94, left), whilst for the granular sub-ballast a layer of 220 mm of height was compacted at the bottom of the box (Figure 94, right). In both cases, a squared flat plate (300 mm x 300 mm) was used to load the materials. With this test it was possible to calculate the static and dynamic modulus of each material, whilst also assessing the influence of temperature on the strength of bituminous sub-ballast. In addition, a pressure cell was used under the sub-ballast with the aim of analysing the capacity of each solution to dissipate the stress applied over the material.

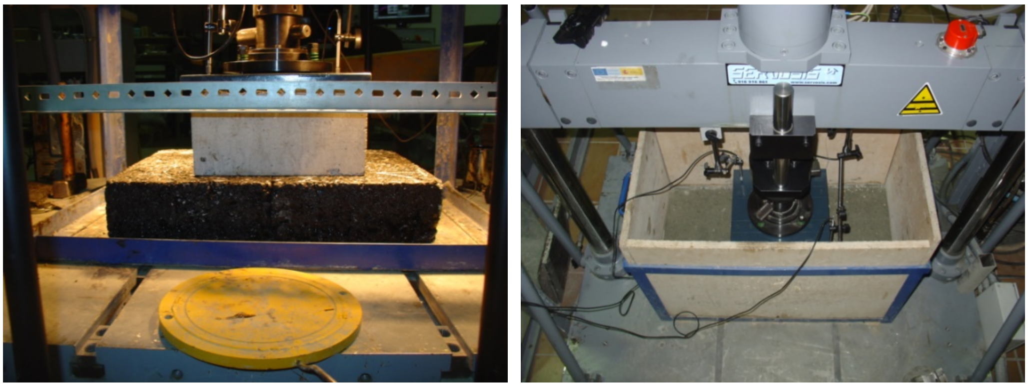

Figure 94. Plate bearing test on bituminous sub-ballast (left), and on granular sub-ballast (right).

4.3.4. PERMEABILITY

Permeameter test

With respect to the permeameter test, this was developed in consonance with the Standard EN 103403:1999, commonly used to determine the permeability of soils by applying the constant-head method. For this study, however, the permeameter device was a box with appropriate dimensions (a surface of 300 mm x 300 mm, and 500 mm in height) for testing samples with 220 mm and 120 mm (Figure 95 left and right, respectively) in height for granular and bituminous sub-ballast, respectively. At the bottom of the box, a geotextile and geomembrane were used to avoid losing fine particles of the samples, whilst water flow was not limited. In addition, a pipe (with 50 mm of diameter) was connected to the bottom of the box to collect the water drained by the sub-ballast. This system was also in consonance with those used by other authors (Parson et al., 2012). The parameter calculated was the evolution of the permeability for each type of sub-ballast, by applying the Darcy law.

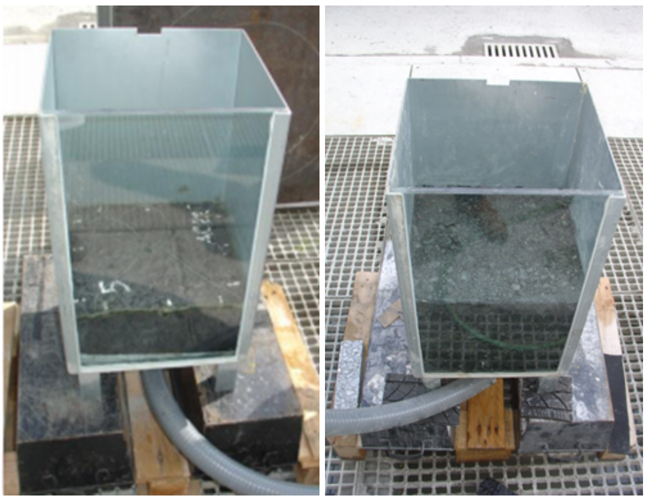

Figure 95. Permeameter test on bituminous sub-ballast (left), and on granular sub-ballast (right).

4.3.5. CRACK RESISTANCE

UGR-Fact Test

The UGR-FACT method (Moreno, 2013; Moreno et al., 2013; Moreno et al., 2014) was used in the present study, as it simulates the conditions that lead to the appearance of fatigue cracking in pavements, using a specimen glued to two sliding supports that induce flexion, tensile, and shear efforts (Figure 96).

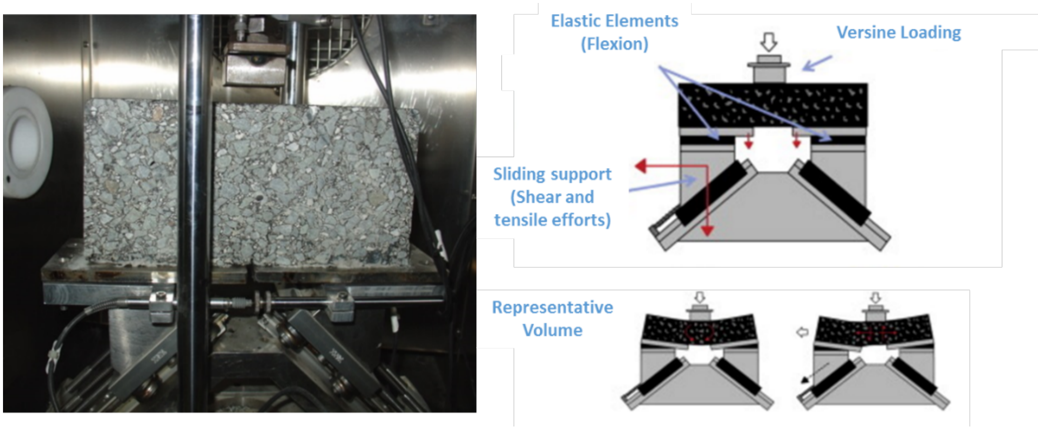

Figure 96. UGR-FACT test device.

Using versine cyclical loads, the device is able to simulate a controlled fatigue cracking process, and its development is studied through the energy dissipated by the material in a representative volume. This procedure avoids the problems associated with both the three-dimensional dispersion and random nature of fatigue cracking. The test was carried out at a frequency of 4 Hz and a stress of 200 kPa over the specimens (200 mm in length, 60 mm in width, and 120 mm in height) of bituminous sub-ballast, in accord with Moreno and Rubio (Moreno, 2013; Moreno et al., 2014). To evaluate the influence of the temperature on the cracking resistance of the bituminous specimens, the parameters used were the evolution of dissipated energy, the speed of cracking propagation, and the Mean Damage Parameter (γ), which is calculated as follows:

$$\gamma = \sum_{i=1}^{Nf} RDEC/Nf$$

Were:

Nf is the cycle in which the macro-crack appeared at the bottom of the sub-ballast layer.

The RDEC (Ratio of Dissipated Energy Change) was calculated according to the follow equation:

$$RDEC_{N+1} = (\omega_{n+1} - \omega_n)/\omega_n$$

Where:

ω_n is the energy dissipation produced in loading cycle number n (in J/m^3);

ω_{n+1} is the energy dissipation in loading cycle n + 1 (in J/m^3).

4.3.6. FULL SCALE ASSESSMENT

Full-Scale Test

To evaluate the effect of each configuration on the mechanical performance of the global railway section (from sub-ballast layer to the system sleeper-rail), a dynamic test was conducted to simulate the passage of trains. The test was carried out twice for each configuration studied, applying dynamic loads at a frequency of 4 Hz and an amplitude of 25 kN over a piece of rail. This value was fixed to reproduce a stress level of 900 kPa over the rail pad and 250–300 kPa over the ballast surface; these are values appropriate for the simulation of conventional loading conditions that are expected in railway tracks under permissible axle loads (Indraratna et al., 2006; Ho et al., 2013). The number of loading cycles was established at 200,000 in order to obtain a stable behaviour of the system and to measure the main parameters such as settlement, stiffness modulus, and energy dissipated by the section in both the short and long-term. The number of loading cycles was fixed by reference to other authors (Indraratna et al., 2006) who indicate that ballast behaviour in laboratory boxes is stable from 100,000 cycles. In addition, its capacity to dissipate stress was recorded by using pressure cells over and under the sub-ballast layer (Figure 97).

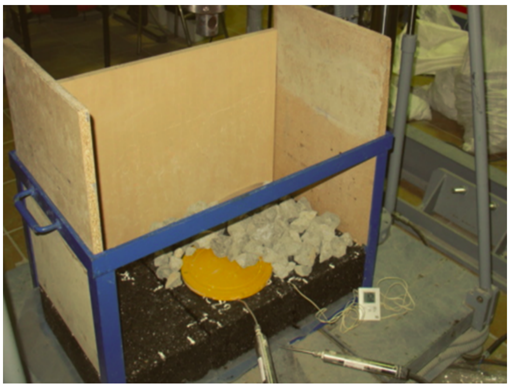

Figure 97. Full-Scale Test.

During the test, the evolution of the vertical settlement was measured in order to obtain the final total settlement recorded at the end of the test for each configuration. Regarding the parameters of vertical stiffness and dissipated energy, they were obtained as an average of the values recorded during the last 50,000 cycles when a stable behaviour of the system was presented. The stiffness values were obtained from the force-displacement curve (recorded per each loading cycle) as the relationship between the load and strain amplitude, whilst the dissipated energy was calculated from the area into the hysteresis loops.

4.4. WORK PLAN

4.4.1. PHASE 1 - REFERENCE SECTION

The purpose of the first phase of the methodology is to design, characterize, and optimize the reference section. For this purpose, the first phase can be divided into three sub-phases. The firs sub-phase (1.1) is focused on the analysis of the mechanical behaviour of conventional bituminous sub-ballast under various conditions that are expected to produce failure of the material. As a reference to evaluate the response of the bituminous material, the behaviour of conventional granular sub-ballast commonly used in railway tracks was also analysed.

With the aim of going into more depth in the study of the reference section, the following sub-phases analyse the behaviour of the track when different variables in the vertical configuration were included, analysing various types of sub-ballast, as well as the use of different elastic mats and even analysing the behaviour of the section without the sub-ballast layer.
In detail, Sub-phase 1.2 evaluates the influence of the bearing capacity of the bed layers under the ballast, whilst Sub-phase 1.3 assesses the effect of the thickness of the ballast layer considering only sections with bituminous sub-ballast layer.

4.4.1.1. PHASE 1.1 - CHARACTERISATION OF CONVENTIONAL BITUMINOUS SUB-BALLAST

In this part, an in-depth study was conducted in order to examine the feasibility of using bituminous sub-ballast under a range of conditions of service (including adverse climate conditions) in reference to granular sub-ballast (Figure 98).

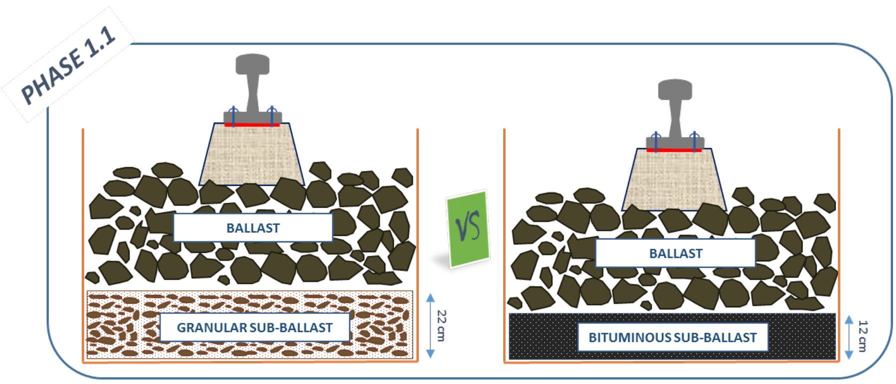

Figure 98. Sections analysed in Phase 1.1.

With this aim in mind, a series of conventional and specific laboratory tests were carried out. Marshall test (EN 12697-34:06), water sensitivity test (EN 12697-12:2009) and indirect tensile stiffness modulus test (EN 12697-26:2012, Annex C) were developed to characterize the conventional bituminous sub-ballast. Table 19 summarises the conventional test.

Test	Test temperature (°C)	Material tested	Main parameters
Marshall test	60	Bituminous sub-ballast	– Bulk density – Maximum density – Air voids – Marshall stability – Marshall flow
Water Sensitivity	15	Bituminous sub-ballast	– Retained indirect tensile strength
Indirect tensile tests	25	Bituminous sub-ballast	– Stiffness modulus

Table 19. Conventional laboratory test phase 1.1.

The cyclic triaxial test (EN 12697-25:2006, Method B) and a punching test were developed to assess its resistance to plastic deformations (associated with track settlement); a plate bearing test (EN 103808:2006) was conducted to measure the bearing capacity of the sub-ballast as well as its capacity to dissipate the stress transmitted to sub-grade; UGR-FACT test was used to study the resistance to cracking, which is a fundamental parameter in asphalt materials; a permeameter test was used to evaluate the capacity of the materials to protect the subgrade from water infiltration; and a full-scale test in a laboratory box was employed to measure the effect of the bituminous sub-ballast on the railway track section.
All of these tests (with the exception of the UGR-FACT test) were carried out for both types of sub-ballast. Table 20 summarises the specific laboratory test.

In addition, given that bituminous mixtures change their properties with temperature, exhibiting more rigid behaviour at lower temperatures whilst showing a softer response when the temperature increases (Hafeez et al., 2013; Moreno et al., 2015), the influence of this parameter on the behaviour of bituminous sub-ballast was evaluated. This evaluation was conducted in order to determine the feasibility of using the sub-ballast under the range of temperatures that this material can be expected to withstand when used in railway tracks, including both standard and adverse conditions, depending on the property studied.

<table>
<tr><th>Test</th><th>Test condition</th><th>Test temperature (°C)</th><th>Material tested</th><th>Main parameters</th></tr>
<tr><td rowspan="2">Triaxial cyclic test (Plastic deformation)</td><td rowspan="2">– Pa = 200 Kpa
– Pc = 80 Kpa
– f=3 Hz
– 1000 cycles</td><td>25</td><td>Granular sub-ballast</td><td rowspan="2">– Creep modulus
– Creep slope
– Permanent strain</td></tr>
<tr><td>25, 40, 60</td><td>Bituminous sub-ballast</td></tr>
<tr><td rowspan="2">Punching test (Plastic deformation)</td><td rowspan="2">– P = 200 Kpa
– f = 4 Hz
– 50000 cycles</td><td>25</td><td>Granular sub-ballast</td><td rowspan="2">– Permanent deformation by ballast punching</td></tr>
<tr><td>25, 40, 60</td><td>Bituminous sub-ballast</td></tr>
<tr><td rowspan="2">Plate bearing test (Bearing capacity, stress dissipation)</td><td rowspan="2">– Static:
P= 20, 50, 150, 250 Kpa
– Dynamic:
f = 4 hz - P = 200 Kpa
1000 cycles</td><td>25</td><td>Granular sub-ballast</td><td rowspan="2">– Static modulus
– Dynamic elastic modulus
– Stress under the sub-ballast</td></tr>
<tr><td>15, 25, 40</td><td>Bituminous sub-ballast</td></tr>
<tr><td>UGR-FACT (Cracking resistance)</td><td>– P = 200 Kpa
– f = 4 hz</td><td>15, 25, 40</td><td>Bituminous sub-ballast</td><td>– Evolution of dissipated energy
– Mean damage parameter</td></tr>
<tr><td rowspan="2">Permeameter (Permeability)</td><td rowspan="2">– Constant-head</td><td rowspan="2">25</td><td>Granular sub-ballast</td><td rowspan="2">– Time of saturation of the specimen
– Evolution of permeability</td></tr>
<tr><td>Bituminous sub-ballast</td></tr>
<tr><td rowspan="2">Full-scale test (Response of the track section)</td><td rowspan="2">– P = 25 Kn
– f = 4Hz
– 200000 cycles</td><td rowspan="2">25</td><td>Granular sub-ballast</td><td rowspan="2">– Settlement
– Vertical stiffness
– Dissipated energy
– Stress dissipation</td></tr>
<tr><td>Bituminous sub-ballast</td></tr>
</table>

Table 20. Specific laboratory test phase 1.1.

4.4.1.2. PHASE 1.2 - ANALYSIS OF DIFFERENT BED LAYER CONFIGURATIONS

The second sub-phase of the study of the reference section was concerned with examining the effect of varying the configuration of track section under the ballast layer (Figure 99), analysing various types of sub-ballast as well as the use of various elastic mats at different levels.

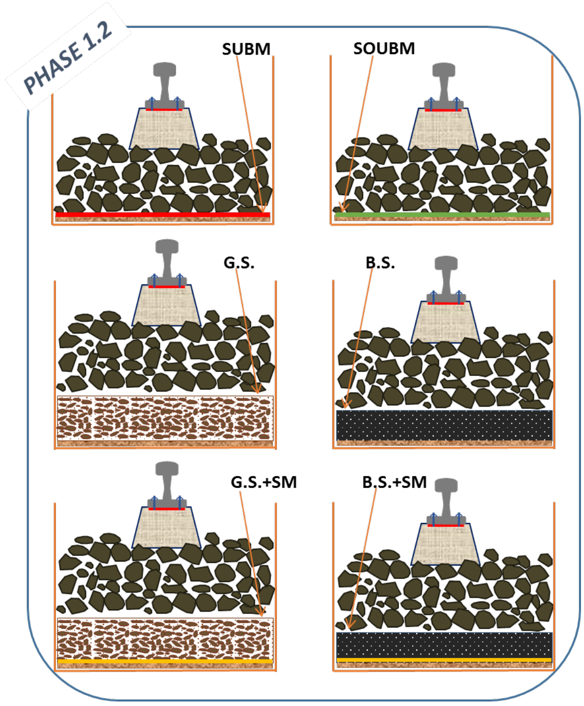

Figure 99. Sections analysed in Phase 1.2.

All these configurations included a sandy subgrade (on which the various solutions were placed), a ballast layer (30 cm thick), a piece of sleeper, the fastenings, whilst a rail and a constant stiff rail pad was used for all systems.

These 6 configurations also included the following:

- a stiff under-ballast mat (directly over the subgrade) ''SUBM";
- a soft under-ballast mat ''SOUBM";
- a granular sub-ballast layer between the subgrade and ballast ''G.S.";
- a bituminous sub-ballast ''B.S.";
- a granular sub-ballast and a stiff under sub-ballast mat ''G.S.+SM";
- a bituminous layer under the ballast and a stiff mat under the sub-ballast ''B.S.+SM".

For all these configurations, the static modulus of the system under the ballast was evaluated through a loading test that was developed in consonance with the loading conditions collected in the plate-bearing test (Table 21). This parameter was recorded with the aim of matching the influence of the bearing capacity of the system with its behaviour.

Test	Test condition	Test temperature (°C)	Section tested	Main parameters
Plate bearing test (Bearing capacity)	5 kN/min up to 300 kPa	25	– SUBM – SOUBM – G.S. – B.S. – G.S.+SM – B.S.+SM	– Static modulus – Vertical stiffness – Dissipated energy – Vertical stiffness

Table 21. Planning test phase 1.2.

4.4.1.3. PHASE 1.3 - INFLUENCE OF VARYING THE THICKNESS OF THE BALLAST LAYER

The last step evaluates the influence of varying the thickness of the ballast layer; two configurations were studied with a reduction in the ballast layer from 30 cm to 20 cm in order to compare its behaviour with that recorded for the configurations with 30 cm of ballast. Both sections with 20 cm of ballast were placed over bituminous sub-ballast and sandy ground (Figure 100), and one of them also included a very stiff mat under the asphalt sub-ballast to compare the technique of modifying ballast thickness with the effect of varying the configuration of elastic elements used in the railway track. Thus, these systems were:

- 20 cm ballast over bituminous sub-ballast ‘‘20 cm B.S.”;
- 20 cm ballast over bituminous sub-ballast and a stiff under sub-ballast mat ‘‘20 cm B.S.+SM”.

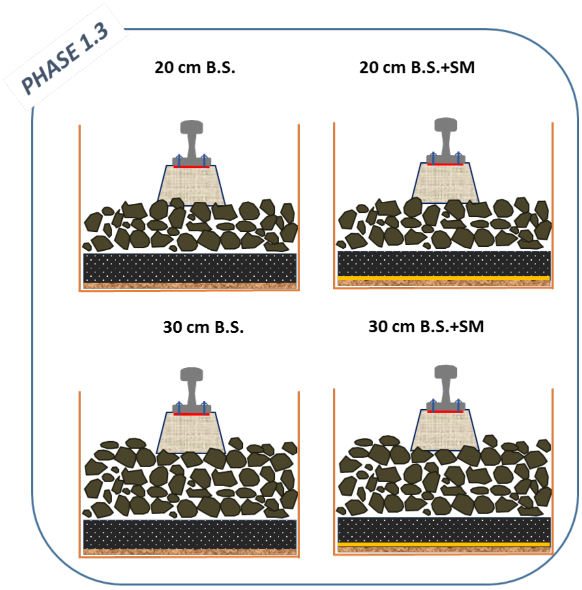

Figure 100. Sections analysed in Phase 1.3.

For this comparative analysis, the configurations ‘‘B.S.” and ‘‘B.S.+SM” were used as references, and for the purposes of this stage of the study they were denoted as ‘‘30 cm B.S.” and ‘‘30 cm B.S+SM”.

To evaluate the effect of each configuration on the mechanical performance of the global railway section, a dynamic test was conducted to simulate the passage of trains (Table 22).

Test	Test condition	Test temperature (°C)	Material tested	Main parameters
Full-scale test (Response of the track section)	– P = 25 Kn – f = 4Hz – 200000 cycles	25	– 20 cm B.S. – 20 cm B.S.+SM – 30 cm B.S. – 30 cm B.S.+SM	– Settlement – Vertical stiffness – Dissipated energy

Table 22. Planning test Phase 1.3.

In order to assess ballast behaviour, 4 LVDTs (one LVDT in each corner of the foot of the rail) were used to measure the section settlement and the mechanical behaviour. The main parameters measured were the global vertical stiffness of the section and its vertical settlement (both parameters associated with track deterioration, and therefore maintenance costs), as well as the dissipated energy (related to rolling resistance, and thus to service costs).

4.4.2. PHASE 2 - SUSTAINABLE BITUMINOUS SUB-BALLAST THROUGH REDUCTION ENERGY CONSUMPTION AND GAS EMISSIONS

The second phase of this thesis aims to compare the effects of using a WMA as sub-ballast with those of the conventional bituminous sub-ballast optimized in the previous phase (reference section) (Figure 101).

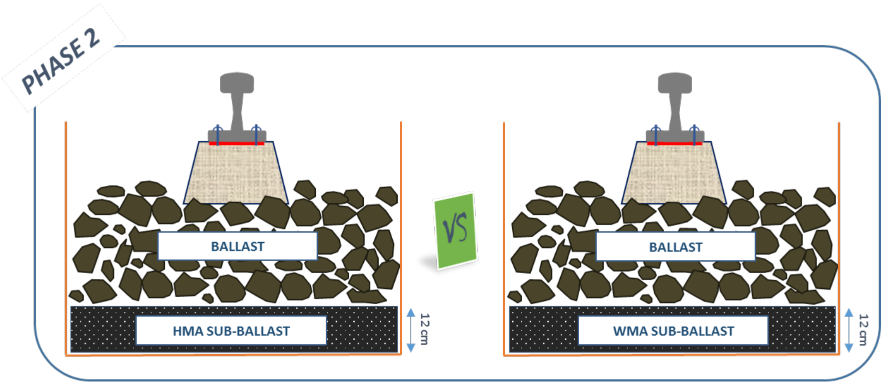

Figure 101. Sections analysed in the phase 2.

Even in this case, the first step was to characterize both types of bituminous sub-ballast with the same test used in the previous phase, which were: Marshall test (EN 12697-34:06), water sensitivity test (EN 12697-12:2009) and indirect tensile stiffness modulus test (EN 12697-26:2012, Annex C). Conventional bitumen type B 50/70 was used for both bituminous mixtures but a chemical additive was used to manufacture the WMA at 135 °C, while the temperature for the conventional mix (HMA) was 160 °C, whilst the same optimum bitumen content found for the HMA was used to manufacture the WMA.
Regarding the specific laboratory tests, in order to compare the mechanical performance of the WMA with that presented by conventional HMA, a number of laboratory tests were carried out to evaluate only the

main properties required of the sub-ballast layer. In particular, these tests evaluated resistance to plastic and punching deformations due to ballast punching, bearing capacity, stress dissipation, and waterproofing properties, whilst taking into account both standard temperatures of service and adverse climate conditions. In the final phase of the methodology, resistance to cracking and the effect on the performance was evaluated in a full-scale testing box. Table 23 summarises the specific laboratory test used in Phase 2.

Test	Test condition	Test temperature (°C)	Material tested	Main parameters
Triaxial cyclic test (Plastic deformation)	– Pa = 200 Kpa – Pc = 80 Kpa – f=3 Hz – 1000 cycles	25, 40, 60	WMA sub-ballast HMA sub-ballast	– Creep modulus – Creep slope – Permanent strain
Punching test (Plastic deformation)	– P = 200 Kpa – f = 4 Hz – 50000 cycles	25, 40	WMA sub-ballast HMA sub-ballast	– Permanent deformation by ballast punching
Plate bearing test (Bearing capacity, stress dissipation)	– Static: P= 20, 50, 150, 250 Kpa – Dynamic: f = 4 hz - P = 200 Kpa 1000 cycles	25, 40	WMA sub-ballast HMA sub-ballast	– Static modulus – Dynamic elastic modulus – Stress under the sub-ballast
Permeameter (Permeability)	– Constant-head	25	WMA sub-ballast HMA sub-ballast	– Time of saturation of the specimen – Evolution of permeability

Table 23. Specific laboratory test phase 2.

4.4.3. PHASE 3 - SUSTAINABLE BITUMINOUS SUB-BALLAST USING WASTE RECOVERY

4.4.3.1. PHASE 3.1 - DESIGN, CHARACTERIZATION, AND ANALYSIS OF THE MECHANICAL BEHAVIOUR OF RUBBERIZED BITUMINOUS SUB-BALLAST

The aim of Phase 3.1 is to evaluate the mechanical behaviour of bituminous sub-ballast crumb rubber modified by wet process (WRA) and dry process (DRA) with respect to its main functions and requirements in railway tracks, and to compare their response with the conventional bituminous sub-ballast (HMA), as shown in Figure 102.

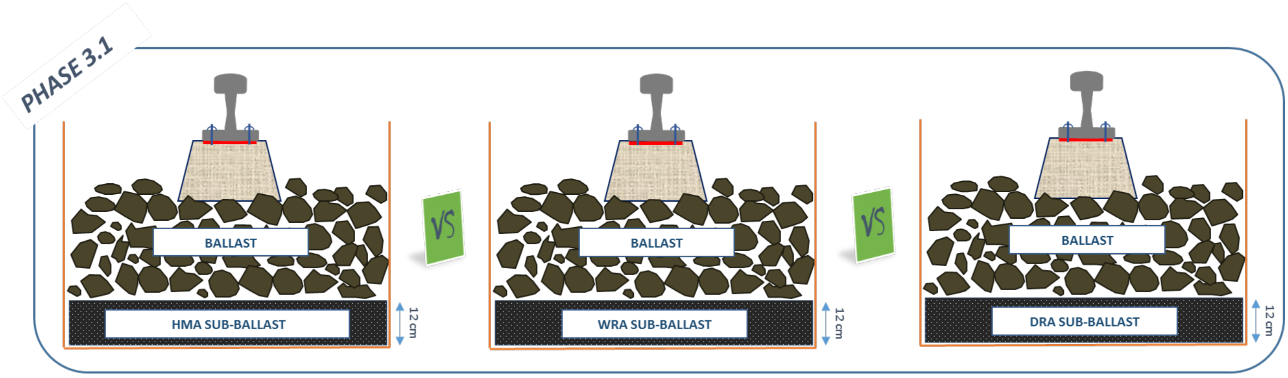

Figure 102. Sections analysed in Phase 3.1.

This phase follows the methodology of Phase 2 for both the characterization tests (Marshall test, water sensitivity test and indirect tensile stiffness modulus test) and specific tests. Table 23 summarises the specific laboratory test for Phase 3.1.

4.4.3.2. PHASE 3.2 - DESIGN, CHARACTERIZATION, AND ANALYSIS OF THE MECHANICAL BEHAVIOUR OF RECLAIMED ASPHALT PAVEMENT SUB-BALLAST

As in the previous phase, and staying on the subject of waste recovery, the aim of Phase 3.2 is to evaluate the mechanical behaviour of HWMA with 100% RAP sub-ballast (half-warm mix reclaimed pavement) and to compare again its response with the conventional bituminous sub-ballast (HMA), as shown in Figure 103.

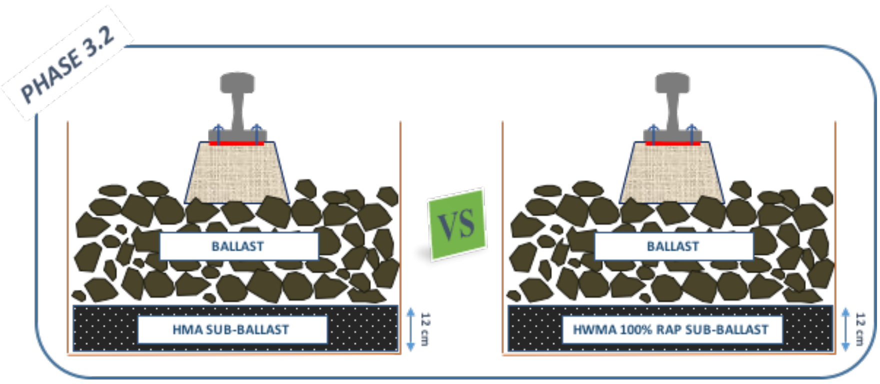

Figure 103. Sections analysed in Phase 3.2.

This phase followed the methodology of the previous phases for the characterization tests (Marshall test, water sensitivity test and indirect tensile stiffness modulus test) and specific tests (Table 24).

Test	Test condition	Test temperature (°C)	Material tested	Main parameters
Triaxial cyclic test (Plastic deformation)	– Pa = 200 Kpa – Pc = 80 Kpa – f=3 Hz – 1000 cycles	25, 40, 60	HMA sub-ballast	– Creep modulus – Creep slope – Permanent strain
			HWMA 100%RAP Sub-ballast	
Punching test (Plastic deformation)	– P = 200 Kpa – f = 4 Hz – 50000 cycles	25, 40	HMA sub-ballast	– Permanent deformation by ballast punching
			HWMA 100%RAP Sub-ballast	
Plate bearing test (Bearing capacity, stress dissipation)	– Static: P= 20, 50, 150, 250 Kpa – Dynamic: f = 4 hz - P = 200 Kpa – 1000 cycles	25, 40	HMA sub-ballast	– Static modulus – Dynamic elastic modulus – Stress under the sub-ballast
			HWMA 100%RAP Sub-ballast	
Permeameter (Permeability)	– Constant-head	25	HMA sub-ballast	– Time of saturation of the specimen – Evolution of permeability
			HWMA 100%RAP Sub-ballast	

Table 24. Specific laboratory Phase 3.2.

RESULTS AND DISCUSSION

5. RESULTS AND DISCUSSION

5.1. INTRODUCTION

This chapter includes the results obtained in this doctoral thesis, with the analysis of the results being conducted in consonance with the different phases of the present research, as described in the methodology chapter.

5.2. PHASE 1 – REFERENCE SECTION

The first phase has been divided into three sub-phases:

- Characterisation of conventional sub-ballast;
- Analysis of different bed layer configuration;
- Influence of different thickness of the ballast layer.

5.2.1. PHASE 1.1 – CHARACTERISATION OF CONVENTIONAL SUB-BALLAST

The asphalt layer studied as sub-ballast was a dense-grade mixture type AC 22 S (EN 13108-1:2007) with a maximum aggregate size equal to 22 mm. This material was manufactured using limestone aggregates and conventional bitumen type B 50/70, whilst the filler was cement type CEM II/B-L 32,5 N. The results of characterization obtained for the conventional bituminous sub-ballast are shown in Table 25, listing the main properties of this material.

Properties	Standard	Bituminous sub-ballast
Marshall test		
Bitumen Content (% over the total weight of the mixture)	-	4.25
Maximum Density (Mg/m^3)	EN 12697-5:10	2.643
Bulk Density (Mg/m^3)	EN 12697-6:12	2.573
Air Voids (%)	EN 12697-8:03	2.6
Marshall Stability (kN)	NLT-159/00	13.306
Marshall Flow (mm)	NLT-159/00	3.4
Water sensitivity test		
Indirect tensile strength for the dry set (kPa)	EN 12697-12:09	2159.9
Indirect tensile strength for the wet set (kPa)	EN 12697-12:09	1857.8
Index of retained tensile strength after water action (%)	EN 12697-12:09	86
ITSM		
Stiffness Modulus at 25 °C (MPa)	EN 12697-26:12	5338

Table 25. Main properties of the asphalt mixture used as sub-ballast

PLASTIC-PUNCHING DEFORMATIONS

Two tests were carried out to evaluate plastic deformation: the *triaxial test,* and the *punching test* to evaluate the resistance to plastic deformations under more realistic load conditions.

Figure 104 displays the results obtained during the triaxial test for the granular sub-ballast and conventional bituminous sub-ballast, analysing the effect of temperature on the behaviour of the bituminous sub-ballast. The parameters shown are the permanent deformation (P.D.) recorded for each sample under the different conditions, along with the mean value of creep modulus and the slope of creep deformation (S.C.D.), this last parameter being measured during the final 5000 loading cycles.

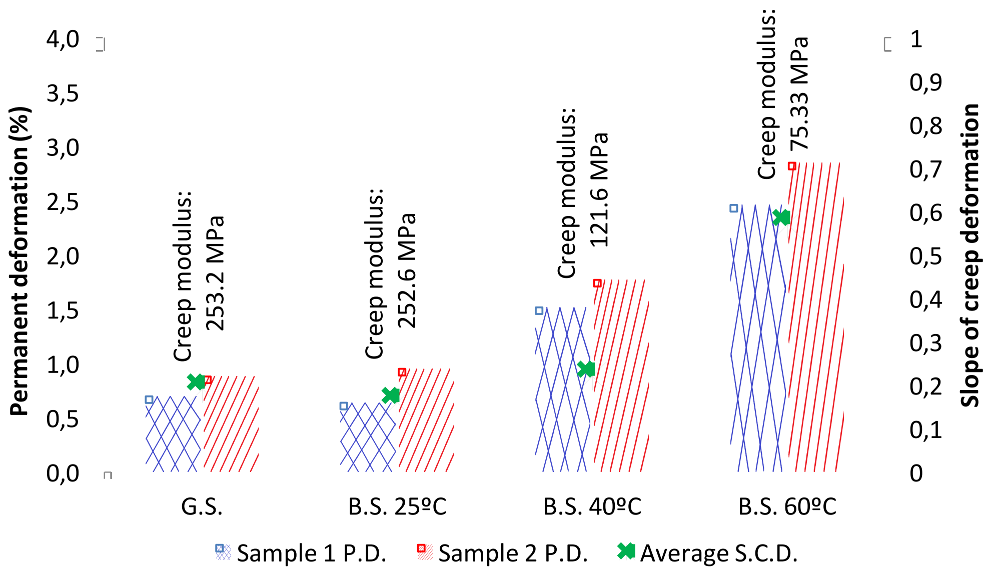

Figure 104. Results of the triaxial test for conventional granular and bituminous sub-ballast.

The results indicate that, at least under routine in-service temperature conditions, the bituminous sub-ballast displayed a resistance to plastic deformations similar to that obtained for the conventional granular sub-ballast, since both layers recorded comparable mean values of permanent deformation, slope of deformation, and even creep modulus. This fact indicates the potential for using bituminous sub-ballast in railway tracks without increasing plastic deformations due to bitumen creep.

Moreover, the increase in sub-ballast temperature that can occur in warm climates led to a notable decrease in the resistance of the bituminous material against plastic deformations, recording an important increase in final deformation and the slope of the creep curve, whilst the creep modulus decreased up to a value of around 50% and 30% in the case of 40 °C and 60 °C, respectively. This decrease in resistance to deformation could limit the use of this type of sub-ballast in railway lines where the temperature is expected to be high for this layer, although it is also worth noting that the ballast layer protects the sub-ballast from high temperatures. Therefore, before applying the bituminous material in warm regions, it is recommended that a preliminary study be conducted in order to assess the expected temperature of service for the sub-ballast.

Regarding the punching test, Figure 105 shows an example of the deformation curves obtained in the punching test during this phase, which allows for a more realistic reproduction of the loads transmitted by the ballast to the sub-ballast layer. Based on the curve displayed in Figure 107, there are three phases of the behaviour of the sub-ballast that are delimited by two inflexion points:

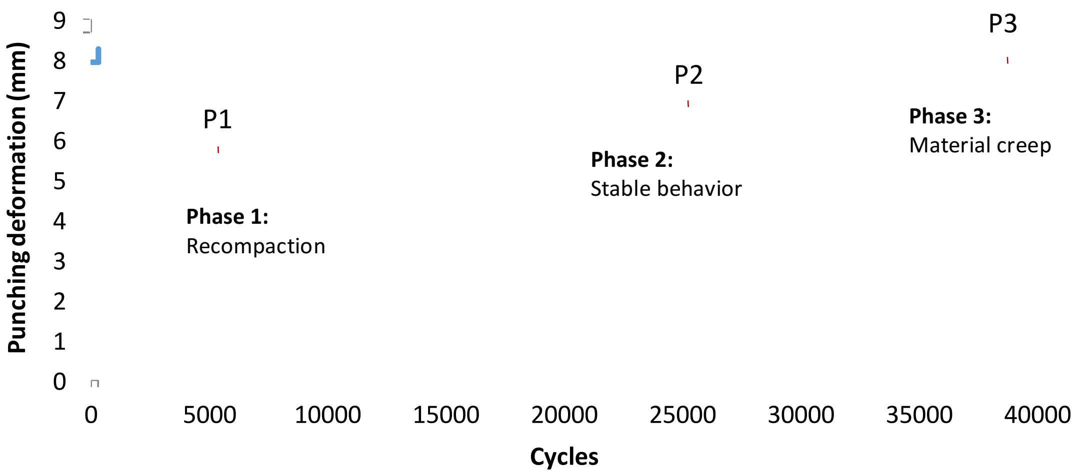

Figure 105. Example of the deformation curves recorded during the punching test.

‘‘P1” separates the initial deformation (primarily associated with the compaction and reorganisation of particles) from a phase where the deformation response is stabilised; and a second inflexion point ‘‘P2” separates the latter from a phase of creep deformation of the material. In addition, there is a further point ‘‘P3” that indicates the final permanent deformation under punching efforts.

From these points, the response of both types of sub-ballast under various temperature conditions was analysed through the values of initial deformation (P1), slope of the curve in the second phase (between P1 and P2), and the final permanent deformation (P3), all listed in Table 26. Again, these results show that the bituminous sub-ballast recorded a resistance to plastic deformations similar to (or even higher than) that measured for the granular material under routine in-service temperatures for this layer. Nonetheless, the bituminous sub-ballast demonstrated a significant susceptibility to higher temperatures, since both higher initial and final deformations were recorded under extreme conditions (40 °C, and particularly 60 °C) and the tendency towards developing long-term deformation was more pronounced than in the case of the material tested under routine temperature conditions (25 °C).

Materials	Temperature (°C)	Initial deformation (mm)	Slope of the curve in the stable phase (mm/cycle)	Final deformation (mm)
Granular sub-ballast	25	1.8	5.65E-05	8.1
Bituminous sub-ballast	25	2.0	5.14E-05	7.9
	40	3.1	6.85E-05	8.3
	60	5.2	1.78E-04	11.1

Table 26. Results of the punching test for bituminous sub-ballasts and granular sub-ballast under different temperatures.

BEARING CAPACITY-STRESS DISTRIBUTION

In relation to the bearing capacity of the materials, Figure 106 displays the static and dynamic modulus measured in the *plate-bearing test* for both granular sub-ballast (G.S.) and bituminous sub-ballast (B.S.) under the range of in-service temperatures that can be expected in railway tracks for this layer.

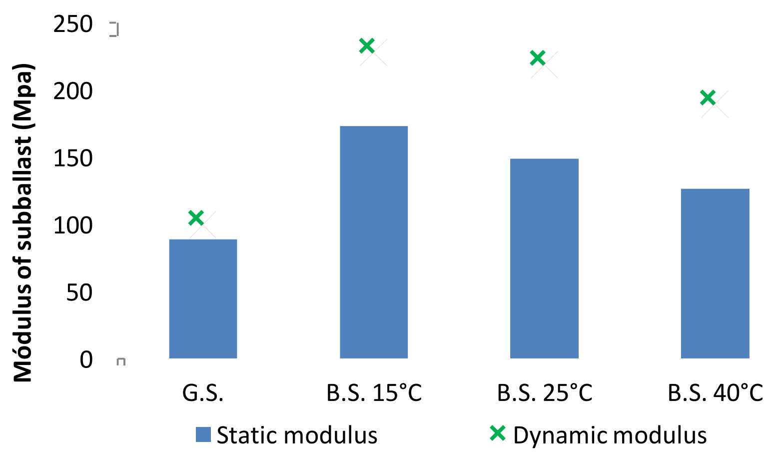

Figure 106. Static and dynamic modulus for bituminous sub-ballasts and granular sub-ballast.

It is clear that the bituminous sub-ballast presented a higher bearing capacity (static and dynamic) than the conventional granular layer, even under the adverse temperature conditions (40 °C) that could prevail in extreme climates. This observation, which is in agreement with results described by other authors (Rose J.G., 2014), indicates that the use of bituminous sub-ballast could lead to an increase in the strength of the railway structure, offering higher protection of the bed layers and foundation of the track, particularly under low temperatures (15 °C) at which the highest modulus was recorded. In addition, this increase in bearing capacity associated with bituminous sub-ballast was even more marked under the dynamic loads that reproduce the real conditions expected in railway tracks with passing trains, an observation that is likely to be linked to an increase in the elasticity of bituminous materials under dynamic loads.

The results related to bearing capacity are compatible with those obtained from the measurement (by using pressure cells) of stress dissipation during the plate-bearing test for both types of sub-ballast under various loading and temperature conditions (Figure 107).

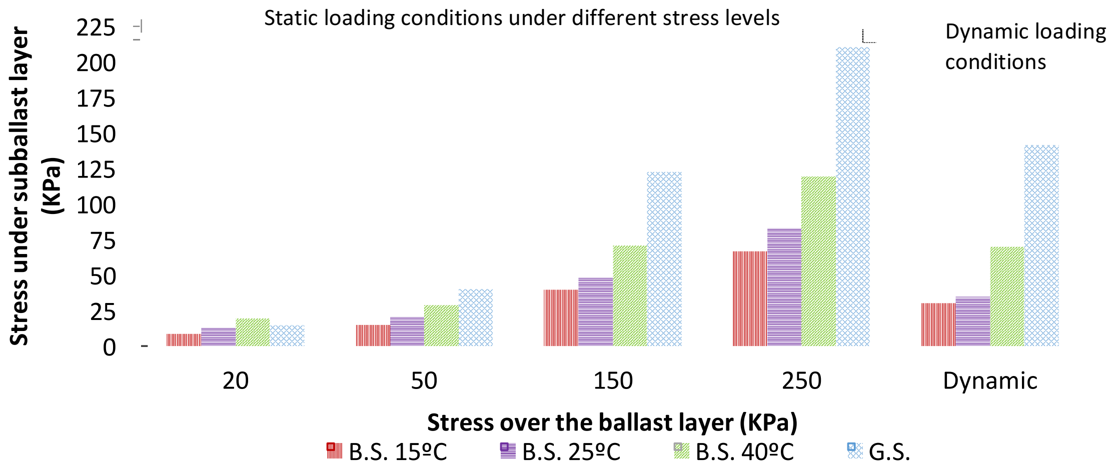

Figure 107. Pressure transmitted by bituminous sub-ballasts and granular sub-ballast under various loading and temperature conditions.

The results, which are in consonance with other studies (Rose et al., 2002), indicate that under low levels of stress, there is little impact of the temperature and the type of sub-ballast. However, when the stress is increased up to the levels expected in railway tracks (between 150 kPa and 250 kPa), the influence of the temperature is higher on the bituminous sub-ballast that showed a lower capacity to dissipate the stress when temperature is increased, which must be related to a decrease in its strength. Nonetheless, under the various temperatures used in this study (both routine temperatures and adverse temperatures such as 40 °C) and also under the various loading conditions (different stress levels under static conditions as well as dynamic loads), this material presented lower values (up to around 50% lower) of stress under the layer than those measured for the granular sub-ballast. This fact indicates that the use of bituminous sub-ballast allows for higher protection of the remaining bed layers of the railway track, since lower stress is transmitted to these layers under the passage of trains, regardless of the temperature.

PERMEABILITY

Another important parameter for evaluating the feasibility of applying sub-ballast in railway tracks is the capacity of this layer to waterproof the remainder of the substructure. Thus, Figure 108 displays the results measured in the permeameter test (constant-head method) for both types of sub-ballast used in this study, showing the evolution of the drained flow and the permeability coefficient (k) once the flow is stabilised in each case. It is clear that for the bituminous sub-ballast, a longer time (3600 seconds) was recorded without the transmission of water (flow equal to 0 m^3/s) when compared with the conventional granular sub-ballast (570 seconds), which also recorded higher values of flow during the test. In addition, the latter material needed a longer time to stabilise the drained flow, which could be related to the movements of fine particles toward the bottom of the layer, which reduced the permeability up to k = 2.39 x 10-6 m/s, although this value was always higher than that measured for the bituminous sub-ballast (k close to 5.7 x 10-7 m/s), which presented an appropriate coefficient of permeability for its application in railway tracks according to the Spanish Standard for sub-ballast (PF-7, 2006).

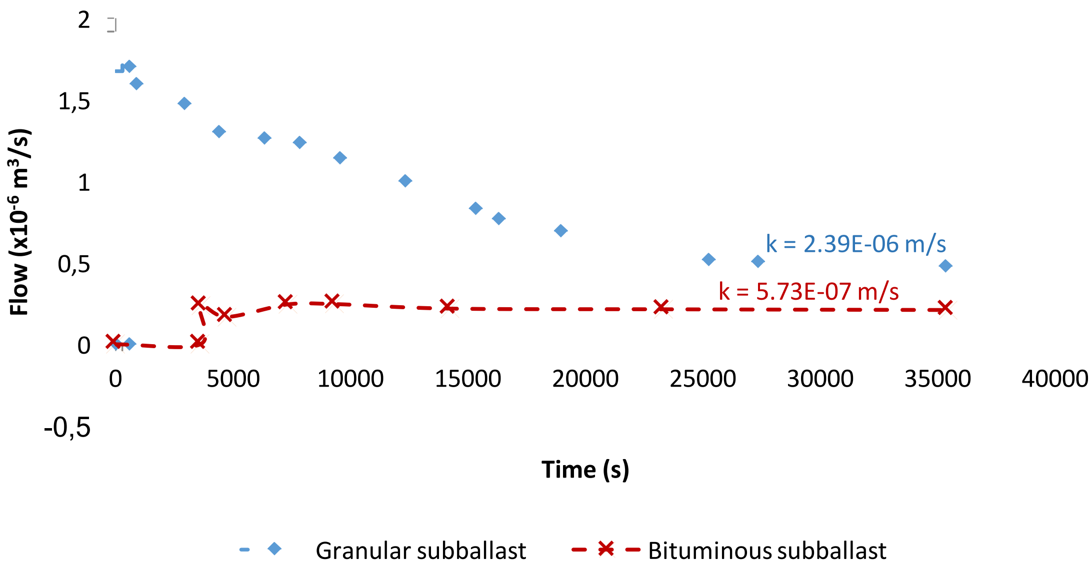

Figure 108. Evolution of the water flow drained by bituminous sub-ballasts and granular sub-ballast: Permeability results.

Based on these results, it is possible that the application of an asphalt layer as sub-ballast can reduce the infiltration of water into the bed layers of the railway track, thereby providing the substructure with higher protection against water action. This is in agreement with the results of other work (Rose and Bryson, 2009) where it has been demonstrated that the use of bituminous sub-ballast leads to a lower variation in the moisture content of the bed layers.

CRACKING RESISTANCE

Figure 109 displays the effect of temperature on the cracking fatigue of bituminous sub-ballast. This figure shows the mean value of the number of cycles needed to initiate the macro-crack at the bottom of the layer, the results of Mean Damage Parameter, and the speed of cracking propagation (measured in mm/cycle after the beginning of the macro-crack in each specimen).

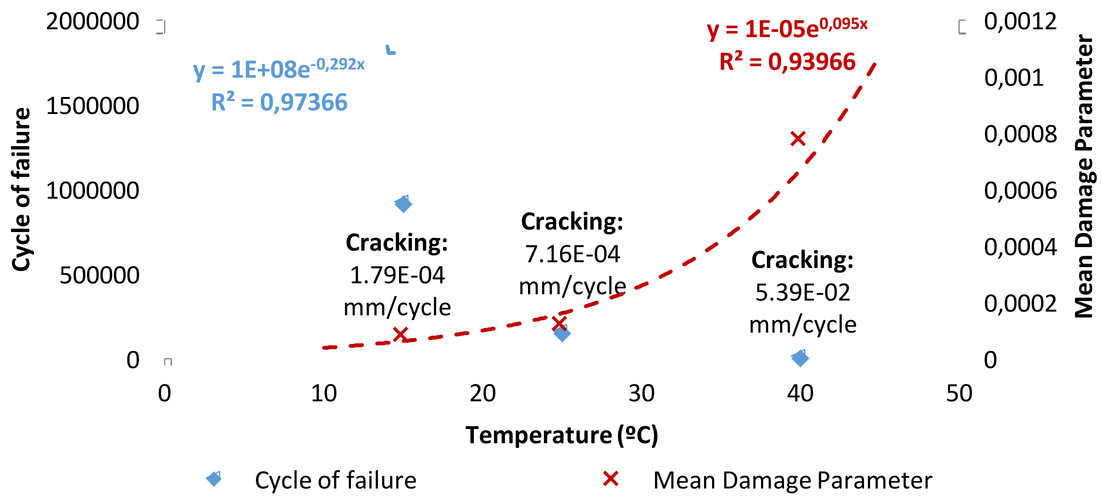

Figure 109. Effect of temperature on the cracking resistance of conventional bituminous sub-ballast.

It appears that temperature plays a very important role in the cracking endurance of bituminous sub-ballast since an increase in this parameter led to a sharp rise in the damage suffered by the material (particularly at higher temperatures such as 40 °C), which caused a notable decrease in the number of cycles needed to provoke cracking of the material. In addition, the change of temperature also caused an important increase in the speed of propagation of the crack, which accelerates the failure of the sub-ballast, especially at 40 °C. Thus, these results indicate that bituminous sub-ballast is more susceptible to cracking under the higher temperatures that can be expected in warm climates. In addition, under these conditions there may also be a significant reduction in the protection of bed layers in the substructure, along with the infiltration of water to the foundation.

FULL-SCALE ASSESSMENT

Having studied the behaviour of each type of sub-ballast, Figure 110 shows its effect on the settlement (left) and stiffness (right) of a full-scale section of the railway track (from sub-ballast to rail) whilst Figure 10 displays the impact of the type of sub-ballast on the capacity of the section to dissipate energy (left) and the stress (right) transmitted by passing trains. This last parameter (recorded by using pressure cells) is presented as the difference in the mean value of stress over and under each sub-ballast layer measured when the section behaviour was stable (after approximately 50,000 loading cycles).

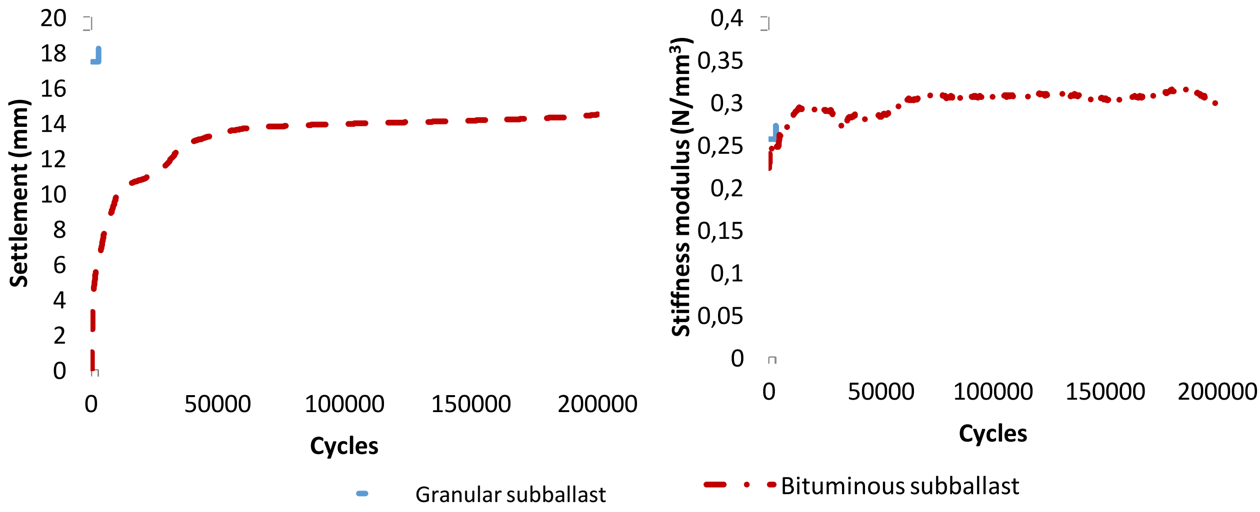

Figure 110. Influence of the type of sub-ballast on track settlement (left) and modulus stiffness (right).

The results indicate that the use of bituminous sub-ballast could lead to a slight reduction in track settlement, particularly in the long-term, when the granular sub-ballast showed a trend toward developing higher vertical deformations compared with the case in which the bituminous material was used. This fact could be related to the difference in vertical stiffness (Figure 111, right) since the section with asphalt layer presented higher strength under the train loads reproduced in the laboratory, which is in agreement with the results of the bearing capacity test where higher strength of the bituminous sub-ballast was recorded.

In addition, it should be noted that in spite of the stiffening of the section with the application of the bituminous layer, its capacity to dissipate the energy transmitted by the trains (Figure 111, left) is quite similar to that recorded when granular sub-ballast is used, which is likely to be related to the viscous behaviour of asphalt materials. Furthermore, despite the fact that the pressure over the sub-ballast (Figure 111, right) is higher when the bituminous layer is used (as a result of the stiffening of the structure), the stress transmitted to the remainder of the bed layers is lower in this case, since the asphalt material presented a higher capacity to dissipate stress. Thus, it appears that the use of bituminous sub-ballast could allow for an improvement of the track quality (associated with the reduction in settlement) and durability (related to higher protection of the bed layers against train loads).

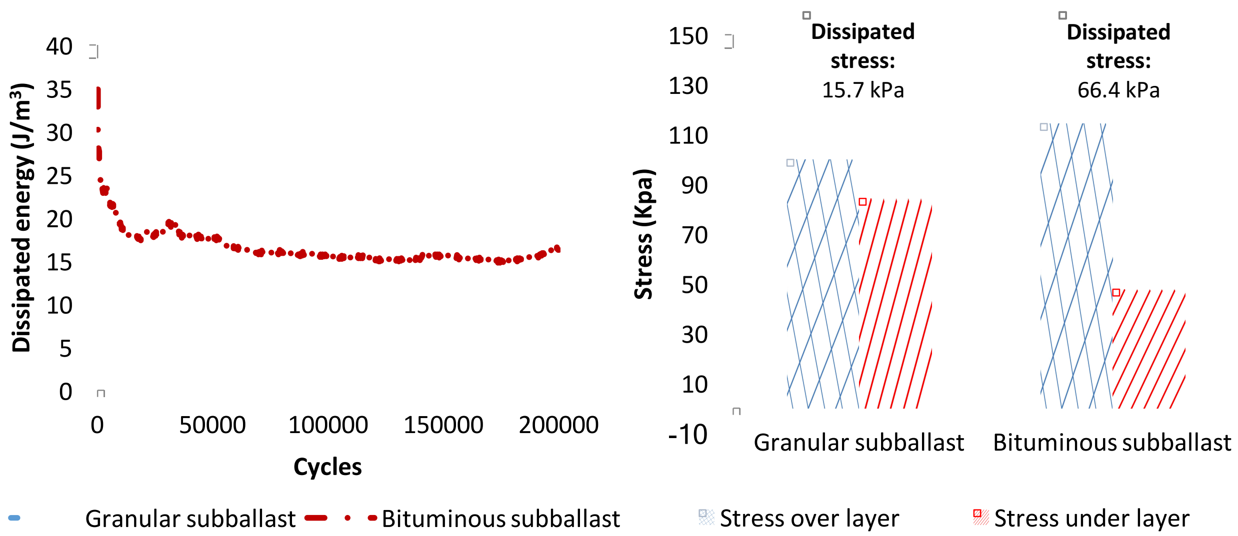

Figure 111. Effect of bituminous sub-ballasts and granular sub-ballast on the capacity of the track to dissipate energy (left) and stress (right) under trains passing.

5.2.2. PHASE 1.2 – ANALYSIS OF DIFFERENT BED LAYER CONFIGURATIONS

With the aim of assessing the influence of the configuration of the railway section under the ballast layer, Figure 112 presents the global modulus stiffness of the system in reference to the bearing capacity (calculated from the plate bearing test) of the bed layers depending on the configuration studied (incorporation of different UBMs, use of various types of sub-ballast, and addition of under sub-ballast mat).

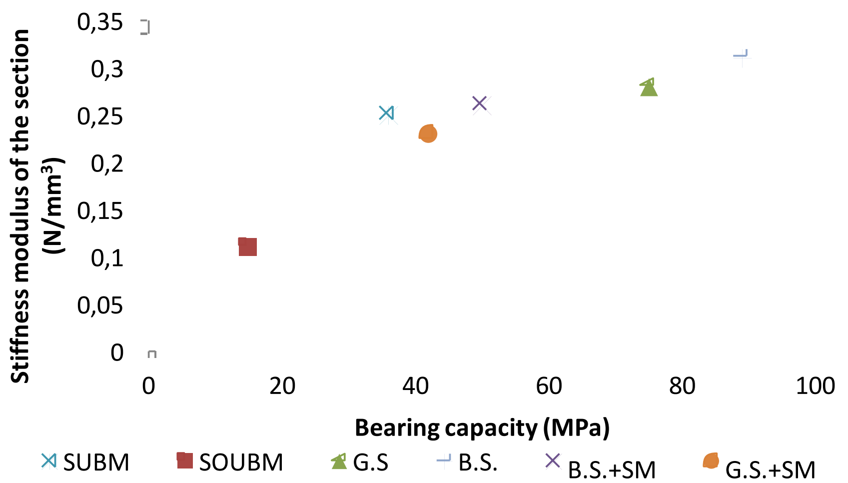

Figure 112. Effect of bed layer configuration on track stiffness.

The results show that the use of the different types of sub-ballast analysed in this phase (granular and bituminous) caused low variations in bearing capacity, which indicates that the use of a granular material can lead to a track strength similar to that obtained with an asphalt layer, as long as the granular sub-ballast presents a high vertical modulus associated with its appropriate compaction. In contrast, the incorporation of elastic elements under the ballast (or even under the sub-ballast) leads to an important reduction in the bearing capacity of the system, an effect that is more marked when softer elements are used.

Regardless of the configuration, it was shown that such reduction in bearing capacity leads to a decrease in the global stiffness of the track section, with the maximum value recorded in this study ranging from 0.308 N/mm^3 (section over bituminous sub-ballast ‘‘B.S.”) to 0.11 N/mm^3 (recorded for the system with soft UBM ‘‘SOUBM”), which corresponds to a variation of almost 63.9% whilst the reduction in bearing capacity was close to 277.5%. This fact indicates that, similar to what occurs when modifying the stiffness of elastic elements over the ballast layer, the changes in the global section are lower than those recorded for the properties of the bed layers.

In addition, Figure 113 shows the influence of the bearing capacity of the bed layers on the density of dissipated energy (dissipated energy per cycle/volume of the section) and settlement of the section. It is again possible to demonstrate that the use of different types of sub-ballast (G.S. or B.S.) caused lower variations in track behaviour than those recorded when elastic mats (either under ballast or under sub-ballast) used between the bed layers, which indicates that the effect of this latter type of component is predominantly on the track response.

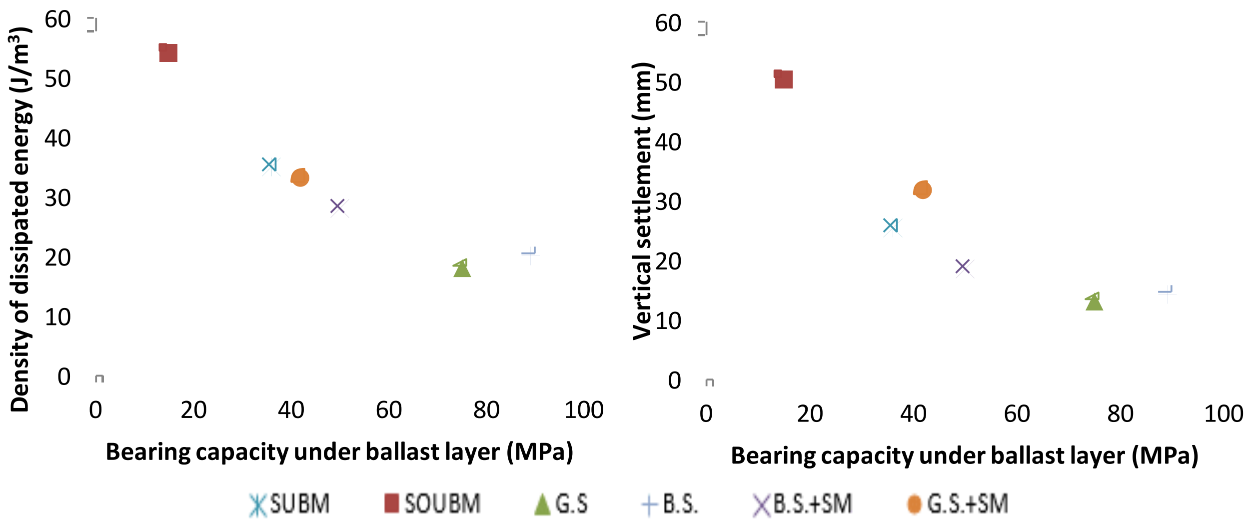

Figure 113. Influence of the bed layers on track behavior

In addition, it was generally observed that the reduction in the bed layer strength was related to a higher capacity of the system to dissipate the energy of passing trains, but higher settlement was also obtained, as indicated by other authors (Hunt G.A., 1997). This fact indicates that the increase in dissipated energy could be associated with an increase in vertical movements of ballast particles that provokes section deformation. Therefore, for modern railway tracks where higher geometric quality is required, the use of bed layers (such as elastic elements under the granular layers) that cause a decrease in bearing capacity should be limited, unless they are used over very rigid structures that can offer an adequate global bearing capacity.

5.2.3. PHASE 1.3 - INFLUENCE OF VARYING THE THICKNESS OF THE BALLAST LAYER

Figure 114 displays the variation in modulus stiffness of the section when the thickness of the ballast is reduced from 30 cm to 20 cm, using as a reference (value of 100%) the section with 30 cm of ballast without an elastic mat (30 cm B.S.). This effect is analysed in two different configurations: over bituminous sub-ballast (using the system with 30 cm as a reference, and therefore assigned a value of 100%), and over sub-ballast with the addition of an elastic mat under this system. Results indicate that the reduction in ballast thickness caused, in both cases, the stiffening of the section in reference to the same configuration, but with 30 cm of ballast. In spite of this increase in stiffness, for the configuration with elastic mat under the sub-ballast the stiffening (close to 8%) was lower than that for the system without a mat (40%), even obtaining a modulus (system ‘‘20 cm B.S.+SM”) lower than the reference section with 30 cm of ballast and without the mat (‘‘30 cm B.S.”). This indicates that the effect of the elastic mat is stronger than the influence of ballast thickness.

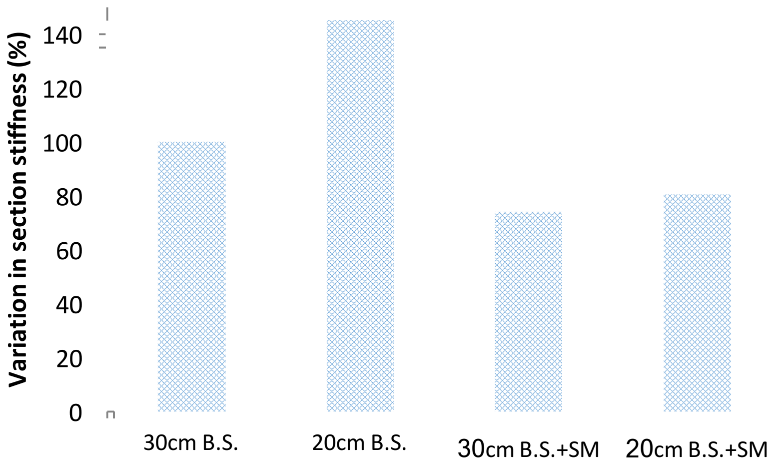

Figure 114. Influence of ballast thickness on track stiffness.

In reference to its effect on the mechanical performance of the section, Figure 115 shows the variations in dissipated energy and settlement. Again, it was seen that the influence of the mat was higher than that of the ballast thickness, since despite the fact that in both cases (20 cm of ballast with and without under sub-ballast mat) the energy dissipated and settlement were reduced in reference to the systems with 30 cm of ballast, the configuration ‘‘20 cm B.S. +SM” presented higher values than those measured for the reference section, ‘‘30 cm B.S.”.

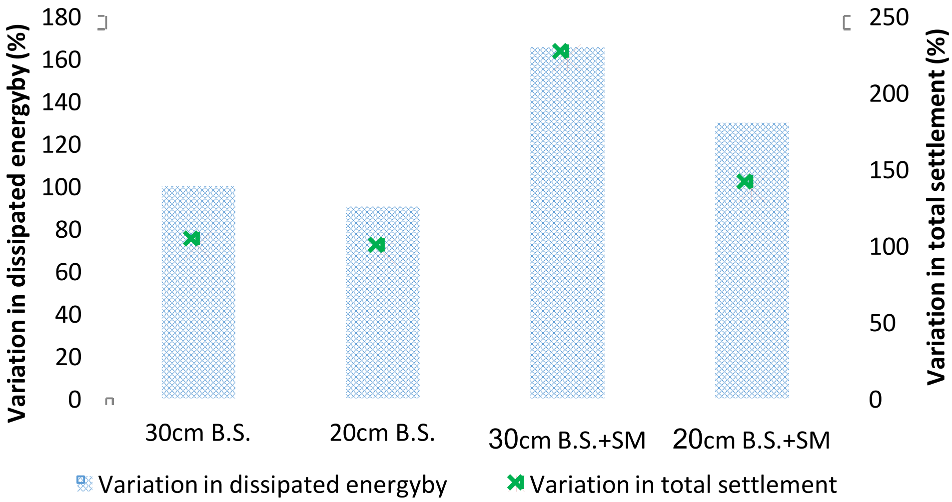

Figure 115. Impact of the ballast thickness on the track behaviour.

The incorporation of elastic elements between the bed layers (under ballast or sub-ballast mats) or the use of more flexible sub-ballast led to lower bearing capacity of the system, which caused an important reduction in global stiffness and an increase in dissipated energy and track settlement. The use of thinner ballast layer produced a stiffening of the track as well as a reduction in the dissipated energy and the settlements. However, when elastic mats were used in the railway track, the effect of reducing the ballast thickness was lower, since the behaviour of the elastic element is predominant, and therefore, lower global stiffness was observed, along with higher dissipated energy and settlement values in comparison with the system that had a thicker ballast layer.

For all these reasons, the decision was made to proceed using a section consisting of 12 cm of bituminous sub-ballast and 30 cm ballast as reference section.

5.3. PHASE 2 – SUSTAINABLE BITUMINOUS SUB-BALLAST THROUGH A REDUCTION IN ENERGY CONSUMPTION AND GAS EMISSIONS

CHARACTERIZATION OF THE MIX

Table 27 lists the main properties for the conventional hot mix asphalt and the warm mix asphalt recorded during the characterization tests.

Properties	Standard	HMA	WMA
Marshall test			
Bitumen Content (% over the total weight of the mixture)	-	4,25	4,25
Maximum Density (Mg/m^3)	EN 12697-5:10	2,643	2,646
Bulk Density (Mg/m^3)	EN 12697-6:12	2,573	2,575
Air Voids (%)	EN 12697-8:03	2,6	2,7
Marshall Stability (kN)	NLT-159/00	13,306	9,967
Marshall Flow (mm)	NLT-159/00	3,4	3,4
Water sensitivity test			
Indirect tensile strength for the dry set (kPa)	EN 12697-12:09	2159.9	1600.3
Indirect tensile strength for the wet set (kPa)	EN 12697-12:09	1857.8	1490.2
Index of retained tensile strength after water action (%)	EN 12697-12:09	86	93,1
ITSM			
Stiffness Modulus at 25 °C (MPa)	EN 12697-26:12	5338	4669

Table 27. Main properties of the HMA and WMA used as sub-ballast.

The Marshall Test results indicate that both mixtures have very similar values of density and air voids. This implies that use of the additive could improve the workability of the WMA, despite a 25 °C reduction in the manufacturing temperature (Rubio-Gámez et al., 2012; You et al., 2008; Zaumanis, 2010). It is also clear that in spite of the values of Marshall Flow being very similar for both mixtures (3,4 mm), there was a decrease of Marshall Stability in the warm mix sub-ballast.

The same occurred during the Water sensitivity test, where indirect tensile strength of WMA decreased with respect to that recorded for the conventional HMA. However, there was an improvement in the indirect tensile strength ratio (ITSR %). This is probably due to the lower compaction temperature that could increase the potential for moisture damage, as established in the studies carried out by Hurley (Rubio-Gámez et al., 2012; Hurley, 2006), since lower mixing and compaction temperatures can result in incomplete drying of the aggregate.

Stiffness (stress/strain ratio) generally decreases as the manufacturing temperature decreases (Sanchez-Alonso et al., 2011; Bennert et al., 2011). The present results revealed a slight decrease of the modulus in the warm mix sub-ballast due to the decrease in manufacturing temperature that reduces the aging of the mixtures, along with its stiffening, which is in accord with the findings of other studies (Sanchez-Alonso et al., 2011).

PLASTIC-PUNCHING DEFORMATIONS

The results of the *triaxial test* (Figure 116) show that the values of permanent deformation, slope of deformation, and creep modulus recorded for the warm mix sub-ballast are very similar to those presented by hot mix sub-ballast at both 25 and 40 °C. This fact indicates the possibility that warm mix could be used as a sub-ballast without increasing plastic deformations, since it has been shown that under the standard temperatures of service expected for sub-ballast in railway tracks (around 25 °C), conventional sub-ballast shows higher resistance to plastic deformations than that of the conventional granular sub-ballast (Sol-Sánchez et al., 2015; Rose et al., 2002). However, increasing the temperature to 60 °C (as expected in extreme climatic conditions) led to a decrease in resistance to permanent deformation for the WMA, with values of final deformation and creep modulus being lower than those obtained for the HMA. This implies that WMA could be more vulnerable to deformations than the granular layer (see Phase 1.1) (Sol-Sánchez et al., 2015). However, it should be noted that it is rare to achieve such extreme temperatures in real-life service, since the ballast layer usually protects the sub-ballast from high temperatures.

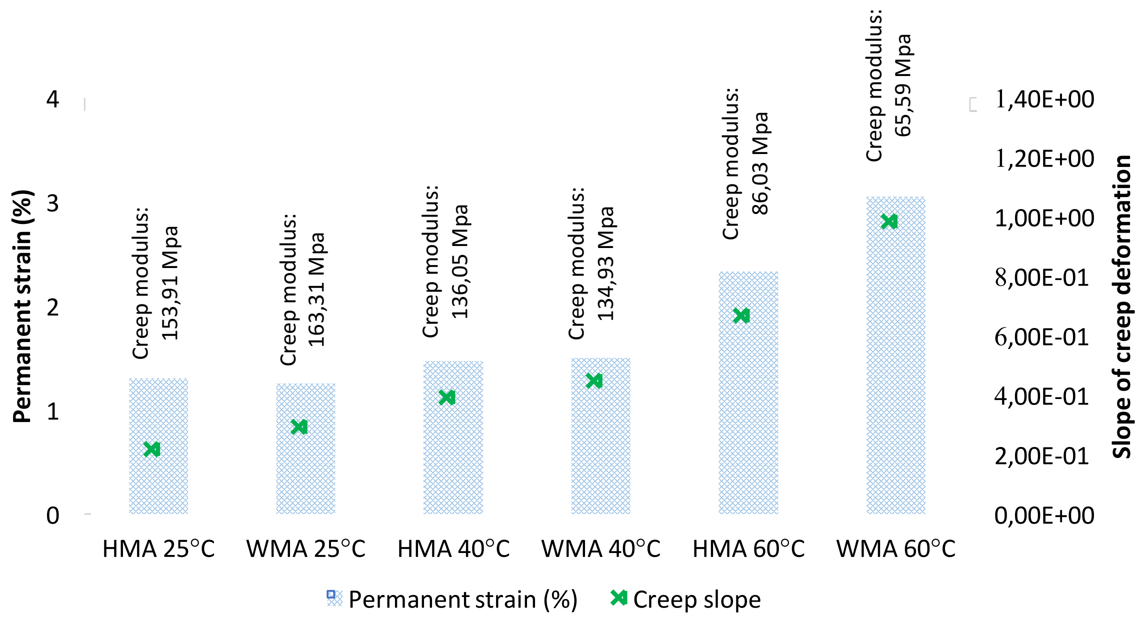

Figure 116. Results measured from the triaxial test for WMA and HMA: Resistance to plastic deformations.

Regarding the punching test, for both bituminous sub-ballast (HMA and WMA) it was possible to determine the initial and final deformation and the slope of the creep curve of the stable phase (for deformation curves obtained during the test at 25 and 40 °C). The initial deformation (primarily associated with the re-compaction and reorganization of particles) was determined at around 700 cycles, the point at which the deformation response tends to stabilize. This point until the end of the test (50000 cycles), may be regarded as the stable phase to determine the slope of the curve. In addition, the final deformation was determined at 50000 cycles.

The results (Figure 117) show that the warm mix sub-ballast presented values of initial and final permanent deformation equal to or very similar to those obtained for the hot mix sub-ballast at both temperatures. The slope of the creep curve increased slightly in the case of WMA, although in the order of very similar values compared to those recorded for the HMA. Thus, under routine in-service temperatures (25 °C) and at higher temperatures (particularly 40 °C), the effects due to ballast punching were very similar for both mixtures in both the short and long-term. Further, and in accord with other studies, the results obtained are lower in comparison with the traditional granular sub-ballast (see Phase 1.1) (Sol-Sánchez et al., 2015). This indicates the possibility of using warm mix asphalt as sub-ballast in railway tracks without increasing the appearance of plastic deformations.

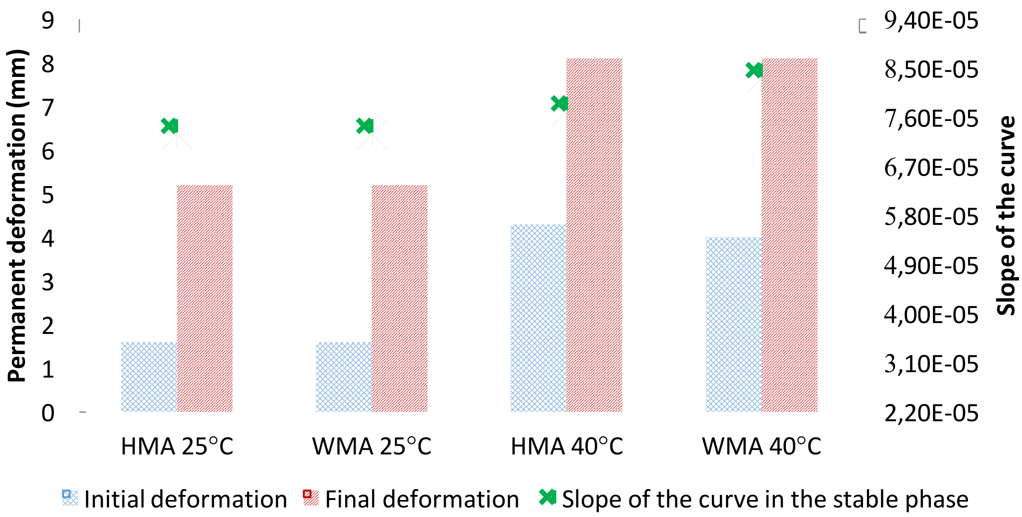

Figure 117. Results of the punching test WMA and HMA under different temperatures.

BEARING CAPACITY-STRESS DISTRIBUTION

Regarding the bearing capacity of both sub-ballast types, Figure 118 displays the static and dynamic modulus obtained during the Plate bearing test at 200 KPa, which was designed to reproduce unfavourable loading conditions expected in railway tracks for this layer. It is clear that both bituminous sub-ballasts recorded similar values of resistance to loads transmitted by trains, even at the higher temperature (40 °C) in both static and dynamic conditions. According to earlier studies, the application of hot mix asphalt as sub-ballast was able to improve the bearing of the layer compared with that obtained by the more traditional granular configuration (see Phase 1.1) (Sol-Sánchez et al., 2015; Rose et al., 2002). For this reason, the present results indicate that WMA could be appropriate for application in railway tracks, since it has presented a similar performance to that measured for conventional bituminous sub-ballast.

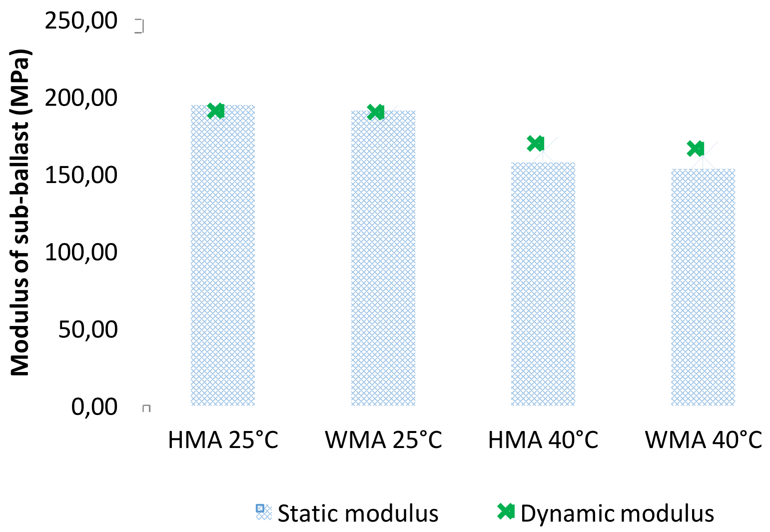

Figure 118. Static and dynamic modulus WMA and HMA as sub-ballast.

The results regarding bearing capacity were in line with the values of pressure recorded under the sub-ballast layer, by using pressure cells under static conditions (Figure 119) and dynamic conditions (Figure 120), for temperatures of 25 and 40 °C. It is clear that the pressure reaching down through the sub-ballast layer is quite similar for the two mixtures (HMA and WMA). This means that the decrease in the manufacturing temperature of the mixture has little effect on its capacity to dissipate the loads transmitted by the passage of trains. It can also be observed that an increase of the test temperature generally decreases the capacity of the mixtures to dissipate the stress. Despite this decrease, the values recorded for the warm mix sub-ballast are very similar to those recorded for the conventional bituminous sub-ballast. Furthermore, it is worth noting that the values of pressure registered are significantly lower (by up to 50%) than those measured under the layer of the granular sub-ballast (Sol-Sánchez et al., 2015; Rose et al., 2002; Rose, 2014). This implies that, in comparison with granular sub-ballast, bituminous sub-ballast is able to provide a more durable system, reducing maintenance and rehabilitation costs regardless of the temperature of manufacture.

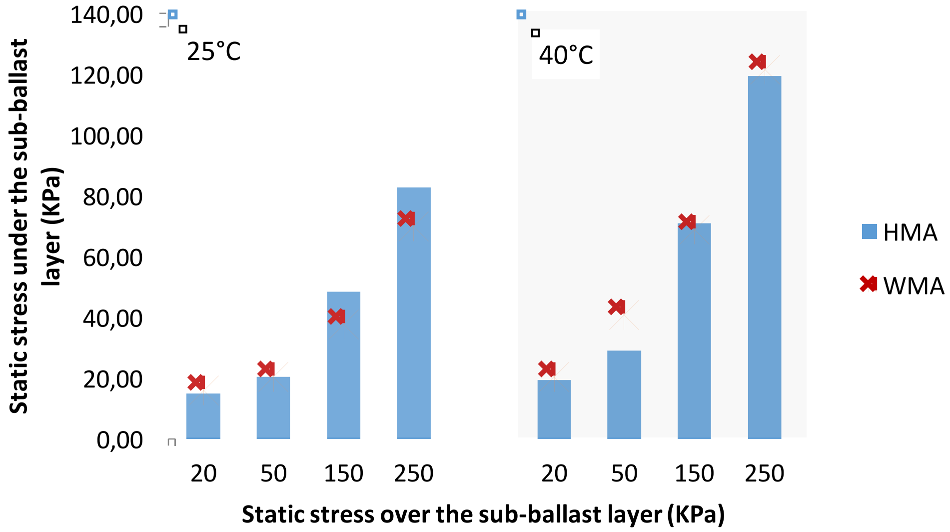

Figure 119 Results of static stress under WMA and HMA as sub-ballast layer during the plate-bearing test.

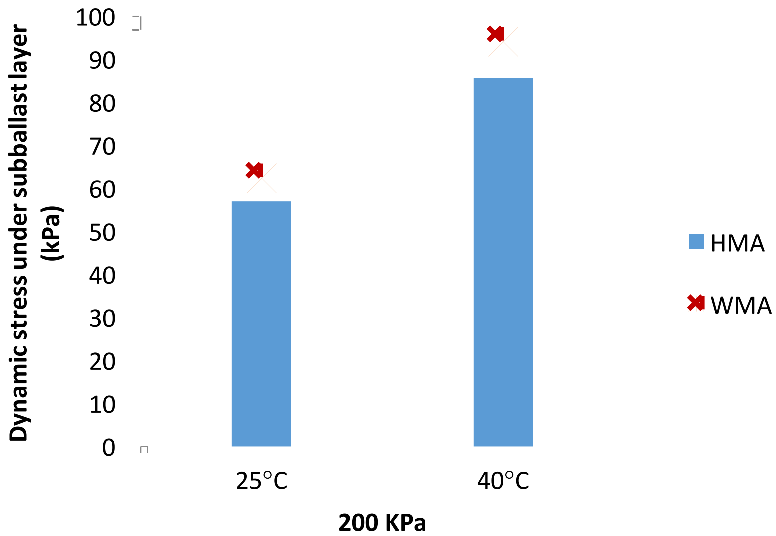

Figure 120. Results of dynamic stress under WMA and HMA as sub-ballast layer during the plate-bearing test.

PERMEABILITY

Figure 121 shows the evolution of the drained flow for both types of sub-ballast used in this phase (with a thickness of 12 cm), analysed using a constant-head permeameter. The HMA presents slightly lower values of flow compared to those obtained by WMA. However, both mixtures have presented an appropriate coefficient of permeability for application in railway tracks according to the Spanish Standard for sub-ballast. The present results suggest that both types of sub-ballast have the capacity to prevent the possible contamination of the sub-structure by the vertical hydraulic transport of mud and fines, offering an impermeable uniform drainage layer that reduces the effects of freeze/thaw action and leads to a lower variation in the moisture content with respect to the granular configuration (Sol-Sánchez et al., 2015; Rose et al., 2009; Policicchio, 2008).

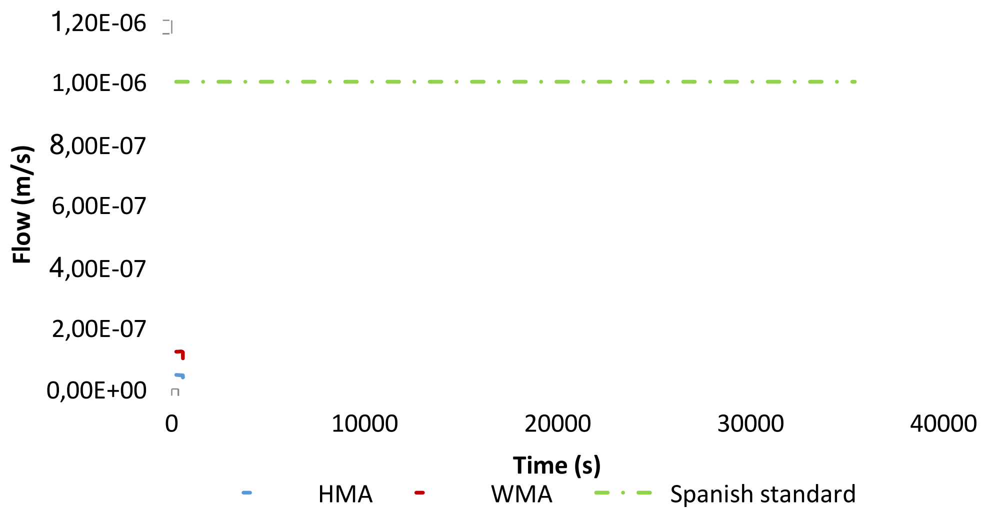

Figure 121. Evolution of the water flow drained by WMA and HMA as sub-ballast: Permeability results.

5.4. PHASE 3 – SUSTAINABLE BITUMINOUS SUB-BALLAST USING WASTE RECOVERY

As already pointed out, Phase 3 has been divided into two sub-phases:

- Design, characterization and analysis of the mechanical behaviour of rubberized bituminous sub-ballast (Phase 3.1);
- Design, characterization and analysis of the mechanical behaviour of reclaimed asphalt pavement sub-ballast (Phase 3.2).

5.4.1. PHASE 3.1 - DESIGN, CHARACTERIZATION AND ANALYSIS OF THE MECHANICAL BEHAVIOUR OF RUBBERIZED BITUMINOUS SUB-BALLAST

CHARACTERIZATION OF THE MIXTURES

Table 28 lists the main properties of the conventional hot mix asphalt and the rubberized asphalt by wet process (WRA) and dry process (DRA) recorded during the characterization tests.

Properties	Standard	HMA	WRA	DRA
Marshall test				
Bitumen Content (% over the total weight of the mixture)	-	4.25	4.25	4.25
Maximum Density (Mg/m^3)	EN 12697-5:10	2.643	2.628	2.611
Bulk Density (Mg/m^3)	EN 12697-6:12	2.573	2.568	2.544
Air Voids (%)	EN 12697-8:03	2.6	2.29	2.35
Marshall Stability (kN)	NLT-159/00	13.306	13.6	18.257
Marshall Flow (mm)	NLT-159/00	3.4	2.7	
Water sensitivity test				
Indirect tensile strength for the dry set (kPa)	EN 12697-12:09	2159.9	1122.1	2075.4
Indirect tensile strength for the wet set (kPa)	EN 12697-12:09	1857.8	1295.3	1998.2
Index of retained tensile strength after water action (%)	EN 12697-12:09	86	86.6	96.3
ITSM				
Stiffness Modulus at 25 °C (MPa)	EN 12697-26:12	5338	5484	5824

Table 28. Main properties of the HMA, WRA and DRA used as sub-ballast

The results obtained in the Marshall Test showed that the physical characteristics of the mixes (i.e. air voids, stability etc.) were affected when crumb rubber was incorporated by both dry and wet process. In particular, it is possible to see that despite the fact that both rubberized asphalts presented similar values of density, the crumb rubber produced a reduction in air voids with respect to the reference mix due to the rubber that occupies the air voids in the mineral skeleton. At the same time, both rubberized asphalt showed better deformation and stability values, especially in the case of rubberized asphalt manufactured by dry process, where the stability is significantly higher than the other mixes. This seems to indicate that adding crumb rubber to the mix improved its resistance to traffic loads and thus reduced the plastic deformations (Moreno et al., 2013; Feiteira et al., 2014).

The same occurred during the Stiffness Modulus Test to determine the effect of the crumb rubber on the bearing capacity of the mixes. The rubberized asphalt manufactured by dry process had a higher stiffness modulus value under the standard temperature of 25 °C than that of the other mixes, which is in accord with other studies (Moreno et al., 2013; Feiteira et al., 2014). This means that this type of mix may be less affected by traffic loads. Similarly, the results obtained in the moisture sensitivity test (UNE-EN 12697-12) showed that the incorporation of crumb rubber induces a decrease in the indirect tensile resistance of the rubberized asphalt manufactured by wet process, results that agree with those obtained by other researchers where the tensile resistance of asphalt mixtures drops when crumb rubber is added (Akisetty et al., 2011; Xiao et al., 2009). Nevertheless, the rubberized asphalt manufactured by dry process presented very similar resistance compared with the reference mixture (HMA), and also the indirect tensile strength ratio (ITSR %) was significantly higher for the rubberized asphalt by dry process and slightly better for the rubberized asphalt by wet process.

PLASTIC-PUNCHING DEFORMATIONS

Figure 122 displays the results obtained during the triaxial test for the conventional hot mix asphalt and rubberizes asphalt manufactured by both dry and wet process in terms of permanent deformation, slope of deformation, and creep modulus, analysing also the effect of temperature.

The results indicate that at 25 °C, the addition of crumb rubber to the mix (whether by the dry process or the wet process) tended to reduce plastic deformations and to increase the creep modulus, although all mixtures presented similar slope of the creep curve. This means that under routine in-service temperature expected for the sub-ballast layer, rubberized asphalt manufactured by wet and by dry process could be used in railways tracks, even improving the resistance to plastic deformations with respect to conventional bituminous sub-ballast, as well as with respect to conventional granular sub-ballast (see Phase 1.1) (Sol-Sánchez et al., 2015; Rose et al., 2002).

The same occurred under a higher temperature (40 °C); again, WRA and DRA showed an increase in resistance to plastic deformations and creep modulus. It is also possible to note that increasing the temperature led to a decrease in the slope of the curves of both rubberized asphalt in comparison with those presented by HMA. This fact indicates that rubberized asphalt can offer a more stable response in different climatic scenarios.

Under extreme climatic conditions (60 °C), the results show that the WRA did not respond as well to permanent deformations with respect to DRA, presenting similar values of plastic deformations, creep modulus, and slope of the creep curve to those obtainable by HMA, which is in accord with the results of Jiménez et al. (2016). This fact could limit the application of these types of bituminous sub-ballast where temperatures can reach very high values. However, it is important to take into account that the ballast layer protects the sub-ballast from high temperatures. In contrast, the addition of crumb rubber by dry process has considerably improved the resistance to plastic deformation and creep modulus of the DRA mix, decreasing the creep modulus only up to a value of around 30% and 15% compared to values obtained at 25 °C and 40 °C, respectively (in accord with other studies, e.g., Moreno et. al., 2014).

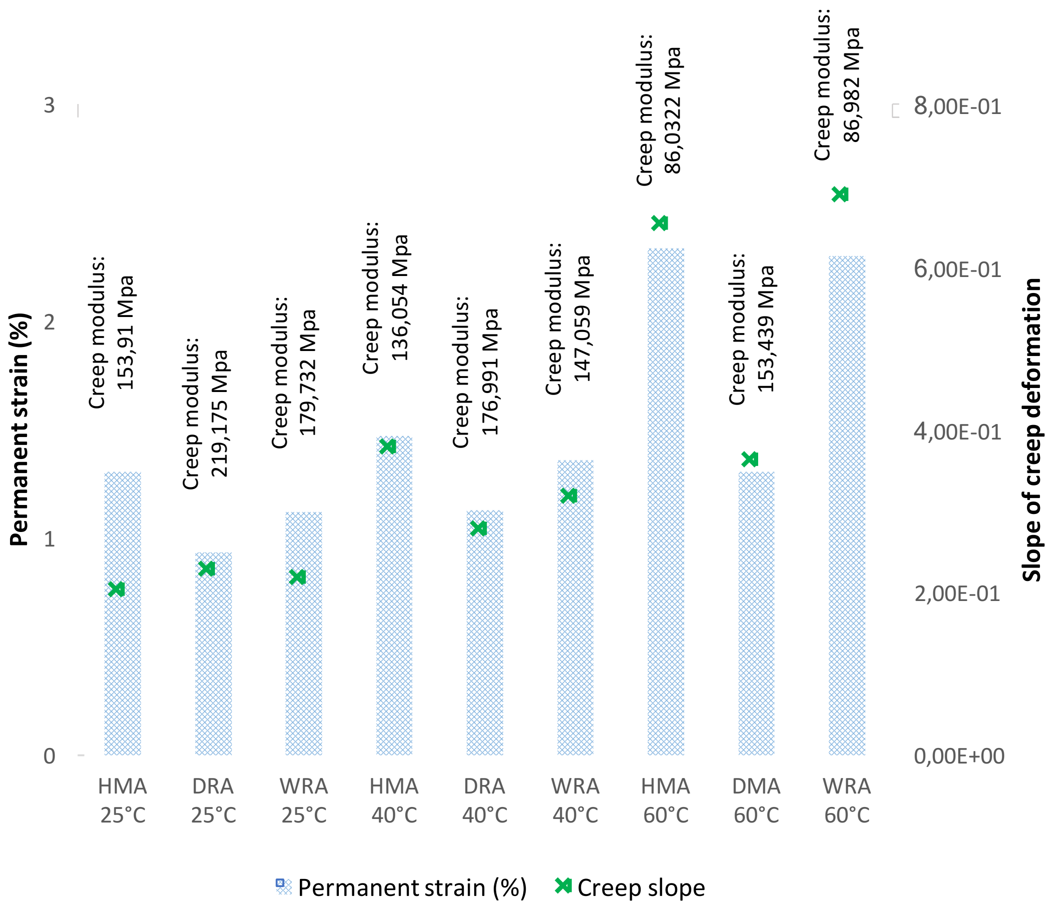

Figure 122. Results of the triaxial test for HMA, WRA and DRA: Resistance to plastic deformations.

As in the previous phases, through the punching test, it was possible to determine the initial deformation (at around 700 cycles), the final deformation (at 50000 cycles) and the slope of the creep curve of the stable phase, at 25 and 40 °C. The results obtained in this test (Figure 123), confirmed those obtained in the triaxial test, where both rubberized bituminous sub-ballasts showed higher resistance to plastic deformations to that measured for the conventional bituminous sub-ballast under routine in-service temperatures for this layer, as well as under a higher temperature. Moreover, it is again possible to notice that the rubberized asphalt manufactured by dry process (DRA) presented lower values in terms of initial and final deformations, as well as slope of the creep curve, compared with those obtained for the conventional bituminous sub-ballast, at both 25 and 40 °C. Furthermore, the results obtained are lower in comparison with the traditional granular sub-ballast (see Phase 1.1) (Sol-Sánchez et al., 2015). This indicates the possibility of using these types of sub-ballast in railway tracks, reducing the appearance of plastic deformations.

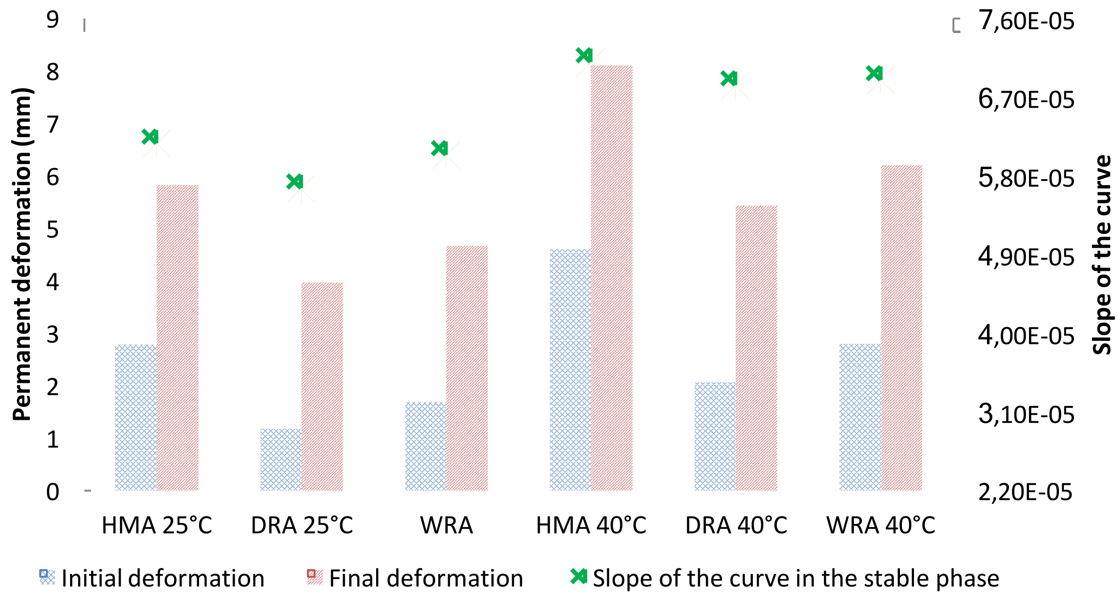

Figure 123. Results of the punching test HMA, DRA and WRA under different temperatures.

BEARING CAPACITY-STRESS DISTRIBUTION

Figure 124 displays the static and dynamic modulus measured in the plate-bearing test for the conventional bituminous sub-ballast (HMA) and for both rubberized asphalt sub-ballast (WRA & DRA) under the range of in-service temperatures that can be expected for this layer, applying 200 KPa to reproduce unfavourable loading conditions. The results show that the addition of crumb rubber to the mix (whether by the dry process or the wet process) tended to improve the resistance to loads transmitted by trains in both static and dynamic load conditions with respect to the conventional bituminous sub-ballast. The same occurred even under a higher temperature (40 °C) that could prevail in extreme climates, showing a slight increase of the bearing capacity of the mixture manufactured by dry process (DRA). In fact, all types of bituminous sub-ballast analysed in this study should be able to improve the bearing capacity of the layer compared with that obtained by the more traditional granular configuration, according to other studies (Sol-Sánchez et al., 2015; Rose et al., 2002).

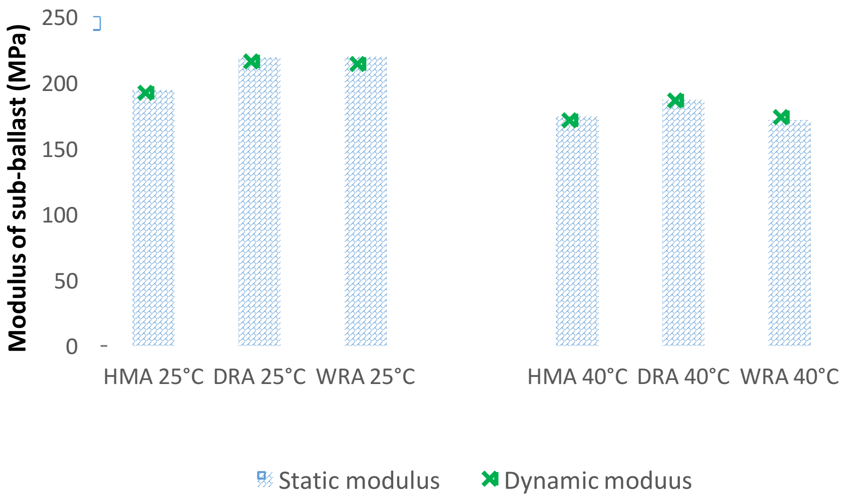

Figure 124. Static and dynamic modulus HMA, DRA and WRA as sub-ballast.

A similar tendency was observed during the measurement of stress dissipation by using pressure cells in the plate-bearing test under various type of loading and temperature as well as in static (Figure 125) and dynamic conditions (Figure 126). The results recorded in the static condition revealed that at 25 °C, there is a considerable impact of adding crumb rubber regardless of the manufacturing process. In fact, it is possible to notice that the values of pressure registered under both types of rubberized asphalt sub-ballast are significantly lower (more than 50%) than those measured under the conventional bituminous sub-ballast. Increasing the temperature of the test (40 °C) again led to both rubberized asphalt sub-ballasts presenting a higher capacity to dissipate the stress compared with conventional bituminous sub-ballast. However, it can also be observed that when the stress is increased up to the levels expected in railway tracks (between 150 kPa and 250 kPa), the DRA presented greater capacity to dissipate stress with respect to the WRA, which is probably due to the higher elastic modulus presented during the plate bearing test at 40 °C. Under dynamic conditions (Figure 126), there was little impact of the temperature since WRA and DRA showed a similar ability to dissipate stress, both being slightly better than the HMA. This means that adding crumb rubber to the mixture has a positive effect on its capacity to dissipate the loads transmitted by the passage of trains.

Nonetheless, it is worth noting that under the various temperatures used in this test all type of bituminous sub-ballast presented lower values of stress under the layer than those measured for the granular sub-ballast (Sol-Sánchez et al., 2015; Rose et al., 2002; Rose, 2014).

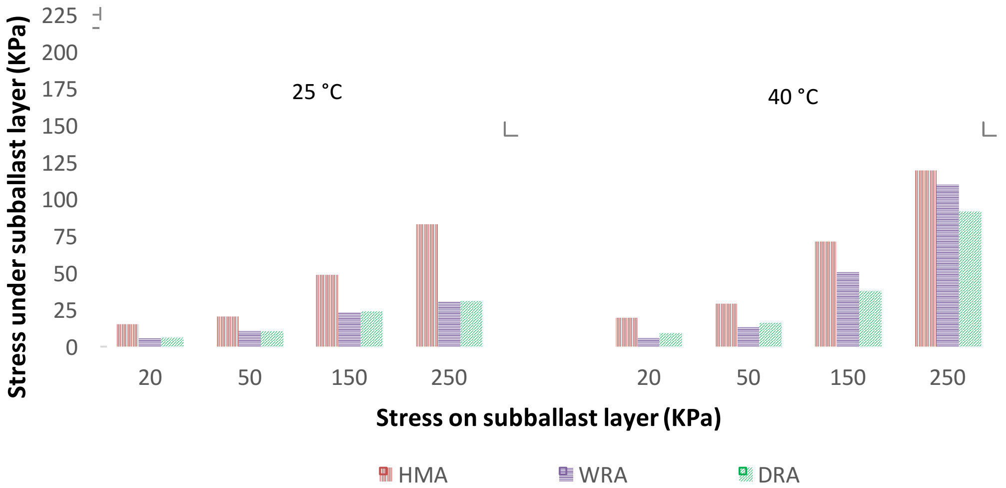

Figure 125. Results of static stress under HMA, WRA and DRA as sub-ballast layer during the plate-bearing test.

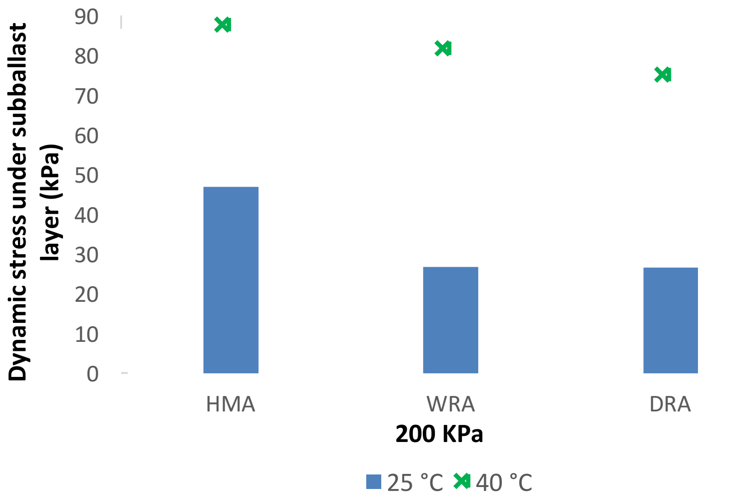

Figure 126. Results of dynamic stress under HMA, WRA and DRA as sub-ballast layer during the plate-bearing test.

PERMEABILITY

Another fundamental parameter for the sub-ballast layer, in addition to bearing capacity, is its capacity to waterproof the remainder of the substructure. This parameter is specified by the Spanish standard, which indicates that the vertical permeability coefficient of the sub-ballast (K) must be less than 10^{-6} m/s (PF-7, 2006). Figure 127 shows the results obtained in relation to the evolution of the drained flow, for the conventional bituminous sub-ballast (HMA) and for both rubberized asphalts manufactured by both dry and wet process (with a thickness of 12 cm). The results clearly show that all three types of sub-ballast presented almost equivalent values of coefficient of permeability K (approximately 5 x 10^{-6} m/s) but such values were considerably low with respect to the Spanish Standard. Therefore, the results again suggest that regardless of the manufacturing process (wet or dry process), the rubberized bituminous sub-ballast represents an impermeable uniform drainage layer that is able to prevent the contamination of the sub-structure by the vertical hydraulic transport of mud and fines, whilst reducing the effects of freeze/thaw action, even leading to a lower variation in the moisture content with respect to the granular configuration (Sol-Sánchez et al., 2015; Rose et al., 2009; Policicchio, 2008).

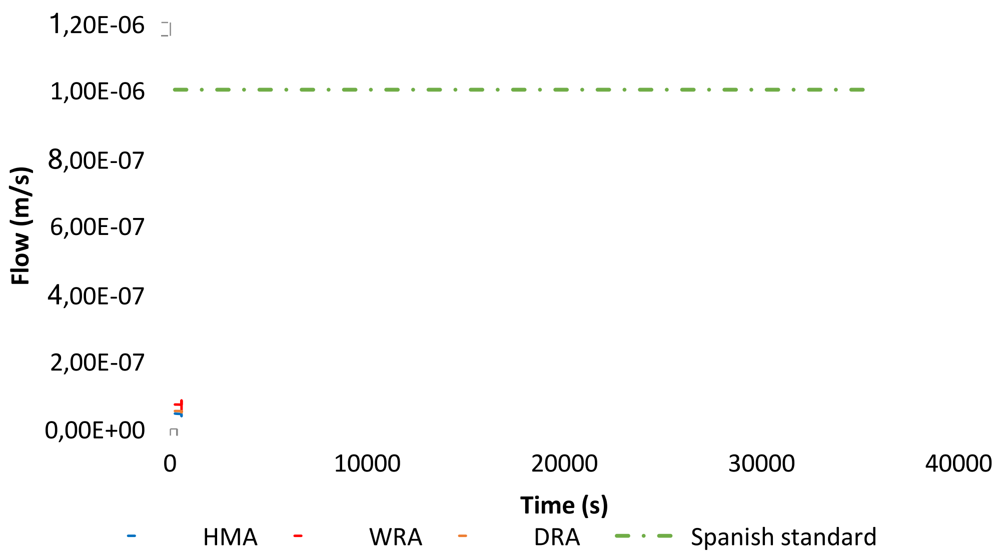

Figure 127. Evolution of the water flow drained by HMA, WRA and DRA as sub-ballast: Permeability results.

5.4.2. PHASE 3.2 - DESIGN, CHARACTERIZATION AND ANALYSIS OF THE MECHANICAL BEHAVIOUR OF RECLAIMED ASPHALT PAVEMENT SUB-BALLAST

CHARACTERIZATION OF THE MIXTURES

The HMA was a dense-graded mix type AC 22 S (EN 13108-1) with a maximum size of aggregates equal to 22 mm, manufactured with bitumen type 50/70.

The HWMA with 100% RAP was a dense-graded mix type AC 16 S with a continuous grain size. To ensure the mechanical cohesion of the HWMA mixture (and in order to complement the amount of binder provided with the RAP), a slow-breaking cationic emulsion was used. Properties of this emulsion include the following: (i) moisture content of 40%; (ii) residual bitumen content of 60%; (iii) residue penetration of 150 mm. In addition, 2% (over the total weight of the mixture) of Portland cement was used as a stabilising agent. The bitumen emulsion content was determined, taking into account the bitumen provided by the RAP skeleton (3.4% over the total weight of the RAP) as well as the bitumen contained in the bitumen emulsion (60% over the total weight of the emulsion). The final emulsion content selected for the manufacture of the HWMA was 2.5% (over the total weight of the mix), which allows for obtaining the recommended air void content of 1-3% (Rose et al., 2010).

Table 29 lists the main properties of the conventional hot mix asphalt and the 100% reclaimed asphalt pavement (RAP) recorded during the characterization tests.

Properties	Standard	HMA	HWMA 100% RAP
Mix design Marshall/Gyratory			
Bitumen Content (% over the total weight of the mixture)	-	4.25	6.5
Maximum Density (Mg/m^3)	EN 12697-5:10	2.643	2.452
Bulk Density (Mg/m^3)	EN 12697-6:12	2.573	2.405
Air Voids (%)	EN 12697-8:03	2.6	2.1
Water sensitivity test			
Indirect tensile strength for the dry set (kPa)	EN 12697-12:09	2159.9	2010.5
Indirect tensile strength for the wet set (kPa)	EN 12697-12:09	1857.8	1990.3
Index of retained tensile strength after water action (%)	EN 12697-12:09	86	99
ITSM			
Stiffness Modulus at 20 °C (MPa)	EN 12697-26:12	5338	5635

Table 29. Main properties of the HMA and RAP used as sub-ballast.

During the Water Sensitivity Test, although the two types of mixtures presented similar values of both Indirect tensile strength, wet and dry set, the HWMA with 100% RAP showed a substantial improvement in the indirect tensile strength ratio (ITSR %) due to a higher resistance of the wet specimens. This fact could be attributed to the properties of the material; indeed, there is less possibility of water filtration in the particles because the RAP aggregates are already covered with asphalt and therefore, in general, high recycled asphalt mixtures are expected to have similar or better moisture susceptibility compared to conventional asphalt (Mogawer et al., 2012; Karlsson and Isacsson, 2006; Tran et al., 2012).
Regarding the stiffness at 25 °C, the HWMA with 100% RAP again presents a higher modulus value than that of the HMA, due to the properties of the aged binder which is stiffer and more elastic, which leads to an increase in mixture stiffness (Al-Qadi et al., 2012; West et al., 2013).

PLASTIC-PUNCHING DEFORMATIONS

Figure 128 shows the result obtained in the triaxial test (EN 12697-25 method B) for the different types of sub-ballast studied. It is possible to notice that under the standard temperatures of service expected for sub-ballast in railway tracks (around 25 °C), the HWMA with 100% RAP presented similar values in terms of slope of deformation whilst presenting a slightly higher creep modulus which has led to a slightly lower permanent deformation at the end of the test in comparison with the conventional hot mix asphalt (HMA). In contrast, an increase in temperature leads to a substantial decrease in the resistance of the mixture with RAP, predominantly at 60 °C (temperatures that could barely be reached, even in extreme climates) where a substantial drop of the modulus is observed with a consequent increase in both the final plastic deformation and deformation slope. This fact could be due to the high content of RAP in the mixtures; indeed other studies have shown that a high percentage of RAP leads to a soft mixture because of the high bitumen content (Howard et al.,2009; Al-Qadi et al., 2007) which can increase the plastic deformations. This finding should therefore be taken into account when applying this type of sub-ballast under adverse temperature conditions, but again it should be noted that the ballast layer should protect the sub-ballast from high temperatures.

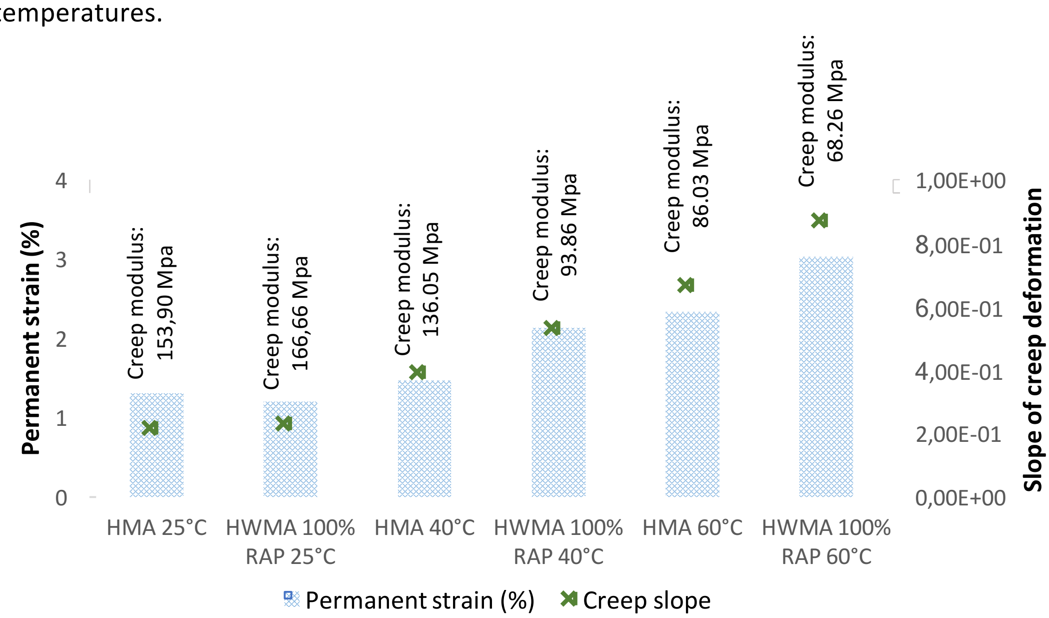

Figure 128. Results measured from the triaxial test for HMA and HWMA 100% RAP: Resistance to plastic deformations.

The results related from the triaxal test are in accordance with those obtained from the measurement of initial deformation (I.D.) (at around 700 cycles), final deformation (F.D.) (at 50000 cycles) and slope of the creep curve (S.C.C.) of the stable phase, during the punching test for both types of sub-ballast under various temperature conditions (25 and 40 °C). The results (Figure 129) confirmed that under standard temperatures of service (around 25 °C) the HWMA 100% RAP as sub-ballast recorded lower values in terms of initial deformation, final deformation, and slope of the creep curve. However, when the temperature is increased, and as already observed during the triaxial test, the bituminous sub-ballast with RAP demonstrated a significant susceptibility to higher temperatures. Despite a slightly lower initial deformation, the final deformations recorded at 40 °C were rather higher than those produced in the conventional bituminous sub-ballast and, moreover, the tendency towards developing long-term deformation was more pronounced than that displayed by the hot mix asphalt.

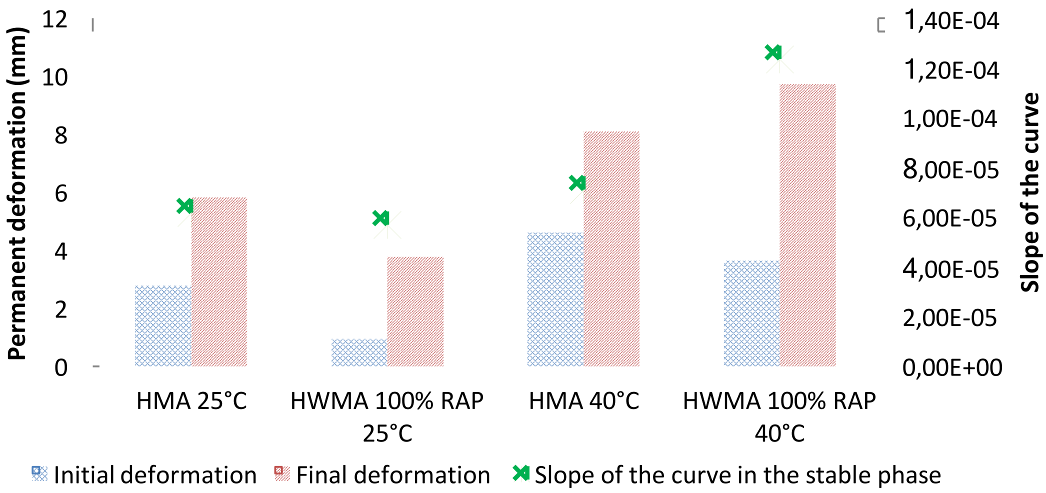

Figure 129. Results of the punching test HMA and HWMA 100% RAP under different temperatures.

BEARING CAPACITY-STRESS DISTRIBUTION

Regarding the bearing capacity, Figure 130 displays the static modulus obtained during the plate-bearing test for both conventional bituminous sub-ballast (HMA) and HWMA 100% RAP sub-ballast at 25 °C and 40 °C (range of in-service temperatures that can be expected in railway tracks for this layer). It is clear that the HWMA 100% RAP sub-ballast presented a slightly higher bearing capacity than the conventional bituminous sub-ballast, even at 40 °C (adverse temperature conditions). This increase in bearing capacity, even more evident under the dynamic loads, means an increase in the strength of the railway structure compared to the conventional bituminous sub-ballast. For this reason, sub-ballast with high content of reclaimed asphalt pavement represents great potential for its application in modern railway tracks, since earlier studies have shown that hot mix asphalt as sub-ballast was already able to improve the bearing of the layer compared to that obtained by the more traditional granular configuration (Sol-Sánchez et al., 2015; Rose et al., 2002).

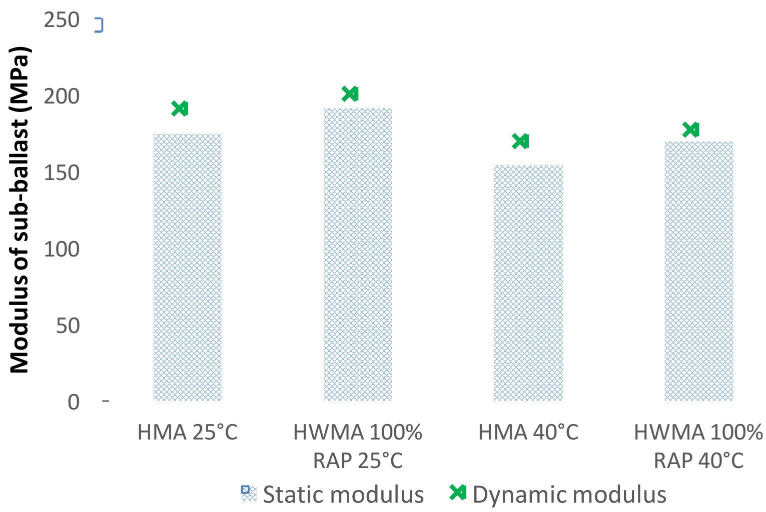

Figure 130. Static and dynamic modulus HMA and HWMA 100% RAP as sub-ballast.

Figure 131 displays the dissipation stress recorded by using pressure cells in the plate-bearing test under static conditions. The results indicate that at 25 °C, there is no impact of the level of stress applied since the pressure that comes down the sub-ballast layer is always considerably lower in the case of HWMA 100% RAP sub-ballast compared with the HMA sub-ballast. However, when the temperature is increased up to 40 °C, the level of stress applied on top of the sub-ballast layer plays a more important role compared with the test at 25 °C. In particular, it is possible to see that under low levels of stress, the HWMA 100% RAP presented a higher capacity to dissipate the stress. However, when increased stress is applied, the behaviour of the HWMA 100% RAP tends to always be more similar to the behaviour of the conventional bituminous sub-ballast up to a certain level of stress (around 230 kPa), which is the point where both types of bituminous sub-ballast showed the same ability to distribute the stress on the subgrade. Figure 131 shows that for levels of stress higher than 230 kPa, the ability to dissipate stress of the HWMA 100% RAP begins to be lower compared with the conventional bituminous sub-ballast. However, it should be taken into account that this level of stress can be considered an unfavourable loading condition (since a normal value for sub-ballast is around 100–120 kPa) that could take place for sub-ballast in railway tracks (Rose et al., 2002).

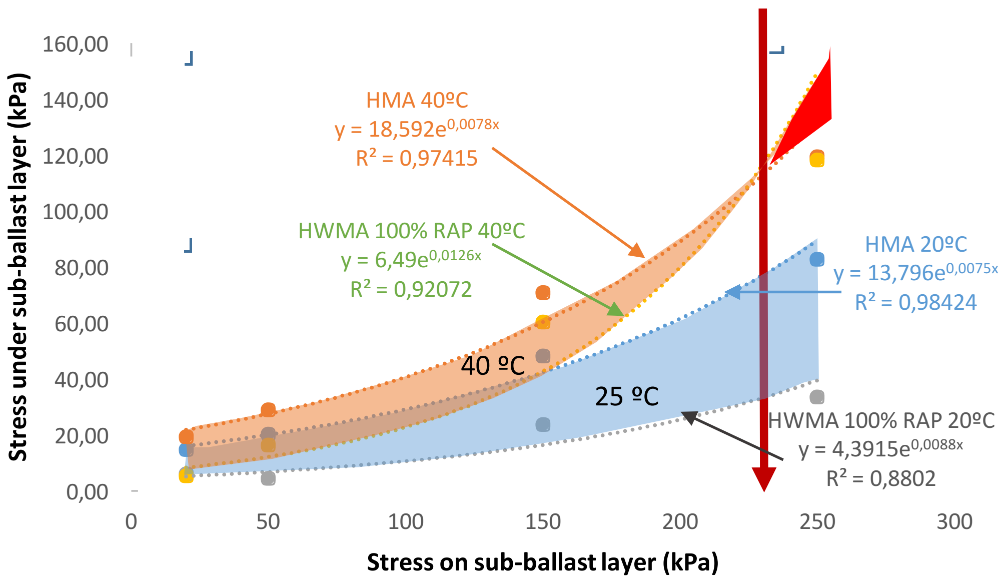

Figure 131. Results of static stress under HMA and HWMA 100% RAP as sub-ballast layer during the plate-bearing test.

A similar tendency was observed during the measurement of stress in dynamic conditions (Figure 132). The HWMA with 100% RAP recorded values of pressure significantly lower at 25 °C and slightly lower at 40 °C compared to the conventional bituminous sub-ballast. Therefore, these results indicate that HWMA with 100% RAP as sub-ballast offers great capacity to protect the rest of the bed layers in railway infrastructure, and, moreover, both bituminous layers present benefits in reference to the conventional granular layer (see Phase 1.1).

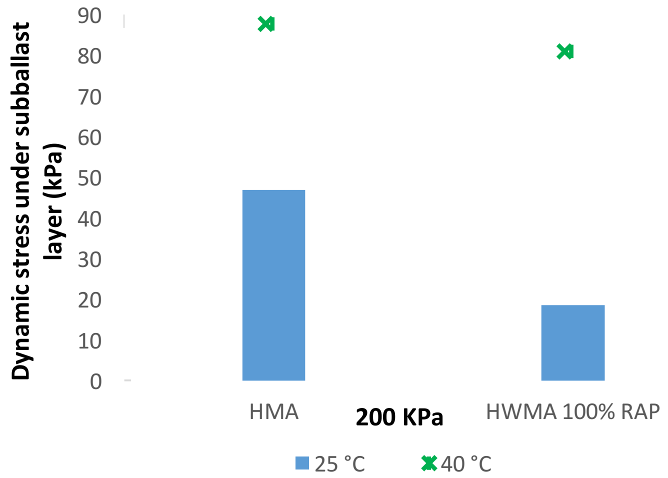

Figure 132. Results of dynamic stress under HMA and HWMA 100% RAP as sub-ballast layer during the plate-bearing test.

PERMEABILITY

Figure 133 shows the evolution of the drained flow for the conventional bituminous sub-ballast (HMA) and for HWMA 100% RAP sub-ballast with a thickness of 12 cm. Both mixtures have presented an appropriate coefficient of permeability for application in railway tracks according to the Spanish Standard for this layer. Moreover, it is possible to see that 100% half-warm reclaimed asphalt pavement (RAP) presented similar values of flow compared to those obtained by HMA, but these values are significantly lower with respect to those recorded for the granular sub-ballast (Sol-Sánchez et al., 2015). This means that both types of sub-ballast presented greater capacity to prevent the possible contamination of the sub-structure by the vertical hydraulic transport of mud and fines with respect to the granular configuration.

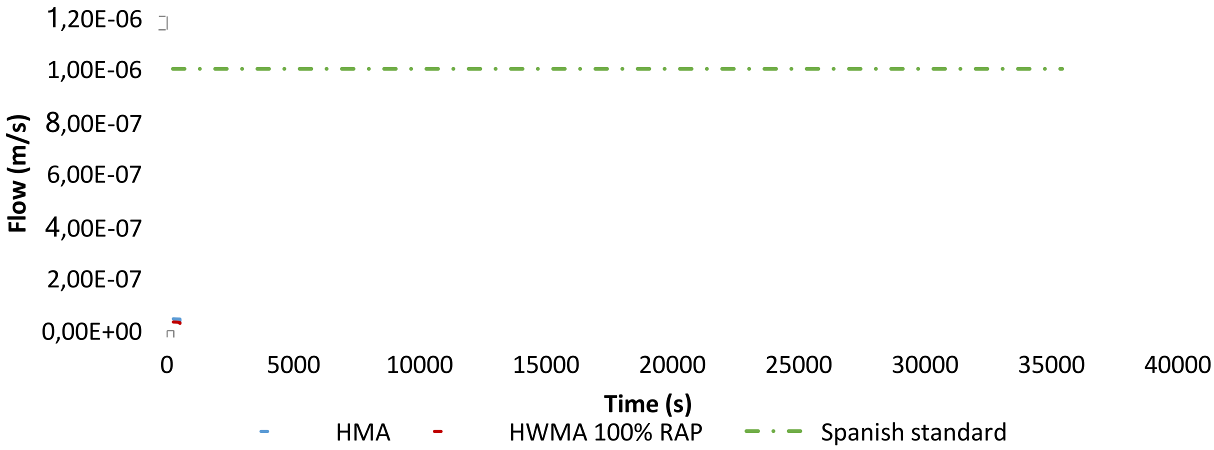

Figure 133. Evolution of the water flow drained by HMA and HWMA 100% RAP as sub-ballast: Permeability results.

5.5. GLOBAL ASSESMENT OF THE DIFFERENT SUSTAINABLE SUB-BALLAST SOLUTIONS STUDIED

With the aim of optimizing the bituminous sub-ballast under sustainable criteria, Table 130 shows the final ranking on the basis of the results obtained in the second and third phases. For each bituminous sub-ballast, as well as for each property tested, a score has been assigned from 1 (best solution from a performance point of view) to 5 (worst solution). Moreover, the green colour has been assigned whenever a sustainable solution has received a score higher than the conventional bituminous sub-ballast (HMA).

From the results obtained it is evident that the best solution for almost all the studied parameters was the rubberized bituminous sub-ballast manufactured by dry process (DRA), obtaining an average score of 1,4. In any case, all the solutions studied, with the exception of WMA, presented a higher average score than the HMA (reference section). This means that these sustainable materials are suitable as sub-ballast layer, since they are able to increase the strength of the tracks whilst achieving sustainable development through the reduction of pollution and energy consumption as well as using waste materials.

Test	Parameters	Temperature	HMA	WMA	WRA	DRA	HWMA 100% RAP
TRIAXIAL	Permanent strain (%)	25 °C	5	4	2	1	3
		40 °C	3	4	2	1	5
		60 °C	3	5	2	1	4
	Slope of creep deformation	25 °C	1	4	2	3	2
		40 °C	3	4	2	1	5
		60 °C	2	5	3	1	4
	Creep modulus (Mpa)	25 °C	5	4	2	1	3
		40 °C	3	4	2	1	5
		60 °C	3	5	2	1	4
PUNCHING	Initial deformation (mm)	25 °C	5	3	4	2	1
		40 °C	5	4	2	1	3
	Final deformation (mm)	25 °C	5	4	3	2	1
		40 °C	4	4	2	1	3
	Slope of creep deformation	25 °C	4	5	3	1	2
		40 °C	3	4	2	1	5
PLATE BEARING	Ed static (Mpa)	25 °C	4	3	1	1	2
		40 °C	4	5	2	1	3
	Ed dynamic (Mpa)	25 °C	4	5	2	1	3
		40 °C	4	5	3	1	2
PLATE BEARING	Static pressure (kPa)	25 °C	5	4	1	2	3
		40 °C	3	4	2	1	5
	Dynamic pressure (kPa)	25 °C	4	5	3	2	1
		40 °C	4	5	3	1	2
Permeability	Costant load (K)	20 °C	2	5	3	4	1
average			***3,7***	***4,4***	***2,3***	***1,4***	***3***

Table 30. Final ranking of the different sustainable sub-ballast solutions studied.

CONCLUSIONS

6. CONCLUSIONS

The aim of the present thesis was to optimize the use of bituminous sub-ballast in railway infrastructure under sustainability criteria through the reuse of waste, as well as the reduction of energy consumption and gas emissions. Therefore, the purpose was to obtain new solutions that are both economically and environmentally more competitive than traditional hot bituminous sub-ballast, whilst ensuring a similar mechanical behaviour. First, the mechanical behaviour of conventional granular and bituminous sub-ballast was studied in order to establish a reference performance. In addition, in order to assess the impact of the sub-ballast layer on the global behaviour of the railway track, the reference solutions were analysed in terms of complete track sections, changing different variables in the vertical configuration such as the type of sub-ballast, using different elastic elements (such as mats, under-sleeper pads, etc.), and analysing different thicknesses of the ballast layer. Afterwards, the same laboratory tests were carried out to design and evaluate the viability of using bituminous mixtures manufactured by low temperature technology as well as bituminous mixtures manufactured with recycled materials as sub-ballast in railways track. On the basis of the results obtained, the following conclusions can be drawn:

- It was demonstrated that the use of bituminous sub-ballast could reduce the track settlement in comparison with the section with granular layer, due to an increase in the stiffness of the substructure. Whilst this also leads to a slight stiffening of the whole track, it does not decrease its capacity to dissipate the energy transmitted by trains. In addition, the bituminous sub-ballast presented higher stress dissipation during the full-scale test, which allows for greater protection of the remainder of the bed layers against the loads transmitted by trains.

- Under higher temperatures, a decline in the cracking resistance of conventional bituminous sub-ballast was observed, although it should be noted that this resistance will always be higher with respect to the unbound granular layer. This finding should therefore be taken into account when applying this type of sub-ballast under adverse temperature conditions. Further, despite the fact that bituminous sub-ballast presented lower permeability than granular sub-ballast (and therefore it is more appropriate to reduce the infiltration of water), its application for protecting the rest of bed layers from water infiltration could be slightly reduced due to an increased presence of cracks. In addition, the use of bituminous sub-ballast can improve waterproofing and filter properties, preventing the contamination of both the sub-structure and the ballast layer whilst also offering a satisfactory coefficient of permeability (K) value.

- When tested under the standard temperatures of service expected for sub-ballast in railway tracks (around 25 °C), the conventional bituminous layer presents a resistance to plastic and punching deformations similar to that recorded for the well-compacted conventional granular sub-ballast. However, under the higher temperatures that could be recorded in warm climates, the bituminous sub-ballast showed a decrease in its resistance thereby showing greater vulnerability to plastic deformations.

- The incorporation of elastic elements between the bed layers (under ballast or sub-ballast mats) or the use of more flexible sub-ballast led to lower bearing capacity of the structure, which causes an important reduction in global stiffness and an increase in dissipated energy and track settlement. The variation of these latter two parameters is higher than that measured for global vertical stiffness. In addition, these variations in track performance were more pronounced with softer bed layers, but always lower than those measured in the bearing capacity for the bed layers.

- The modification of the track section caused by varying the configuration of bed layers exerted higher influence than the reduction of the stiffness of elastic elements (and even higher than the incorporation of new elements) used over the ballast layer. However, it is important to note that reducing track stiffness by the use of more flexible bed layers (such as the incorporation of under ballast mat (UBM) to reduce ground vibrations) causes an increase in ballast settlement, whilst decreasing the stiffness by using elastic elements over the granular layers reduces settlement and increases the capacity of the track to damp train loads.

- In order to ensure the sustainability of the bituminous sub-ballast, several ways have been proposed, which include reducing the manufacturing temperature of the mixtures, replacing raw materials with waste materials, and manufacturing more durable materials through the use of sustainable modifiers. In this respect, warm mix asphalt (WMA), half-warm 100% recycled asphalt pavement (HWMA 100% RAP) and rubberized asphalt mixtures (using wet process, WRA, and dry process, DRA) were studied as bituminous sub-ballast.

- In terms of mechanical behaviour, the proposed sustainable alternatives offer similar properties to those presented by the traditional solution. In terms of susceptibility to water action, strength and stiffness modulus, it was found that the use of the surfactant additives to decrease the manufacturing temperature of bituminous sub-ballast (WMA) could also reduce the susceptibility to water action with respect to the hot bituminous sub-ballast (HMA). However, for the WMA, a slight decrease in strength and stiffness modulus was observed, obtaining a material that was less rigid and more flexible. Regarding the rubberized bituminous sub-ballast, it was found that adding crumb rubber by both dry and wet process served to reduce its susceptibility to water action, as well as to improve strength and stiffness modulus (particularly in the case of rubberized bituminous sub-ballast manufactured by dry process), when it is compared with the traditional hot bituminous sub-ballast without crumb rubber. This seems to indicate that adding crumb rubber to the bituminous sub-ballast could improve its resistance to train loads and thus reduce plastic deformations. Similar results were obtained in the case of the HWMA 100% RAP manufactured with bitumen emulsion modified with rejuvenators, where lower susceptibility to water action and higher stiffness modulus than the traditional hot bituminous sub-ballast was observed. Moreover, since sub-ballast layer is not directly exposed to the traffic load, the eventual problem of material losses or disintegration associated with these types of mixtures with high percentages of RAP could be reduced.

- In terms of resistance to plastic deformation of the sustainable solutions, under routine in-service temperatures (around 25 °C) all types of sustainable bituminous sub-ballasts presented higher resistance to plastic and punching deformations (particularly in the case of DRA) with respect to conventional bituminous sub-ballast. This means that at 25 °C, all sustainable sub-ballasts could be used in railways tracks, even improving the resistance to plastic deformations. The rise in temperature to 40 °C led to an increase of resistance to plastic and punching deformations of both rubberized asphalt (again particularly in the case of DRA) while the WMA presented very similar levels of resistance compared with the conventional hot mix asphalt. In contrast, HWMA 100% RAP showed a slight decrease in its resistance to permanent deformations at these temperatures. Increasing the temperature to 60 °C (extreme temperature), which is typically recorded in warm climates, led to an important decrease in resistance to permanent deformations in the WMA and HWMA 100% RAP with respect to both the conventional and rubberized asphalt sub-ballast manufactured by wet process (which showed very similar values of deformation). However, it is important to note that the rubberized asphalt manufactured by dry process showed lower vulnerability to deformations than the others bituminous layer.

- Although the strength of the bituminous materials and their capacity to dissipate stress is reduced with an increase in temperature, all types of bituminous sub-ballast presented higher bearing capacity and protection for the remainder of the bed layers than the granular sub-ballast in both static and dynamic conditions. Moreover, it has been highlighted that the rubberized asphalt manufactured by dry process registered higher values of resistance to the loads transmitted by trains in comparison with the other bituminous sub-ballasts.

Based on the results presented in this thesis, it can be said that all the studied sustainable solutions offer an adequate standard of performance as sub-ballast for railway tracks from a mechanical behaviour point of view. In addition, they can offer advantages such as reducing greenhouse emissions, fuel consumption, and waste, as in the case of HWMA 100% RAP. Furthermore, rubberized bituminous mixtures (DRA and WRA) make the sub-ballast layer more durable whilst allowing for the recovery of waste. Finally, the use of WMA — despite the fact that its performances were slightly lower with respect to the other solutions studied — achieved acceptable results for its use as a sub-ballast layer. Moreover, it is a solution that guarantees a reduction in pollution and energy consumption thanks to its ability to reduce mixing and compaction temperatures.

FUTURE LINES OF RESEARCH

7. FUTURE LINES OF RESEARCH

During the development of this doctoral thesis, in which sustainable bituminous sub-ballast have been developed through the reuse of waste, reducing energy consumption and gas emissions, new lines of research have emerged that are considered as future studies in order to complete and optimize the study of the sustainable bituminous sub-ballast

In this sense, different lines of study are proposed in relation to the work presented in this doctoral thesis:

- Advanced characterisation of sustainable bituminous sub-ballast: further studies are needed to assess the performance of sustainable bituminous sub-ballasts under a range of failure modes expected for asphalt materials, including, for instance, resistance to cracking, which is a fundamental parameter in asphalt materials since it is of crucial importance in protecting the substructure as well as the response of full scale.

- Assess the fatigue law of the sustainable bituminous sub-ballast under diverse service conditions such as different temperature, humidity, etc., analysing the main failure distresses such as permanent deformations or cracking, which are essential for its application in railway tracks.

- Based on the technologies studied in this doctoral thesis, one of the future aims will be the evaluation of the life cycle assessment (LCA) by a tool that is developing in another work package belonging to the European project "SUP&R ITN - SUSTAINABLE PAVEMENTS & RAILWAYS INITIAL TRAINING NETWORK"

- It would also be of particular interest to analyse the mechanical response of the sustainable bituminous sub-ballast in a trial section in a high-speed line in order to evaluate the long-term behaviour of the sub-bituminous ballast.

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ANNEX A

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Advanced characterisation of bituminous sub-ballast for its application in railway tracks: The influence of temperature

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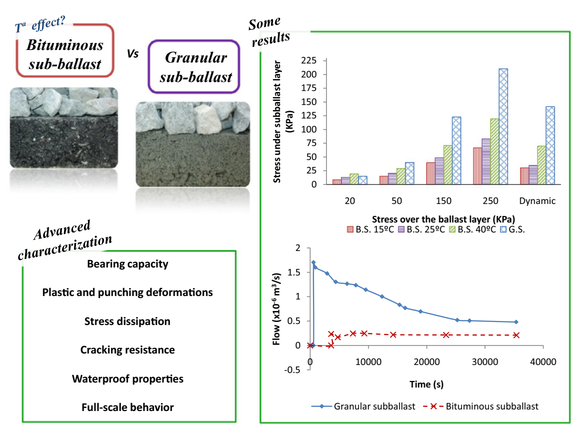
HIGHLIGHTS

- Bituminous sub-ballast has been characterised under service life temperature.
- A full scale test evaluated the sub-ballast under different load conditions.
- Bituminous sub-ballast improves the mechanical response of the track.
- Bituminous sub-ballast exhibits higher strength against the trains loads.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of bituminous sub-ballast in railway tracks is regarded as an appropriate solution for improving the strength of the section. However, for its widespread application, more in-depth studies are needed to assess its efficacy with respect to the main requirements that this material must meet under various service conditions. Such conditions include the range of temperatures that can occur during the service life of the railway tracks, which can modify the behaviour of bituminous material. This paper therefore focuses on evaluating the mechanical behaviour of bituminous material (under both routine and adverse temperatures that are expected in railway lines in extreme climates) in comparison to that presented by conventional granular sub-ballast. In particular, performance is examined with respect to the main requirements that need to be met by these materials (resistance to plastic and punching deformations, bearing capacity, stress dissipation, cracking resistance, and waterproof properties) for their use in railway tracks. At the same time, their influence on the performance of the global section was assessed for both types of sub-ballast by means of a full-scale test. The results demonstrated that the use of bituminous sub-ballast could improve both the mechanical response of the track and the protection of the remainder of the track bed layers, since this material exhibited higher strength against the loads imposed by passing trains, lower permeability, and a higher capacity to dissipate stresses transmitted by the ballast to the substructure. However, it is also important to consider that temperature plays a fundamental role in the resistance of bituminous sub-ballast to plastic and punching deformations, whilst its resistance to cracking declines sharply at higher temperatures. This could limit its application in railway lines in regions where values of this parameter are expected to be higher than those commonly recorded for this layer.

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1. Introduction

Traditional ballasted tracks have been widely used in railway transportation all around the world. However, the development of high speed railway and the increase in the loading capacity of trains have led to the need for enhancing the track substructure by adding stiffer granular layers (one of them being known as sub-ballast) between the subgrade and the ballast, with the aim of lengthening the service life of the track and reducing its maintenance costs. Nonetheless, this solution may require excessively thick granular layers in order to meet the minimum bearing capacity required, and therefore, significant consumption of high quality aggregates is needed. Thus, to reduce the thickness of sub-layers and to limit the deterioration of the track geometry to a minimum, an alternative solution consists of the application of hot-mix asphalt, material commonly used in other infrastructures like road pavements [14], between the ballast and subgrade to replace part of the conventional granular layers, a material known as bituminous sub-ballast [21,18].

Bituminous sub-ballast has been widely used in a number of railway lines (particularly in high-speed railways) in countries such as the United States, Italy and Japan, whilst other instances of its use can be found in European countries such as Austria, France and Spain [21,18]. The asphalt layer is generally applied with a thickness of around 12–15 cm, and is composed of a dense-graded bituminous mixture with a maximum aggregate size of 22–25 mm [16]. The asphalt mixture is generally designed with the same characteristic as that used in highways, although for its application as sub-ballast the bitumen content is increased by 0.5% in reference to the optimum for highways. Furthermore, the air void percentage is reduced to 1–3% in order to be used as an impermeable layer that can also avoid rutting problems, since the pressure is applied through the ballast over a wide area [18].

From an investment/cost viewpoint, it has been demonstrated that the use of bituminous sub-ballast is more appropriate than granular material when transport distances from the quarry are higher than 60–80 km, although the cost of granular sub-ballast is highly dependent on the local availability of quarries with materials that are suitable for meeting high-speed track standards [2]. In addition, it has also been demonstrated that the application of bituminous sub-ballast generally allows for a more homogenous behaviour of the track [2] whilst registering lower acceleration levels of vibrations [8]. However, before proceeding with the widespread application of this system, studies concerning the short and long-term efficacy of bituminous sub-ballast are needed to confirm that the main requirements of service can be met (mainly impermeability, bearing capacity, stress dissipation and durability) under the various service conditions expected during its application in railway tracks. In addition, it is important to consider that temperature variations cause changes in the performance of asphalt mixtures (more elastic at low temperatures and more viscous at higher temperatures) [4]. Thus, the benefits of using bituminous sub-ballast could depend on the temperature of service, which is subject to considerable variations, particularly in regions with extreme climates such as desert areas.

The present paper therefore focuses on the analysis of the mechanical behaviour of bituminous sub-ballast under various conditions that are expected to produce failure of the material, whilst also examining the influence of temperature on its performance. As a reference to evaluate the response of the bituminous material, the behaviour of conventional granular sub-ballast commonly used in railway tracks was also analysed. Thus, an in-depth study was conducted in order to examine the feasibility of using bituminous sub-ballast under a range of conditions of service (including adverse climate conditions) in reference to granular sub-ballast. The main properties studied for both materials (granular and bituminous sub-ballast) were resistance to plastic and punching deformations, bearing capacity, stress dissipation, and waterproofing properties. In addition, resistance to cracking was measured for the bituminous material, since this characteristic is fundamental in ensuring its durability. Finally, the effect of both types of sub-ballast on the performance of railway sections was assessed in the laboratory by means of a full-scale testing box.

2. Methodology

2.1. Materials

During this study, two main materials were utilised: granular sub-ballast; and asphalt mixture to be used as sub-ballast in railway tracks. The conventional sub-ballast analysed is commonly applied in Spanish high-speed railway tracks, sourced from Cerro Sillado quarry, in Guadix, Spain. This type of sub-ballast was composed of ophite aggregates with a continuous granulometry from 40 mm to 0.063 mm, as shown in Table 1. In addition, the granular material presented appropriate physical and mechanical properties for its utilisation as sub-ballast according to the Spanish Standard [20]. In addition to the properties listed in Table 1, its maximum density (2.73 g/cm^3) and optimal moisture (5.28%) were calculated by using the proctor test (UNE-EN 103-500) in order to obtain an adequate compaction of this material for its application in railway tracks.

The asphalt layer studied as sub-ballast was a dense-grade mixture type AC22S (UNE-EN 13108-1:2007) with a maximum size of aggregates equal to 22 mm. This material was manufactured using limestone aggregates and conventional bitumen type B50/70, whilst the filler was cement type CEM II/B-L 32.5 N. Table 2 lists the

Table 1
Main properties of ballast and sub-ballast.

Properties	Sieve (mm)	Standard	Ballast % passing	Sub-ballast % passing
Granulometry	*63*	EN 933-1:12	100	100
	50		85	100
	40		37	100
	31.5		8	100
	16		–	85
	8		–	66
	4		–	50
	2		–	30
	0.5		–	17
	0.2		–	14
	0.063		–	4.2
Content of fine particles (<0.5 mm) (%)		EN 933-1:12	0.08	–
Fines content (<0.063 mm) (%)		EN 933-1:12	0.03	–
Faces of fracture (%)		EN 933-5:99	100	100
Density (Mg/m^3)		EN 1097-6:01	3.24	3.24
Resistance to fragmentation (L.A.) (%)		EN 1097-2:10	5	14
Determination of particle shape – flakiness index (%)		EN 933-3:12	6	10
Sand equivalent (%)		EN 933-8:12	–	61

Table 2
Main properties of the asphalt mixture used as sub-ballast.

Properties	Standard	Bituminous sub-ballast
Bitumen content (% over the total weight of the mixture)	–	4.25
Maximum density (Mg/m^3)	EN 12697-5:10	2.65
Bulk density (Mg/m^3)	EN 12697-6:12	2.57
Air voids (%)	EN 12697-8:03	2.8
Marshall stability (kN)	NLT-159/00	11.85
Marshall flow (mm)	NLT-159/00	3.9
Index of retained tensile strength after water action (%)	EN 12697-12:09	86.0
Stiffness at 25 °C (MPa)	EN 12697-26:12	3391.11

main properties of this material, which was designed by means of the Marshall method (NLT-159/00), given that, on the basis of previous work the air void content should be in the range from 1% to 3% [18]. In addition, conventional tests (UNE-EN 12697-12:2009 and UNE-EN 12697-26:2012 Annex C, respectively) used for the application of asphalt mixtures in highways were employed to assess both its resistance against water action and its stiffness modulus.

In addition to these two types of sub-ballast, a full-scale box was utilised with the aim of analysing the effect of these layers on the mechanical performance of railway track sections. This box, shown in Fig. 1, had a length of approximately 750 mm, a width of 440 mm, and a height of 500 mm in order to reproduce the railway structure from the bottom of the sub-ballast layer to the rail (type UIC-54, with a length of 250 mm). In addition, this box included a piece of concrete sleeper (250 mm in width and 357 mm in length) with a fastening system commonly used in Spanish lines. Further, a ballast layer of 300 mm in thickness (from the bottom of the sleeper) was used between the components of the superstructure and the sub-ballast layer in order to complete the railway track section. The ballast used in this study was sourced from ophitic rocks at the Cerro Sillado quarry, and this material presented appropriate characteristics (Table 1) to be used in high-speed lines according to the Standard UNE-EN 13450:2003.

2.2. Methods

With the aim of studying the mechanical behaviour of bituminous sub-ballast with respect to its main functions and requirements in railway tracks, a series of laboratory tests were carried out for this material: (i) a cyclic triaxial test (UNE-EN 12697-25:2006, Method B); (ii) a punching test to assess its resistance to plastic deformations (associated with track settlement); (iii) a plate bearing test (UNE-EN 103807:2008) to measure the bearing capacity of the sub-ballast as well as its capacity to dissipate the stress transmitted to sub-grade; (iv) UGR-FACT test [10] to study the resistance to cracking, which is a fundamental parameter in asphalt materials; (v) a permeameter test to evaluate the capacity of the materials to protect the subgrade from water infiltration; (vi) and a full-scale test in a laboratory box to measure the effect of the bituminous sub-ballast on the railway track section. All of these tests (with the exception of the UGR-FACT test) were also carried out for the conventional granular sub-ballast that was used as a reference. Table 3 summarises the testing plan.

In addition, given that bituminous mixtures change their properties with temperature, exhibiting more rigid behaviour at lower temperatures whilst showing a softer response when the temperature increases [4,12], the influence of this parameter on the behaviour of bituminous sub-ballast was evaluated. This evaluation was conducted in order to determine the feasibility of using the sub-ballast under the range of temperatures that this material can be expected to withstand when used in railway tracks, including both standard and adverse conditions, depending on the property studied.

Thus, the triaxial and punching tests were conducted out at 25 °C, 40 °C, and 60 °C since these values represent the expected temperature (25 °C) as well as unfavorable and extreme temperatures for sub-ballast (40 °C and 60 °C respectively) at which plastic deformations are more likely to develop in asphalt mixtures. In addition, the plate bearing test and UGR-FACT test were developed at 15 °C, 25 °C and 40 °C which represents expected temperatures (25 °C) for sub-ballast in railways as well as low and high temperatures (15 °C and 40 °C respectively) that can modify the endurance of bituminous sub-ballast [9]. With regard to the permeameter test and the full-scale box test, these were carried out at 25 °C, since it was assumed that the temperature has little influence on the permeability of the material, whilst in the section test in box the ballast protects the sub-ballast, and therefore negligible changes in temperature are anticipated in the laboratory.

The cyclic triaxial test (Fig. 2a), which is considered appropriate for the evaluation of plastic deformations in bituminous materials [6,3], was conducted for 2 specimens (cylinders with a height of around 60 mm and a diameter of 101.6 mm) of each material and was tested under the different temperature conditions analysed in the case of the bituminous sub-ballast. This test was carried out according to the Standard UNE-EN 12695-25:2006 (method B), applying a cyclic sinusoidal axial loading of 200 kPa and a confining load of 80 kPa at a frequency of 3 Hz for 10,000 load cycles. The maximum stress was fixed in 200 kPa in order to study the material resistance under unfavorable loading conditions (since a normal value for sub-ballast is around 100–120 kPa) that could take place for sub-ballast in railway tracks [15]. The parameters of creep modulus, creep slope at the final 5000 loading cycles, and permanent deformation were calculated for each pair of specimens.

Another method used to assess the resistance to permanent deformations was the punching test, which was conducted for two squared (300 mm × 300 mm) specimens for each case studied (granular sub-ballast, and bituminous sub-ballast at different temperatures). The specimens had a height of 220 mm in the case of granular sub-ballast, and 120 mm for the bituminous sub-ballast, since these are common values found for the thickness of these layers in railway tracks. The test consisted of applying a stress of 200 kPa (regarded as an unfavorable loading condition that can occur over the sub-ballast layer) [17] on the contact between the sub-ballast specimen and a standard ballast plate (Fig. 2b). The parameter calculated was to represent the evolution of the permanent deformation caused by the punching of ballast particles.

The plate-bearing test was developed in the laboratory following the loading conditions established in the UNE-EN 103807:2008 to measure the bearing capacity of the sub-ballast. This test was carried out under static (at various stress levels: 20, 50, 150 and 250 kPa) and dynamic (at a frequency of 4 Hz and a pressure of 150 kPa) loads. For this test, prismatic samples (512 mm × 408 mm and 120 mm of height) were placed at the bottom of a box in the case of bituminous sub-ballast, whilst for the granular sub-ballast a layer of 220 mm of height was compacted at the bottom of the box (Fig. 2c). In both cases, a squared flat plate (300 mm × 300 mm) was used to load the materials. With this test it was possible to calculate the static and dynamic modulus of each material, whilst also assessing the influence of temperature on the strength of bituminous sub-ballast. In addition, a pressure cell was used under both types of sub-ballast with the aim of analysing the capacity of each solution to dissipate the stress applied over the material.

With regard to the UGR-FACT method (Fig. 2d), this test was carried out at a frequency of 4 Hz and a stress of 200 kPa over the specimens (200 mm in length, 60 mm in width, and 120 mm in height) of bituminous sub-ballast, in accord with Moreno and Rubio [10]. To evaluate the influence of the temperature on the cracking resistance of the bituminous specimens, the parameters used were the evolution of dissipated energy, the speed of cracking propagation, and the Mean Damage Parameter (γ), which is calculated as follows: $\gamma = \sum_{i=1}^{N_f} RDEC_i / N_f$ [11], where N_f is the cycle in which the macro-crack appeared at the bottom of the

Fig. 1. Visual appearance of the full-scale test developed in a laboratory box.

Table 3
Testing plan.

Test	Property tested	Material tested	Temperature (°C)	Main parameters
Triaxial cyclic test	Plastic deformation (settlement)	Granular sub-ballast Bituminous sub-ballast	25 25, 40, 60	- Creep modulus - Creep slope - Permanent strain
Punching test		Granular sub-ballast Bituminous sub-ballast	25 25, 40, 60	- Permanent deformation by ballast punching
Plate bearing test	- Bearing capacity - Stress dissipation	Granular sub-ballast Bituminous sub-ballast	25 15, 25, 40	- Static and dynamic elastic modulus - Stress under the sub-ballast
UGR-FACT	Cracking resistance	Bituminous sub-ballast	15, 25, 40	- Evolution of dissipated energy - Mean Damage Parameter
Permeameter	Permeability	Granular sub-ballast Bituminous sub-ballast	25 25	- Time of saturation of the specimen - Evolution of permeability
Full-scale test	Response of the track section	Granular sub-ballast Bituminous sub-ballast	25 25	- Settlement - Vertical stiffness - Dissipated energy - Stress dissipation

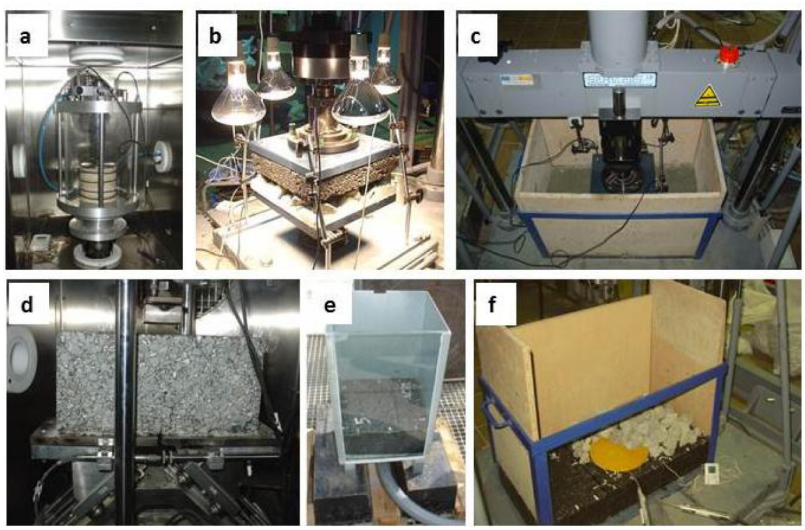

Fig. 2. Configuration of some of the tests used in this study.

sub-ballast layer, whilst the *RDEC* (Ratio of Dissipated Energy Change) was calculated according to the equation $RDEC_{n+1} = (\omega_{n+1} - \omega_n)/\omega_n$ where ω_n is the energy dissipation produced in loading cycle number n (in J/m^3); and ω_{n+1} is the energy dissipation in loading cycle $n + 1$ (in J/m^3).

With respect to the permeameter test (Fig. 2e), this was developed in consonance with the Standard UNE-EN 103403:1999, commonly used to determine the permeability of soils by applying the constant-head method. For this study, however, the permeameter device was a box with appropriate dimensions (a surface of 300 mm × 300 mm, and 500 mm in height) for testing samples with 220 mm and 120 mm in height for granular and bituminous sub-ballast, respectively. At the bottom of the box, a geotextile and geomembrane were used to avoid losing fine particles of the samples, whilst water flow was not limited. In addition, a pipe (with 50 mm of diameter) was connected to the bottom of the box to collect the water drained by the sub-ballast. This system was also in consonance with those used by other authors [13]. The parameter calculated was the evolution of the permeability for each type of sub-ballast, by applying the Darcy law.

Having studied each type of sub-ballast as an individual layer, a full-scale test was conducted in a laboratory box with the aim of assessing the impact of the bituminous sub-ballast on the mechanical performance of the railway track section (from sub-ballast layer to the system sleeper-rail). This test consisted of applying dynamic loads at a frequency of 4 Hz and an amplitude of 25 kN over a piece of rail, transmitting a stress close to 280 kPa over the ballast surface, which is appropriate for simulating the loads imposed on railway tracks [7,1,5]. The number of loading cycles was established at 200,000 in order to obtain a stable behaviour of the system and to measure the main parameters such as settlement, stiffness modulus and energy dissipated by the section in the short and long-term. In addition, its capacity to dissipate stress was recorded by using pressure cells over and under the sub-ballast layer (Fig. 2f).

3. Analysis of results

3.1. Resistance to plastic deformations

Fig. 3 displays the results obtained in the triaxial test for both types of sub-ballast, analysing the effect of temperature on the behaviour of the bituminous sub-ballast. The parameters shown are the permanent deformation (P.D.) recorded for each sample under the different conditions, along with the mean value of creep modulus and the slope of creep deformation (S.C.D.), this last parameter being measured during the final 5000 loading cycles. The results indicate that, at least under routine in-service temperature conditions, the bituminous sub-ballast displayed a resistance to plastic deformations similar to that obtained for the conventional granular sub-ballast, since both layers recorded comparable mean values of permanent deformation, slope of deformation, and even creep modulus. This fact indicates the potential for using bituminous sub-ballast in railway tracks without increasing plastic deformations due to bitumen creep.

It should also be noted, however, that the increase in sub-ballast temperature that can occur in warm climates led to a notable decrease in the resistance of the bituminous material against plastic deformations, recording an important increase in final

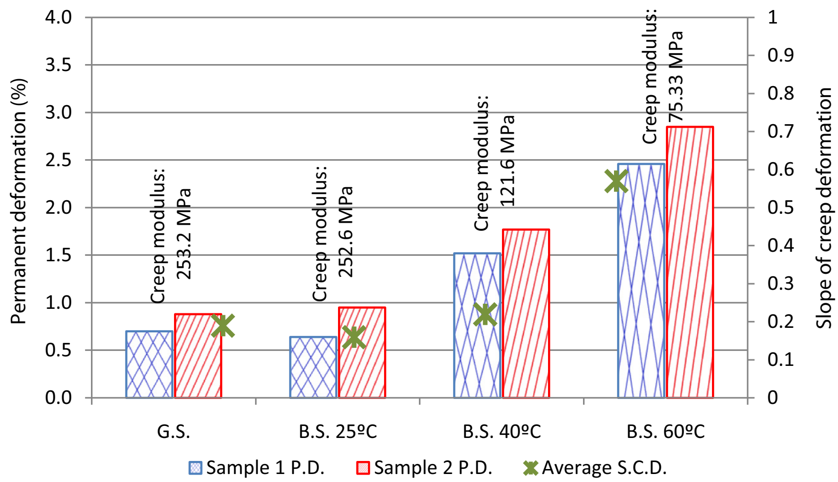

Fig. 3. Results measured from the triaxial test: resistance to plastic deformations.

deformation and the slope of the creep curve, whilst the creep modulus decreased up to a value of around 50% and 30% in the case of 40 °C and 60 °C, respectively. This decrease in resistance to deformation could limit the use of this type of sub-ballast in railway lines where the temperature is expected to be high for this layer, although it is also worth noting that the ballast layer protects the sub-ballast from high temperatures. Therefore, before applying the bituminous material in warm regions, it is recommended that a preliminary study be conducted in order to assess the expected temperature of service for the sub-ballast.

With the aim of developing a more in-depth evaluation of the behaviour of both types of sub-ballast against plastic deformations, Fig. 4 shows an example of the deformation curves obtained in the punching test, which allows for a more realistic reproduction of the loads transmitted by the ballast to the sub-ballast layer. Based on the curve displayed in Fig. 4, there are three phases of the behaviour of the sub-ballast that are delimited by two inflexion points: "P1" that separates the initial deformation (primarily associated with the recompaction and reorganisation of particles) from a phase where the deformation response is stabilised; and a second inflexion point "P2" that separates the latter from a phase of creep deformation of the material. In addition, there is a further point "P3" that indicates the final permanent deformation under punching efforts.

From these points, the response of both types of sub-ballast under various temperature conditions was analysed through the values of initial deformation (P1), slope of the curve in the second phase (between P1 and P2), and the final permanent deformation (P3), all listed in Table 4. Again, these results show that the bituminous sub-ballast recorded a resistance to plastic deformations similar to (or even higher than) that measured for the granular material under routine in-service temperatures for this layer. Nonetheless, the bituminous sub-ballast demonstrated a significant susceptibility to higher temperatures, since both higher initial

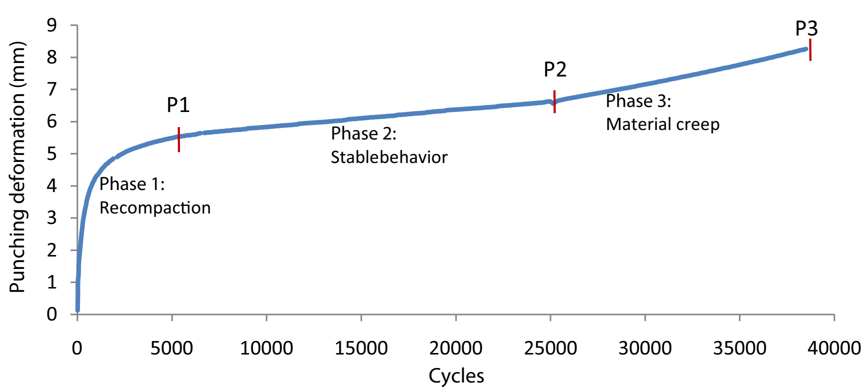

Fig. 4. Example of the deformation curves recorded during the punching test.

Table 4
Results of the punching test for both sub-ballasts under different temperatures.

Materials	Temperature	Initial deformation (mm)	Slope of the curve in the stable phase (mm/cycle)	Final deformation (mm)
Granular sub-ballast	25	1.8	5.65E−05	8.1
Bituminous sub-ballast	25	2.0	5.14E−05	7.9
	40	3.1	6.85E−05	8.3
	60	5.2	1.78E−04	11.1

and final deformations were recorded under extreme conditions (40 °C, and particularly 60 °C) and the tendency towards developing long-term deformation was more pronounced than in the case of the material tested under routine temperature conditions (25 °C).

3.2. Bearing capacity and dissipation of stress

In relation to the bearing capacity of the materials, Fig. 5 displays the static and dynamic modulus measured in the plate bearing test for both granular sub-ballast (G.S.) and bituminous sub-ballast (B.S.) under the range of in-service temperatures that can be expected in railway tracks for this layer.

It is clear that the bituminous sub-ballast presented a higher bearing capacity (static and dynamic) than the conventional granular layer, even under the adverse temperature conditions (40 °C) that could prevail in extreme climates. This observation, which is in agreement with results described by other authors [19], indicates that the use of bituminous sub-ballast could lead to an increase in the strength of the railway structure, offering higher protection of the bed layers and foundation of the track, particularly under low temperatures (15 °C) at which the highest modulus was recorded. In addition, this increase in bearing capacity associated with bituminous sub-ballast was even more marked under the dynamic loads that reproduce the real conditions expected in railway tracks with passing trains, an observation that is likely to be linked to an increase in the elasticity of bituminous materials under dynamic loads.

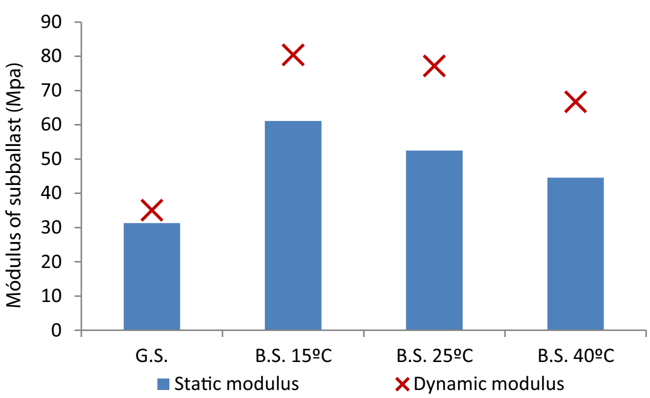

Fig. 5. Static and dynamic modulus for both types of sub-ballast: Influence of temperature.

The results related to bearing capacity are compatible with those obtained from the measurement (by using pressure cells) of stress dissipation during the plate-bearing test for both types of sub-ballast under various loading and temperature conditions (Fig. 6). The results, which are in consonance with other studies [15], indicate that under low levels of stress, there is little impact of the temperature and the type of sub-ballast. However, when the stress is increased up to the levels expected in railway tracks (between 150 kPa and 250 kPa), the influence of the temperature is higher on the bituminous sub-ballast that showed a lower capacity to dissipate the stress when temperature is increased, which must be related to a decrease in its strength. Nonetheless, under the various temperatures used in this study (both routine temperatures and adverse temperatures such as 40 °C) and also under the various loading conditions (different stress levels under static conditions as well as dynamic loads), this material presented lower values (up to around 50% lower) of stress under the layer than those measured for the granular sub-ballast. This fact indicates that the use of bituminous sub-ballast allows for higher protection of the remaining bed layers of the railway track, since lower stress is transmitted to these layers under the passage of trains, regardless of the temperature.

3.3. Cracking resistance

Due to the fact that the cracking resistance of asphalt materials is of fundamental importance in protecting the substructure, Fig. 7 displays the effect of temperature on the cracking fatigue of bituminous sub-ballast. This figure shows the mean value of the number of cycles needed to initiate the macro-crack at the bottom of the layer, the results of Mean Damage Parameter, and the speed of cracking propagation (measured in mm/cycle after the beginning of the macro-crack in each specimen).

It appears that temperature plays a very important role in the cracking endurance of bituminous sub-ballast since an increase in this parameter led to a sharp rise in the damage suffered by the material (particularly at higher temperatures such as 40 °C), which caused a notable decrease in the number of cycles needed to provoke cracking of the material. In addition, the change of temperature also caused an important increase in the speed of propagation of the crack, which accelerates the failure of the sub-ballast, especially at 40 °C. Thus, these results indicate that bituminous sub-ballast is more susceptible to cracking under the higher temperatures that can be expected in warm climates. In addition, under these conditions there may also be a significant reduction

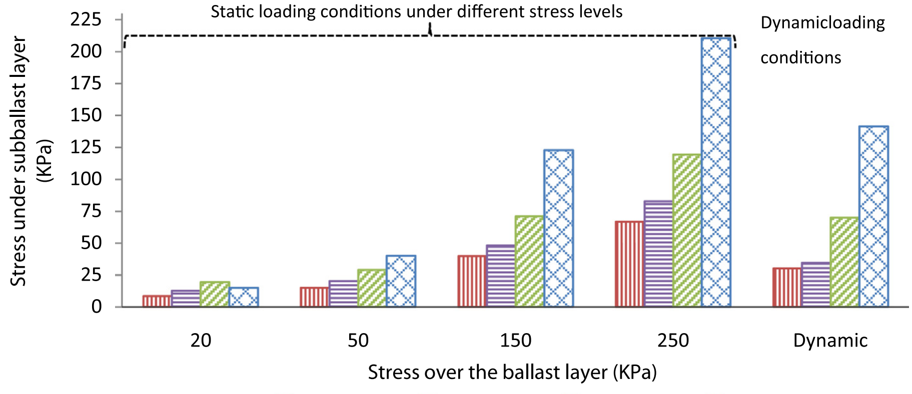

Fig. 6. Pressure transmitted by each type of sub-ballast under various loading and temperature conditions.

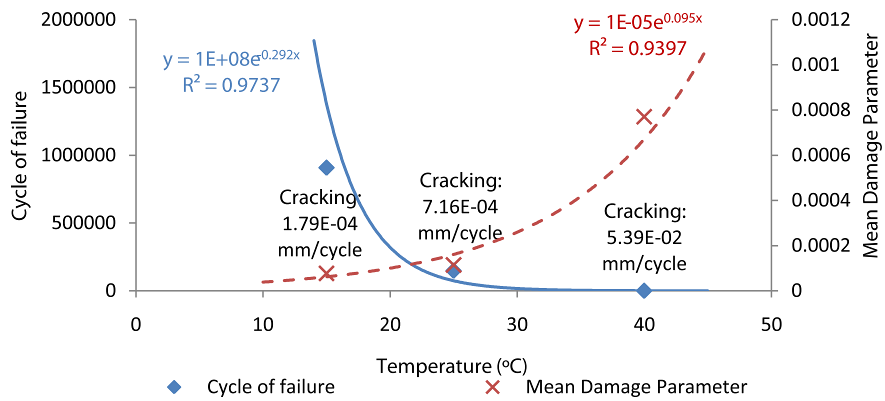

Fig. 7. Effect of temperature on the cracking resistance of bituminous sub-ballast.

in the protection of bed layers in the substructure, along with the infiltration of water to the foundation.

3.4. Permeability

Another important parameter for evaluating the feasibility of applying sub-ballast in railway tracks is the capacity of this layer to waterproof the remainder of the substructure. Thus, Fig. 8 displays the results measured in the permeameter test (constant-head method) for both types of sub-ballast used in this study, showing the evolution of the drained flow and the permeability coefficient (k) once the flow is stabilised in each case. It is clear that for the bituminous sub-ballast, a longer time (3600 s) was recorded without the transmission of water (flow equal to 0 m^3/s) when compared with the conventional granular sub-ballast (570 s), which also recorded higher values of flow during the test. In addition, the latter material needed a longer time to stabilise the drained flow, which could be related to the movements of fine particles towards the bottom of the layer, which reduced the permeability up to $k = 2.39 \times 10^{-6}$ m/s, although this value was always higher than that measured for the bituminous sub-ballast (k close to 5.7×10^{-7} m/s), which presented an appropriate coefficient of permeability for its application in railway tracks according to the Spanish Standard for sub-ballast [20].

Based on these results, it is possible that the application of an asphalt layer as sub-ballast can reduce the infiltration of water into the bed layers of the railway track, thereby providing the substructure with higher protection against water action. This is in agreement with the results of other work [16] where it has been demonstrated that the use of bituminous sub-ballast leads to a lower variation in the moisture content of the bed layers.

3.5. Behaviour of full-scale section

Having studied the behaviour of each type of sub-ballast, Fig. 9 shows its effect on the settlement (left) and stiffness (right) of a full-scale section of the railway track (from sub-ballast to rail) whilst Fig. 10 displays the impact of the type of sub-ballast on the capacity of the section to dissipate energy (left) and the stress (right) transmitted by passing trains. This last parameter (recorded by using pressure cells) is presented as the difference in the mean value of stress over and under each sub-ballast layer measured when the section behaviour was stable (after approximately 50,000 loading cycles).

The results indicate that the use of bituminous sub-ballast could lead to a slight reduction in track settlement, particularly in the long-term, when the granular sub-ballast showed a trend towards developing higher vertical deformations compared with the case in which the bituminous material was used. This fact could be related to the difference in vertical stiffness (Fig. 9, right) since the section with asphalt layer presented higher strength under the train loads reproduced in the laboratory, which is in agreement with the results of the bearing capacity test where higher strength of the bituminous sub-ballast was recorded.

In addition, it should be noted that in spite of the stiffening of the section with the application of the bituminous layer, its

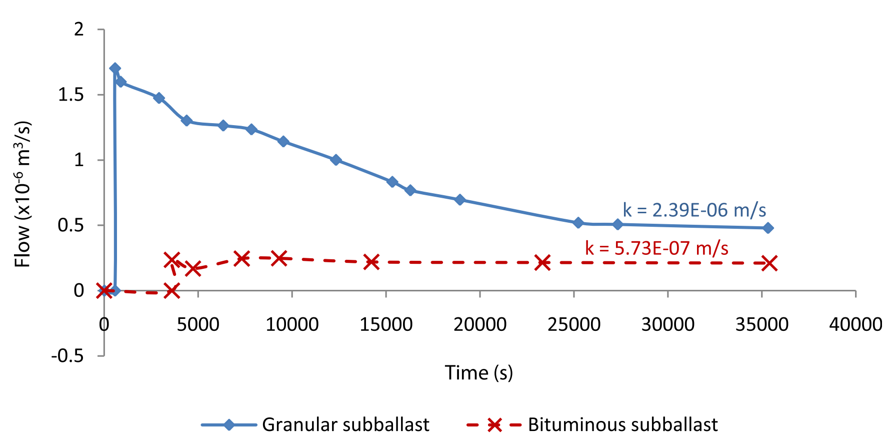

Fig. 8. Evolution of the water flow drained by each type of sub-ballast: permeability results.

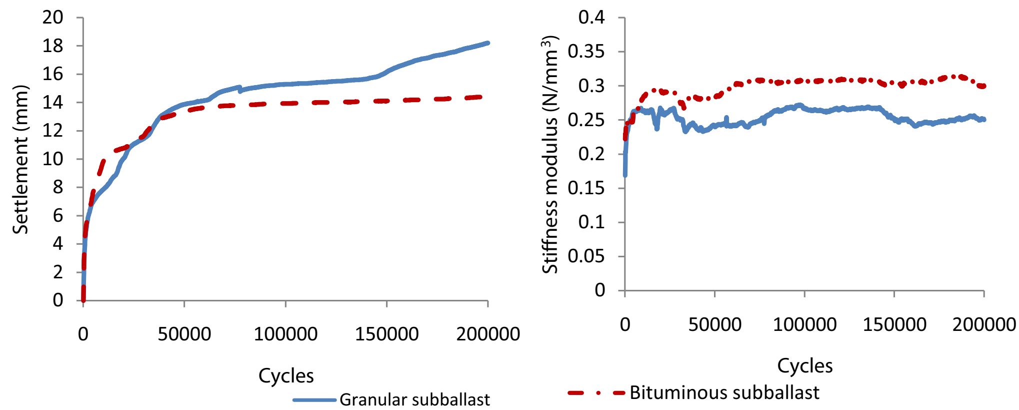

Fig. 9. Influence of the type of sub-ballast on track settlement (left) and modulus stiffness (right).

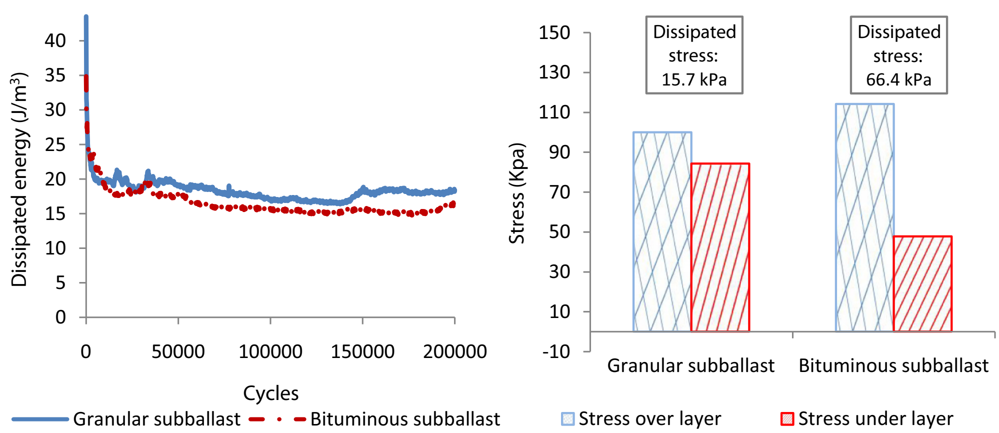

Fig. 10. Effect of each sub-ballast on the capacity of the track to dissipate energy (left) and stress (right) under trains passing.

capacity to dissipate the energy transmitted by the trains (Fig. 10, left) is quite similar to that recorded when granular sub-ballast is used, which is likely to be related to the viscous behaviour of asphalt materials. Furthermore, despite the fact that the pressure over the sub-ballast (Fig. 10, right) is higher when the bituminous layer is used (as a result of the stiffening of the structure), the stress transmitted to the remainder of the bed layers is lower in this case, since the asphalt material presented a higher capacity to dissipate stress. Thus, it appears that the use of bituminous sub-ballast could allow for an improvement of the track quality (associated with the reduction in settlement) and durability (related to higher protection of the bed layers against train loads).

4. Conclusions

This aim of this paper was to examine the mechanical performance of bituminous sub-ballast under the range of loading and temperature conditions that can cause failure of the material, thereby limiting its functionality in railway tracks. To this end, a series of laboratory tests were conducted in order to assess the behaviour of this material in terms of its ability to meet a number of requirements for its application in railway tracks. These tests were also carried out for conventional granular sub-ballast, which served as a reference. On the basis of the results obtained in this study, the following conclusions can be drawn:

- When tested under the standard temperatures of service expected for sub-ballast in railway tracks (around 25 °C), the bituminous layer presented a resistance to plastic and punching deformations similar to that recorded for the conventional granular sub-ballast. However, under the higher temperatures that could take place in warm climates, the bituminous sub-ballast showed an important decrease in its resistance to permanent deformations, thereby showing greater vulnerability to deformations than the granular layer.
- Although the strength of the bituminous sub-ballast and its capacity to dissipate stress are reduced with an increase in temperature, this layer presented higher bearing capacity and protection for the remainder of the bed layers than the granular sub-ballast.
- Under higher temperatures, a sharp decline in the cracking resistance of bituminous sub-ballast was observed. This finding should therefore be taken into account when applying this type of sub-ballast under adverse temperature conditions. Further, despite the fact that bituminous sub-ballast presented lower permeability than granular sub-ballast (and therefore it is more appropriate to reduce the infiltration of water), its application for protecting the rest of bed layers from water infiltration could be limited under severe temperatures given the observed decrease in structure strength and its higher susceptibility to cracking.
- It was demonstrated that the use of bituminous sub-ballast could reduce the track settlement in comparison with the section with granular layer, due to an increase in the stiffness of the substructure. Whilst this also leads to a slight stiffening of the whole track, it does not decrease its capacity to dissipate the energy transmitted by trains. In addition, the bituminous sub-ballast presented higher stress dissipation during the

full-scale test, which allows for greater protection of the remainder of the bed layers against the loads transmitted by trains.

Based on the results presented in this study, it is suggested that the majority of the properties of bituminous sub-ballast make it a suitable solution for enhancing the strength of railway tracks. Nonetheless, it is important to note that temperature plays an important role in both its mechanical performance and service life, and this could limit the potential for its use in regions where the material is expected to perform under particularly high temperatures.

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A study into the mechanical performance of different configurations for the railway track section: A laboratory approach

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ABSTRACT

A traditional railway track is composed of rails, sleepers, fastenings (included rail pads), ballast, and a formation layer. More recently, other configurations have been commonly used in the track section in order to improve its quality and durability. However, the use of different configurations can lead to important changes in fundamental parameters such as the global vertical stiffness of the track, as well as its settlement and rolling resistance. This paper therefore focuses on a laboratory study of the mechanical performance of a number of different track sections, assessing the effect of using various types of elastic elements with varying properties, various types of sub-ballast, and different thicknesses of ballast layer. The results showed that reducing track stiffness by modifying the elastic elements over the ballast layer leads to an increase in the capacity of the track to dissipate energy and to reduce its settlement. However, the reduction in stiffness induced by modifying the configuration under the ballast (by, for example, adding elastic mats) causes an increase in settlement, the latter exerting the strongest influence (even more so than the change in ballast thickness) on track performance. Furthermore, it was seen that changes in track behaviour are lower (particularly in track stiffness) than those observed in the properties of its components.

1. Introduction

A traditional railway track generally consists of rails, sleepers, rail pads, fastenings, ballast and an over ground formation layer. However, with the continuous increase in train speeds and loading capacity, a number of modifications of the track section have been developed with the aim of obtaining a section with a higher bearing capacity whilst increasing the durability of the system. In addition, given the ever-increasing concerns for the environment, new components are being used to not only increase track quality and travel comfort, but also to limit the vibrations and noise that are generated by passing trains.

To this end, modern tracks have utilised an increasing number and thickness of granular layers between ballast and ground in order to obtain a section with a higher bearing capacity and to reduce the stress transmitted to the ground [1]. Of particular importance is the use of a highly compacted granular layer known as sub-ballast, which serves to protect the subgrade. With the same objective, other configurations such as track over asphalt layer (used as sub-ballast) are also becoming widely used in the construction of new railway lines around the world [2–4]. However, it should also be noted that all of these changes in the railway section not only lead to higher vertical strength, but also cause an increase in global vertical stiffness, which would in turn lead to higher dynamic overloads on the track, and therefore, higher deterioration of its components [5].

Thus, recent decades have seen a rise in the tendency to conduct work aimed at reducing the stiffness of the elastic pads used between rail and sleeper. The objective of this work has been to attain an optimal value for the global vertical stiffness that allows for a reduction in track deterioration (and therefore maintenance costs) and energy consumption by trains (service costs) [6,7]. With this same purpose in mind, other elastic elements have been developed, such as under sleeper pads or under ballast (or sub-ballast) mats [8,9], which also provides the track with higher capacity to damp the loads transmitted by trains as well as obtaining an important reduction in track vibration and noise, These changes can therefore help to achieve a more durable and higher quality railway track.

However, it should be noted that all these modifications in track configuration, in addition to the changes applied in vertical stiffness, could lead to important variations in other important parameters such as dissipated energy or track settlement [10], which are associated with service and maintenance costs, respectively.

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Further, such changes can also modify, to varying degrees, the mechanical performance of the railway track, and therefore different sections are required depending on the characteristics of the track. In order to address this issue, this paper examines the different configurations that are used in the railway section in order to determine the effect of the properties of a number of components on the mechanical performance of the track.

In this laboratory study, the behaviour of a track section 1:1 was analysed when different variables in the vertical configuration were included: (i) three different rail pads (very stiff, stiff, and soft pads); (ii) two types of under-sleeper pads (medium and soft); (iii) adding two kinds of under-ballast mat (soft and stiff); (iv) including two types of sub-ballast layer (granular and bituminous); (v) incorporating a stiff elastic mat under each type of sub-ballast; (vi) and modifying the thickness of the ballast layer. The parameters used to evaluate the performance of each configuration were global vertical stiffness and settlement of the section (associated with maintenance costs), as well as dissipated energy (related to service costs).

Table 1
Main properties of ballast and sub-ballast used in the study.

Properties		Ballast	Sub-ballast
Granulometry EN 933-1 [14]	Sieve (mm)	% Passing	% Passing
	63	100	100
	50	85	100
	40	37	100
	31.5	8	100
	16	–	85
	8	–	66
	4	–	50
	2	–	30
	0.5	–	17
	0.2	–	14
	0.063	–	4.2
Content of fine particles (<0.5 mm) EN 933-1 [14] (%)		0.08	–
Fines content (<0.063 mm) EN 933-1 [14] (%)		0.03	–
Fractured faces EN 933-5 [15] (%)		100	100
Density EN 1097-6 [16] (Mg/m^3)		3.24	3.24
Resistance to fragmentation (L.A.) EN 1097-2 [17] (%)		5	14
Determination of particle shape – flakiness index EN 933-3 [18] (%)		6	10
Sand equivalent EN 933-8 [19] (%)		–	61

2. Methodology

2.1. Materials

With the aim of evaluating the effect of using different configurations for the railway track, a box was used in laboratory in order to replicate the various track sections that can be applied in railway infrastructures. The box used in this study, whose appearance is shown in Fig. 1a, was 440 mm in width, 750 mm in length, and 500 mm in height, allowing for the simulation of the railway track section under the rail seat area (with a sleeper spacing near 500 mm), where the highest levels of stress over ballast are expected. The testing box includes a piece of a concrete sleeper (250 mm in width and 357 mm in length) with a tension clamp fastening type VM (composed mainly of a metallic clip type SKL-1, screw spike type VAPE, and an elastic pad) commonly used in Spanish railway tracks, whilst the rail used was a type UIC-54 with a length of 250 mm. These components were reused for all the studied sections since its fatigue life is longer than the duration of the tests developed in this study [11,12].

In addition, all configurations used a ballast layer (whose main properties of the particles are listed in Table 1), and a subgrade layer composed of 2 cm of compacted sand over the metallic floor of the box, presenting an elastic modulus of approximately 70 MPa (Fig. 1b). Fig. 1c also shows the control of the density of the granular layers used in this study (by means of a Pavement Quality Indicator device, PQI) in order to guarantee its appropriate compaction [13].

In addition to the components (rail, fastenings, piece of sleeper, and ballast layer) that were common for all configurations, the effect of including three different rail pads was analysed. A very stiff commercial pad of 6 mm of thickness and made of polyethylene (with more than 1000 kN/mm of secant stiffness) [20], and a 4.5 mm thick stiff pad (around 300 kN/mm) and a 7.5 mm soft pad (close to 100 kN/mm) manufactured both from deconstructed tire tread layers [21]. All rail pads used in this study had horizontal dimensions of 140 mm in width and 180 mm in length, which make them suitable for use under rail type UIC-54. The visual appearance of the rail pads is shown in Fig. 2a.

On the other hand, to measure the effect of adding elastic under-sleeper pads (USP), two different pads were used in this

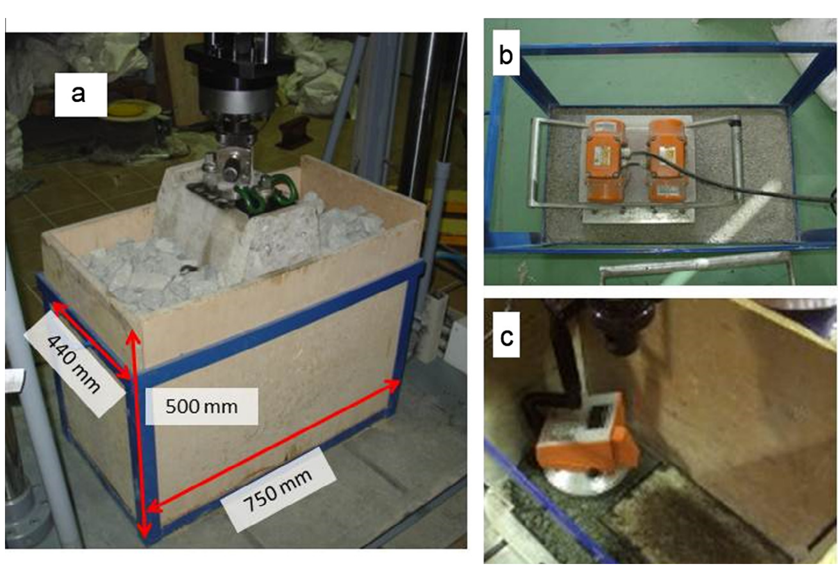

Fig. 1. Visual aspect of (a) the box used for the study, (b) the compaction of a sandy layer to simulate the subgrade, (c) and a control of the compaction of granular layers.

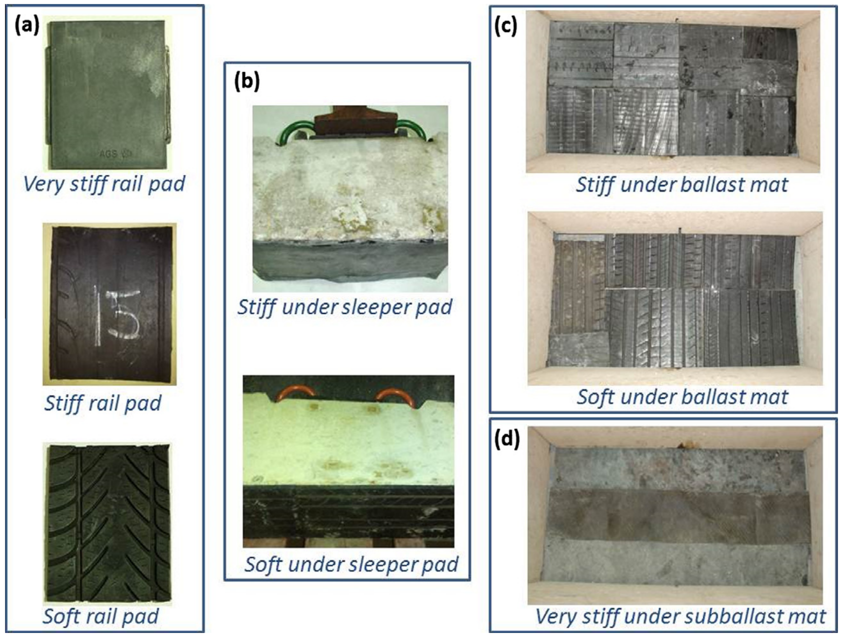

Fig. 2. Elastic elements used during the study.

study, both of which were made from deconstructed end-of-life tire tread layers [22]. One of these had a thickness of 7 mm and its static bearing modulus was close to 0.15 N/mm^3 [23], whilst the other presented a modulus similar to 0.29 N/mm^3 and its thickness was equal to 4.5 mm, materials that qualified as soft and medium USP respectively. Thus, these USP are suitable for use in railway tracks with the aim of reducing the degradation of granular sub-layers, according to [24]. The horizontal dimensions of these elements were quite similar to those of the bottom surface of the piece of sleeper, presenting both components (USP glued to the sleeper bottom) the appearance of which is displayed in Fig. 2b.

Other elastic elements whose influence was analysed in this study were a soft and a stiff under ballast mat (UBM), selected to modify the stiffness of the substructure of the railway track. These mats were also manufactured from end-of-life tire tread layers and their horizontal dimensions were similar to those of the bottom surface of the ballast box. The thickness of the soft element was 21 mm and its dynamic bending modulus at 5 Hz was close to 0.20 N/mm^3 [25], which is appropriate for being used in railway tracks to reduce its deterioration [26], whilst the stiff mat had a thickness of 9 mm and 0.30 N/mm^3 of dynamic modulus. Fig. 2c displays the soft mat at the bottom of the box that was included before adding the ballast.

In addition, the effect of a stiff mat was analysed when it was used as under-sub-ballast mat (in the cases where the sub-ballast layer was studied). This element was also produced from tire layers, but in this case the inner layer of the end-of-life tire was used resulting in a thickness of 5 mm and a dynamic modulus close to 0.32 N/mm^3. Fig. 2d shows this elastic element that was placed at the bottom of the box before introducing the sub-ballast layer (any typology selected) and the remainder of the components (ballast, sleeper, fastenings, stiff rail pad, and rail).

In order to evaluate the effect of adding two types of sub-ballast, a granular layer of 22 cm was compacted under the ballast, whilst a bituminous layer of 12 cm in thickness was also used. The granular sub-ballast studied is commonly used in high-speed railways in Spain, and its properties are listed in Table 1. With regard to the bituminous sub-ballast, it was manufactured from a AC 22 S asphalt mixture [27], and its main characteristics are shown in

Table 2
Main properties of the asphalt mixture used as bituminous sub-ballast.

Properties	Bituminous sub-ballast
Type of bitumen	B 50/70
Type of aggregates	Limestone
Bitumen content (% over the total weight of the mixture)	4.25
Maximum density EN 12697-5 [28] (Mg/m^3)	2.643
Bulk density EN 12697-6 [29] (Mg/m^3)	3.569
Air voids EN 12697-8 [30] (%)	2.8
Marshall stability EN 12697-34 [31] (kN)	11.85
Marshall flow EN 12697-34 [31] (mm)	3.9
Index of retained tensile strength after water action EN 12697-12 [32] (%)	86

Table 2. The visual appearance of these materials (granular and bituminous sub-ballast) is shown in Fig. 3a and b respectively.

2.2. Methods

In order to analyse the effect of using various systems in railway sections, the mechanical performance of 13 different configurations were evaluated. In particular, the aim was to study the influence of adding various types of elastic elements (that differed in terms of their general characteristics), compositions of sub-ballast layer, and thicknesses of ballast layer. For this purpose, the methodology is composed of three stages: (i) analysis of the impact of the properties of components over the ballast layer; (ii) influence of the bearing capacity of the bed layers under the ballast; (iii) and evaluation of the effect of the thickness of the ballast layer. This study also includes a comparative analysis into the influence of varying the design of the track section on different levels (comparison between the effect of varying the properties of elements over and under the ballast layer).

Firstly, it was analysed the effect of the characteristics of elastic elements that are used over the level of the ballast layer, such as rail pads and under-sleeper pads (Fig. 4). All the systems included a ballast layer (30 cm in thickness) over a sandy subgrade, a piece of sleeper, the fastenings, and a rail. However, they had different types of elastic elements, analysing 5 configurations with: (1) a

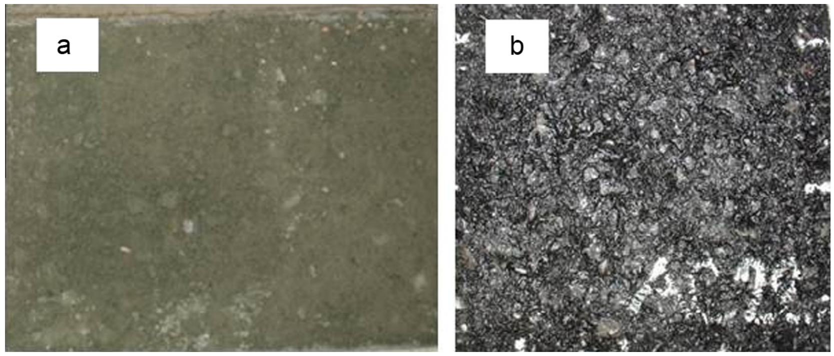

Fig. 3. Visual appearance of (a) granular sub-ballast and (b) bituminous sub-ballast.

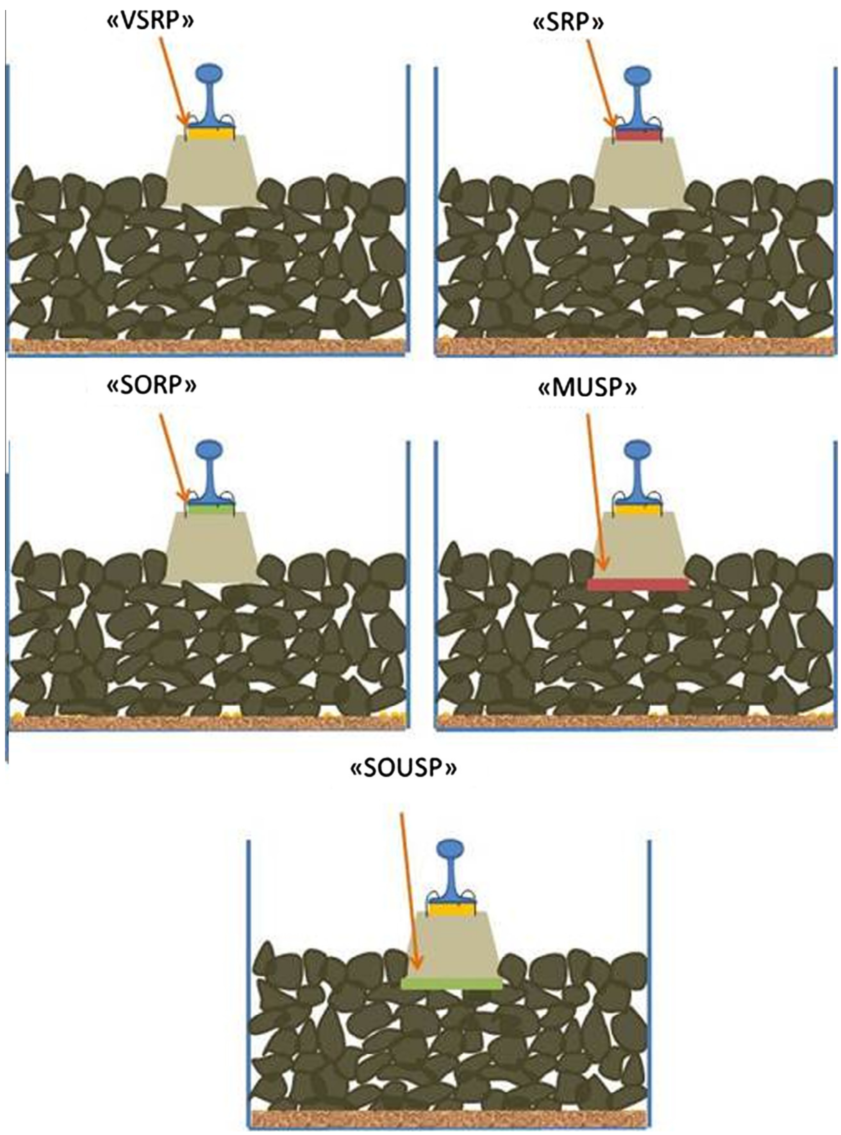

Fig. 4. Configurations studied to vary the stiffness by modifying the properties of elastic elements over the ballast layer.

very stiff rail pad "VSRP" (reference system); (2) a stiff pad under the rail "SRP"; (3) a soft rail pad "SORP"; (4) a very stiff rail pad and a medium under-sleeper pad "MUSP"; (5) a very stiff pad under the rail and a soft USP "SOUSP".

The second step of the study was focused on examining the effect of varying the configuration of track section under the ballast layer (Fig. 5), analysing various types of sub-ballast as well as the use of different elastic mats at different levels. As in the previous case, all these configurations included a sandy subgrade (on which the various solutions were placed), a ballast layer (30 cm thick), a piece of sleeper, the fastenings, and a rail – but in this case a constant stiff rail pad was used for all systems. These 6 configurations

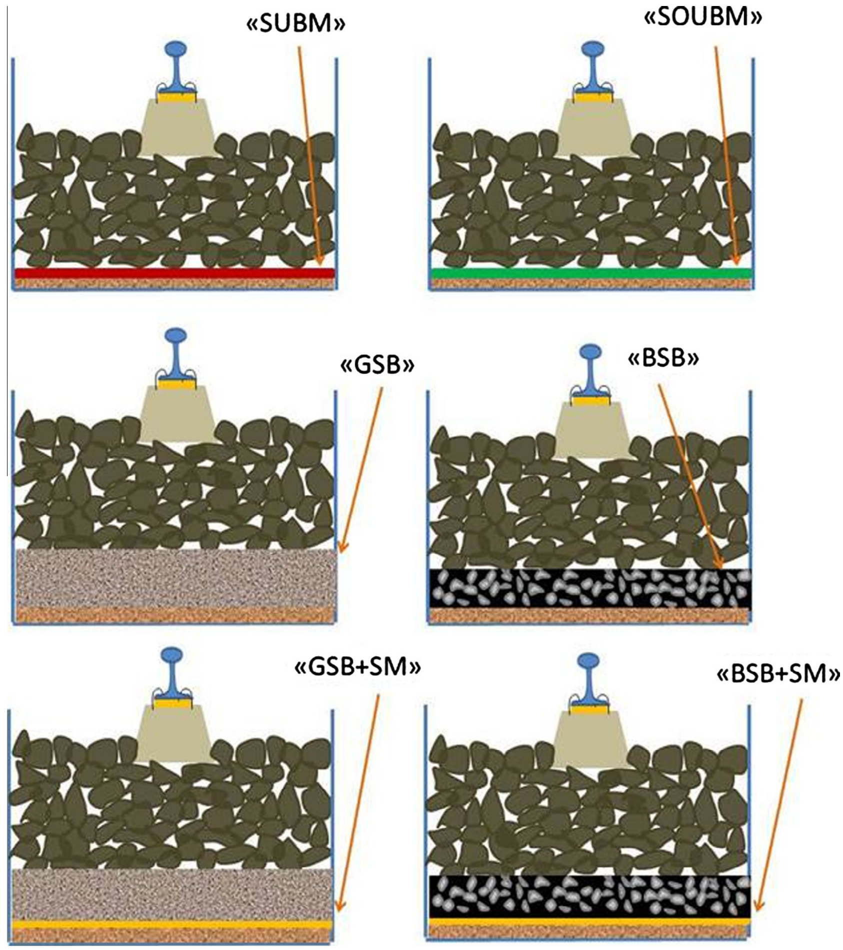

Fig. 5. Sections analysed to study the effect of the bed layer configuration.

also included the following: (6) a stiff under-ballast mat (directly over the subgrade) "SUBM"; (7) a soft under-ballast mat "SOUBM"; (8) a granular sub-ballast layer between the subgrade and ballast "GSB"; (9) a bituminous sub-ballast "BSB"; (10) a granular sub-ballast and a stiff under sub-ballast mat "GSB+SM"; (11) a bituminous layer under the ballast and a stiff mat under the sub-ballast "BSB+SM".

For all these configurations, the static modulus of the system under the ballast was evaluated through a loading test that was developed in consonance with the loading conditions collected in the plate-bearing test [33]. This parameter was recorded with the aim of matching the influence of the bearing capacity of the system with its behaviour. The test consisted of applying two loading cycles with a rate of 5 kN/min up to a stress close to 300 kPa, measuring the bearing capacity as the relationship between the stress and the vertical deflection of the layer.

The last step evaluates the influence of varying the thickness of the ballast layer; 2 configurations were studied with a reduction in the ballast layer from 30 cm to 20 cm in order to compare its behaviour with that recorded for the configurations with 30 cm of ballast. Both sections with 20 cm of ballast were placed over bituminous sub-ballast and sandy ground (Fig. 6), and one of them also included a very stiff mat under the asphalt sub-ballast to compare the technique of modifying ballast thickness with the effect of varying the configuration of elastic elements used in the railway track. Thus, these systems were: (12) 20 cm ballast over bituminous sub-ballast "20 cm BSB"; and (13) 20 cm ballast over bituminous sub-ballast and a stiff under sub-ballast mat "20 cm BSB+SM". For this comparative analysis, the configurations "BSB" and "BSB +SM" were used as references, and for the purposes of this stage of the study they were denoted as "30 cm BSB" and "30 cm BSB +SM".

To evaluate the effect of each configuration on the mechanical performance of the global railway section, a dynamic test was conducted to simulate the passage of trains. The test, which was carried out twice for each configuration studied, consisted of 200,000 cyclic sinusoidal loads with amplitude of 25 kN and at 4 Hz of frequency. This number of cycles was fixed to obtain a stable behaviour of the system, and then, to measure the difference between the various configurations. In reference to the load amplitude, this value was fixed to reproduce a stress level of 900 kPa over the rail pad and 250–300 kPa over the ballast surface (when the traditional configuration of the section is used), which are values appropriate for the simulation of conventional loading conditions expected in railway tracks under permissible axle loads [34–36]. To reproduce the passage of trains, a testing frame (composed of a base where different testing boxes can be included)was used in laboratory; a frame to reproduce the loading conditions; and an actuator with a maximum loading capacity equal to 120 kN at a maximum frequency of 10 Hz.

In order to assess ballast behaviour, 4 LVDTs (one LVDT in each corner of the foot of the rail) were used to measure the section settlement and the mechanical behaviour. The main parameters measured were the global vertical stiffness of the section and its vertical settlement (both parameters associated with track deterioration, and therefore maintenance costs), as well as the dissipated energy (related to rolling resistance, and then to service costs).

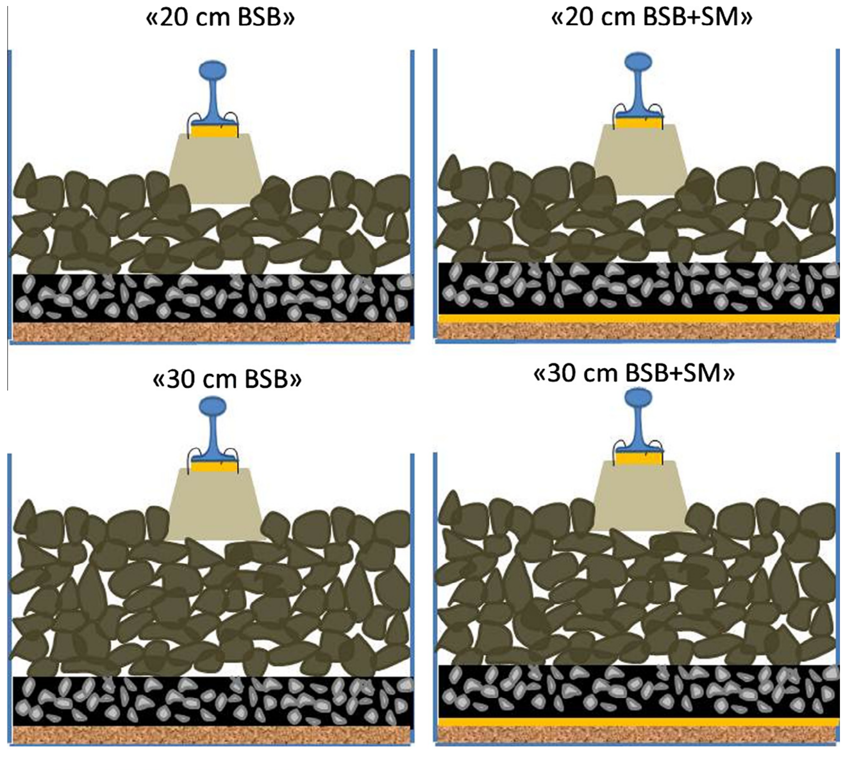

Fig. 6. Systems used to analyse the influence of ballast thickness in different section configurations.

During the test, the evolution of the vertical settlement was measured in order to obtain the final total settlement recorded at the end of the test for each configuration. Regarding the parameters of vertical stiffness and dissipated energy, they were obtained as an average of the values recorded during the last 50,000 cycles when a stable behaviour of the system was presented. The stiffness values were obtained from the force-displacement curve (recorded per each loading cycle) as the relationship between the load and strain amplitude, whilst the dissipated energy was calculated from the area into the hysteresis loops.

3. Analysis of results

3.1. Effect of the stiffness of the elastic components used over the ballast layer

Fig. 7 shows the effect of varying the stiffness of rail pads or the incorporation of USPs with different flexibility on the global vertical stiffness modulus of the section over the ballast layer. For this study, the VSRP system (using a very stiff rail pad) was used as a reference, and therefore, this represented 100% of the stiffness modulus (displaying also the error bars measured for the different tests). Results show that a reduction of 70% in the rail pad stiffness (from very stiff "VSRP" to stiff "SRP") caused a decrease of around 12% in the modulus of the section, whilst the change from very stiff to soft (90% of reduction in pad stiffness) led to a variation near 15%. This fact indicates that the variation in global track stiffness is much lower than the change in rail pad stiffness, obtaining quite similar values of section stiffness when stiff (300 kN/mm) and soft (100 kN/mm) rail pads were used in this study.

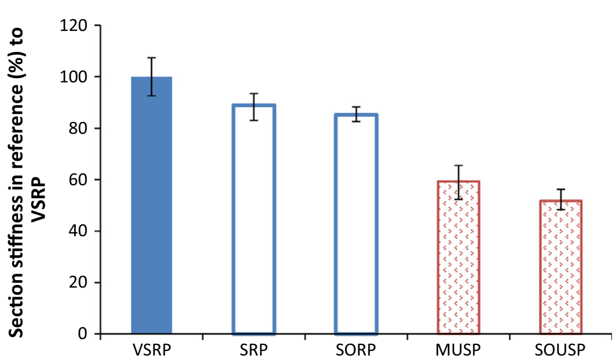

Fig. 7. Variation in section stiffness in reference to the system with a very stiff rail pad (VSRP).

In addition, it was seen that the incorporation of under-sleeper pads (both medium and soft – MUSP and SOUSP respectively) caused an important decrease (higher than 40%) in the section modulus, this variation being higher than the change caused by modifying the rail pad stiffness. With respect to the effect of the stiffness of the USP used, it was seen that a reduction of 51.7% in USP modulus provoked a decrease close to 8% in the section modulus. This again demonstrates that the changes in the track stiffness are lower than those measured for the properties of the elastic elements, the most influential technique being the incorporation of new elastic components (in this case, the incorporation of USP).

To analyse the effect of these variations on track performance, Fig. 8 displays the percentage of dissipated energy (Fig. 8, left) and section settlement (Fig. 8, right) in reference to the system with a very stiff rail pad (VSRP) used as a control (100%). Thus, values lower than 100% indicate that there was a reduction in the parameter measured whilst values higher than 100% represent its increase.

The results indicate that reducing the stiffness of rail pads produced both a significant increase in the energy dissipated by the track section, and a reduction in the ballast settlement, solutions which are appropriate for damping loads and reducing maintenance costs. In addition, this effect was more pronounced when USPs were included (producing more than a 200% increase in dis-

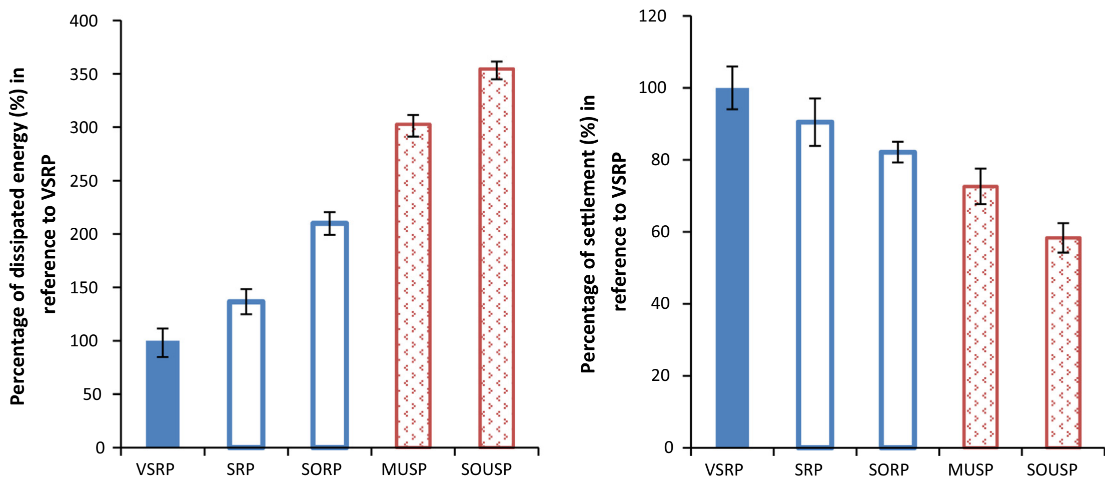

Fig. 8. Effect of varying the configuration of elastic elements over ballast layer.

sipated energy and a reduction in ballast settlement of more than 25%) when compared with varying the stiffness of the rail pads. These results show that the application of this type of soft solutions to reduce the stress transmitted to the sub layers is appropriate to decrease the geometrical degradation of railway tracks, and therefore, the necessity for maintenance. Nonetheless, it is also worth noting that an important increase in rolling resistance (associated with service costs) could take place as a consequence of an important increase in dissipated energy, and then, it should also be avoided [7,37].

For a deeper understanding of the effect of the characteristics of the elastic elements on the track behaviour, Fig. 9 reflects the force-displacement curves measured for the different configurations when a stable response of the section was obtained (around 150,000 cycles). It can be seen that there is little variation in vertical displacement when soft rail pads are used instead of stiff ones (which implies that the change in section stiffness is only near 1%), which could avoid the increase in rolling resistance. Despite this little change in vertical stiffness, it has been seen that this modification caused an increase of more than 70% in dissipated energy and a reduction of more than 8% in section settlement, which shows that soft rail pads are more appropriate for damping loads and reducing track deterioration [38,39].

On the other hand, results reflect that the inclusion of soft under sleeper pads lead to an important variation in vertical displacement that can cause the increase in rolling resistance, and therefore, service costs. Thus, it should be considered during the design of the track section as well as when selecting the stiffness of this elastic element. Nonetheless, due to the fact that the reduction of the modulus of the USPs led to higher changes in dissipated energy (an increase of close to 50% from medium to soft USP) and track settlement (a reduction of more than 14%) than those measured for the stiffness modulus of the section, soft USP could be regarded as more appropriate for reducing ballast degradation [24].

3.2. Effect of the bearing capacity of the configuration used under the ballast

With the aim of assessing the influence of the configuration of the railway section under the ballast layer, Fig. 10 presents the global modulus stiffness of the system in reference to the bearing capacity (calculated from the plate bearing test) of the bed layers depending on the configuration studied (incorporation of different UBMs, use of various types of sub-ballast, and addition of under-sub-ballast mat). The results show that the use of the different types of sub-ballast analysed in this study (granular and bituminous) caused low variations in bearing capacity, which indicates that the use of a granular material can lead to a track strength similar to that obtained with an asphalt layer, as long as the granular sub-ballast presents a high vertical modulus associated with its appropriate compaction. In contrast, the incorporation of elastic elements under the ballast (or even under the sub-ballast) does

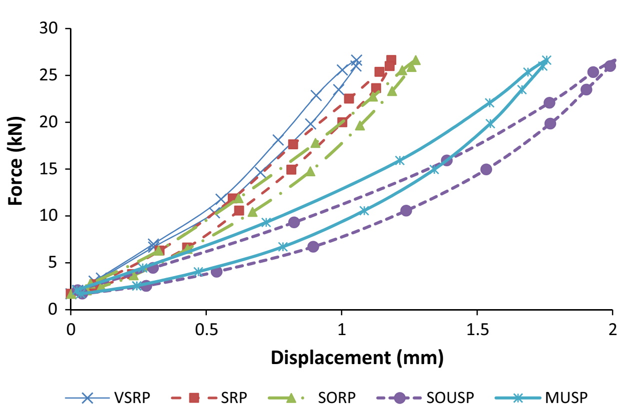

Fig. 9. Force-displacement curves measured for the configurations with different elastic elements over ballast layer.

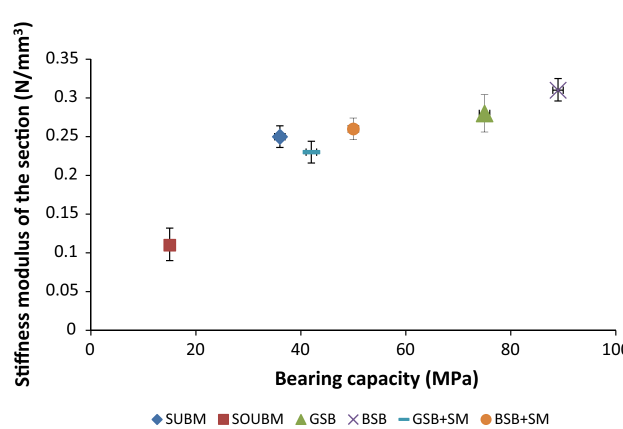

Fig. 10. Effect of bed layer configuration on track stiffness.

causes an important reduction in the bearing capacity of the system, an effect that is more marked when softer elements are used.

Regardless of the configuration, it was shown that such reduction in bearing capacity leads to a decrease in the global stiffness of the track section, with the maximum value recorded in this study ranging from 0.308 N/mm^3 (section over bituminous sub-ballast "BSB") to 0.11 N/mm^3 (recorded for the system with soft UBM "SOUBM"), which corresponds to a variation near 63.9% whilst the reduction in bearing capacity was close to 277.5%. This fact indicates that, similar to what occurs when modifying the stiffness of elastic elements over the ballast layer, the changes in the global section are lower than those recorded for the properties of the bed layers.

In addition, Fig. 11 shows the influence of the bearing capacity of the bed layers on the density of dissipated energy (dissipated energy per cycle/volume of the section) and settlement of the section. It is again possible to demonstrate that the use of different types of sub-ballast (GBS or BSB) caused lower variations in track behaviour than those recorded when elastic mats (either under ballast or under sub-ballast) used between the bed layers, which indicates that the effect of this latter type of component is predominantly on the track response.

In addition, it was generally observed that the reduction in the bed layer strength was related to a higher capacity of the system to dissipate the energy of passing trains, but higher settlement was also obtained, as indicated by other authors [40]. This fact indicates that the increase in dissipated energy could be associated with an increase in vertical movements of ballast particles that provokes section deformation. Therefore, for modern railway tracks where higher geometric quality is required, the use of bed layers (such as elastic elements under the granular layers) that cause a decrease in bearing capacity should be limited, unless they are used over very rigid structures that can offer an adequate global bearing capacity.

3.3. Comparison between the effects of modifying the section over and under the ballast layer

Fig. 12 compares the influence of varying the section configuration by using elastic elements placed over the ballast layer (such as rail pads or USP) of different flexibility versus modifying the configuration of the track system under the ballast layer (such as adding UBMs, different types of sub-ballast, or sub-ballast over elastic mat). Results show that there is a good relationship (R^2 higher than 0.9) between the modulus stiffness of the railway section and its capacity to dissipate energy and its settlement. Both cases (upper and under the ballast modifications) present a linear relationship in which the dissipated energy increases when the stiffness is reduced, although the systems with bed layers under the ballast recorded higher values of dissipated energy. This fact could be related to the incorporation of bed layers between the ballast and the formation layer, which provide the section with a higher capacity to damp the loads transmitted by trains, thus generating a system that is suitable for modern railway tracks [1].

Nonetheless, Fig. 12 (right) also shows that very different behaviour of the track settlement can be obtained depending on the level (under or over the ballast layer) modified to vary the vertical stiffness of the section. Then, it is seen that for a same value of vertical stiffness of the track, a different settlement can take place in reference to the vertical level of the section in which the configuration is changed. In both cases (variation under or over the ballast layer), there is a good linear relationship, but the settlement is reduced when the global stiffness decreases by varying the flexibility of elements over the ballast (rail pads or under sleeper pads) whilst this parameter sharply increased, however, when the stiffness was modified by changing the configuration of the section under the ballast, which is the opposite of what is required from the viewpoint of the durability and maintenance of the track geometry.

This observation could be related to the decrease in bearing capacity of the section that causes its global settlement. However, in this study, as the higher changes in stiffness are obtained when elastic mats are used, it could also be linked to the increase in dynamic movements of the ballast particles associated with the incorporation of such elastic elements under the granular layer, this being more marked when using mats of a lower stiffness grade.

In addition, it was demonstrated that the changes in stiffness caused by the modification of the section under the ballast exerted a higher influence on track settlement than that measured by the elements over the ballast layer, since the first case recorded higher slope ($a = 189.28$, in absolute value) than that obtained for the

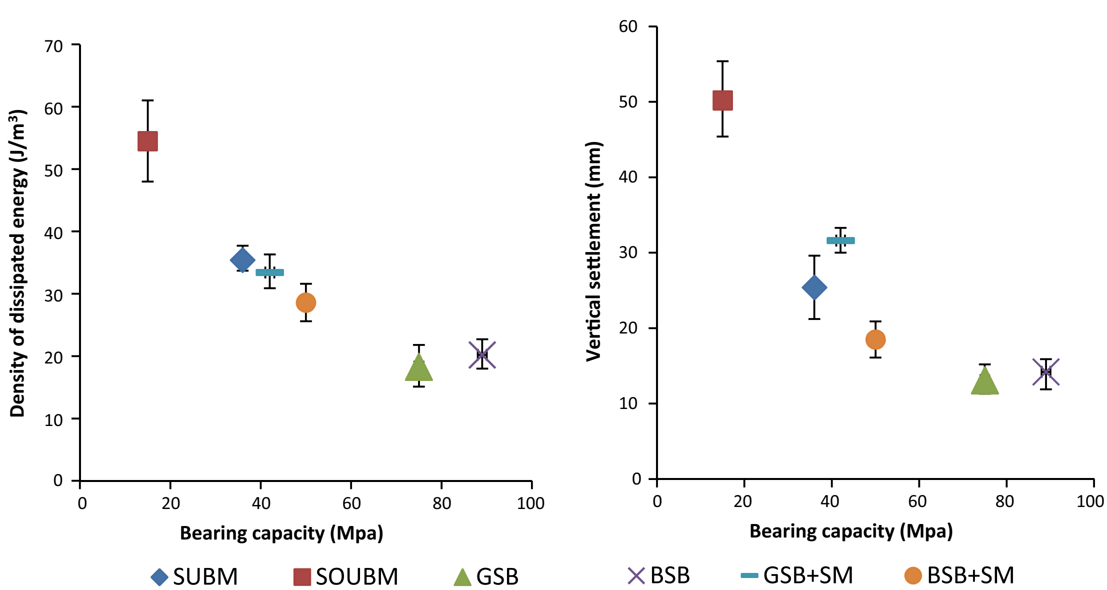

Fig. 11. Influence of the bed layers on track behaviour.

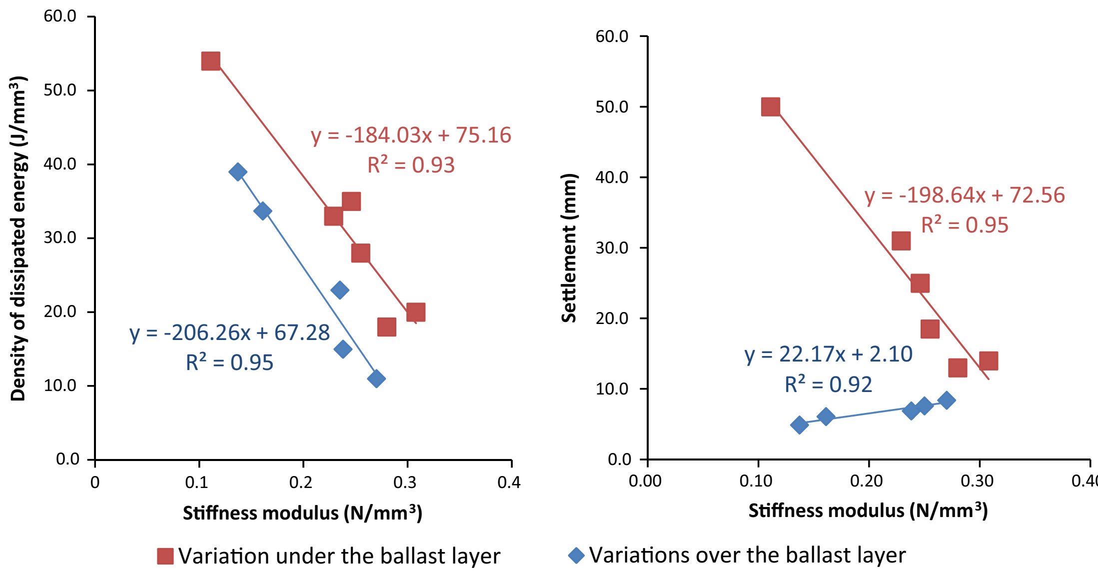

Fig. 12. Effect of varying the track stiffness by modifying the configuration over and under the ballast layer.

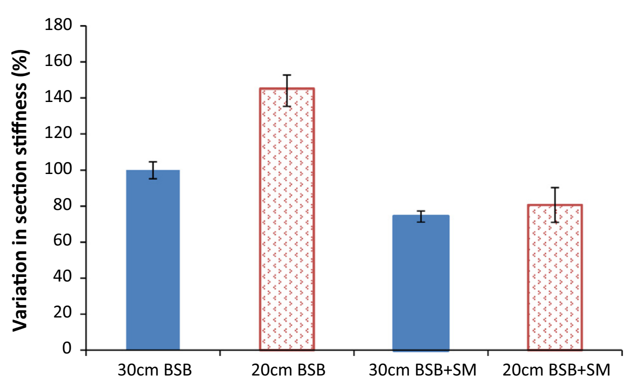

Fig. 13. Influence of ballast thickness on track stiffness.

modifications of components over the ballast (slope of 22.17). Thus, this fact should be taken into consideration during the design of the track section, since the reduction in stiffness by modifying the configuration under the ballast (such as incorporating UBM to reduce vibrations) could serve to accelerate the deterioration of the track, and therefore increase the frequency of maintenance and repairs. Thus, in cases in which components such as UBMs are needed to reduce vibrations in the ground, it is important to ensure that their application does not reduce the bearing capacity of the section.

With regard to the variation in elastic elements over the ballast layer, in spite of exerting a weaker influence on track variations, this can lead to longer life of the ballast when softer components (rail pads and USP) are used, which makes this option the most appropriate for obtaining an optimum value of global stiffness and dissipated energy whilst reducing the deterioration of the track geometry.

3.4. Influence of ballast thickness on the performance of different types of track section

Fig. 13 displays the variation in modulus stiffness of the section when the thickness of the ballast is reduced from 30 cm to 20 cm,

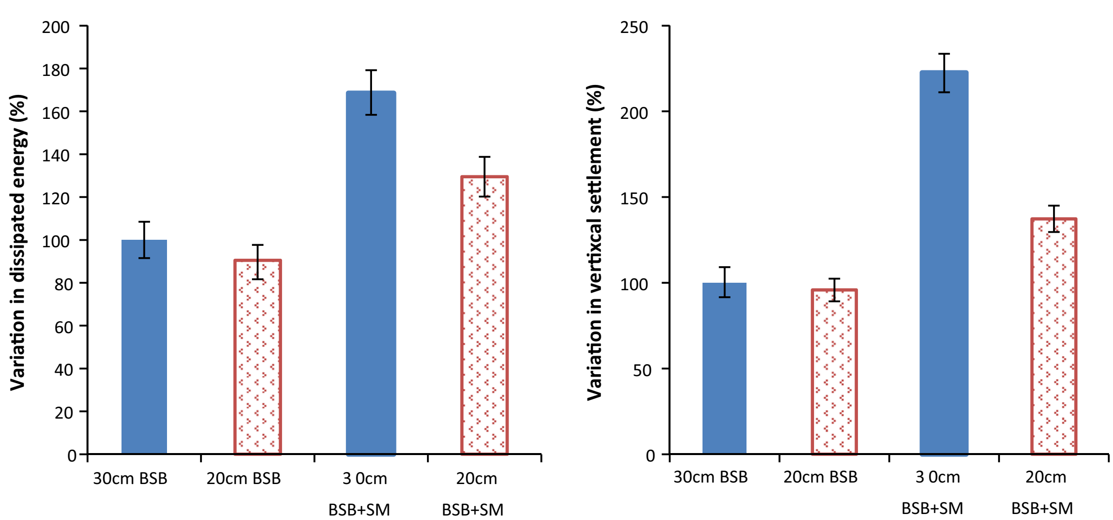

Fig. 14. Impact of the ballast thickness on track behaviour.

using as a reference (value of 100%) the section with 30 cm of ballast without an elastic mat (30 cm BSB). This effect is analysed in two different configurations: over bituminous sub-ballast (using the system with 30 cm as a reference, and therefore assigned a value of 100%), and over sub-ballast with the addition of an elastic mat under this system. Results indicate that the reduction in ballast thickness caused, in both cases, the stiffening of the section in reference to the same configuration, but with 30 cm of ballast. In spite of this increase in stiffness, for the configuration with elastic mat under the sub-ballast the stiffening (close to 8%) was lower than that for the system without a mat (40%), even obtaining a modulus (system "20 cm BSB+SM") lower than the reference section with 30 cm of ballast and without the mat ("30 cm BSB"). This indicates that the effect of the elastic mat is stronger than the influence of ballast thickness.

In reference to its effect on the mechanical performance of the section, Fig. 14 shows the variations in dissipated energy and settlement. Again, it was seen that the influence of the mat was higher than the ballast thickness, since despite the fact that in both cases (20 cm of ballast with and without under sub-ballast mat) the energy dissipated and settlement were reduced in reference to the systems with 30 cm of ballast, the configuration "20 cm BSB +SM" presented higher values than those measured for the reference section "30 cm BSB".

4. Conclusions

The present paper provides an in-laboratory analysis of the mechanical performance of different configurations of railway section in order to assess the influence of modifying the properties of various track components. The properties studied were (i) varying the flexibility of elastic elements used over the ballast layer (rail pads and under sleeper pads); (ii) modifying the configuration of the bed layers under the ballast (incorporation of two types of under ballast mat, different sub-ballast layers, and a mat under the sub-ballast); (iii) changing the thickness of the ballast layer. From the results obtained in this study, the following conclusions can be drawn:

- The reduction of the stiffness of elastic elements used over the ballast layer (rail pads and under sleeper pads) caused a decrease in global track stiffness, although this change was much lower than that applied over the properties of the elastic elements. Nonetheless, it was demonstrated that the incorporation of new elements such as USP exerts a greater influence on track behaviour than modifying the flexibility of the existing elements.
- It was also seen that the variations in dissipated energy (increase) and settlement (decrease) are higher than those measured in track stiffness when the flexibility of the elements is increased.
- The incorporation of elastic elements between the bed layers (under ballast or sub-ballast mats) or the use of more flexible sub-ballast led to lower bearing capacity of the system, which caused an important reduction in global stiffness and an increase in dissipated energy and track settlement, the variation of these latter two parameters being higher than that measured for global vertical stiffness. In addition, these variations in track performance were more pronounced with softer bed layers, but always lower than those measured in the bearing capacity for the bed layers.
- The modification of the track section caused by varying the configuration of bed layers exerted higher influence than the reduction of the stiffness of elastic elements (and even higher than the incorporation of new elements) used over the ballast layer. However, it is important to note that reducing track stiffness by the use of more flexible bed layers (such as the incorporation of UBM to reduce ground vibrations) causes a significant increase in ballast settlement, whilst decreasing the stiffness by using elastic elements over the granular layers reduces settlement and increases the capacity of the track to damp train loads.
- The use of thinner ballast layer produced a stiffening of the track as well as a reduction in the dissipated energy and the settlements. However, when elastic mats were used in the railway track, the effect of reducing the ballast thickness was lower, since the behaviour of the elastic element is predominant, and therefore, lower global stiffness was observed, along with higher dissipated energy and settlement values in comparison with the system that had a thicker ballast layer.

Based on the results obtained in this study, it is clear that, depending on the configuration of the railway track section, a rather different mechanical behaviour of the system can be obtained in spite of presenting similar values of global stiffness, which could imply higher track service and maintenance costs. The current findings highlight the potential importance of using flexible bed layers (such as UBM) that cause a decrease in bearing capacity, leading to higher track settlement and a significant increase in rolling resistance. Further, reducing the stiffness of elastic elements over the level of ballast layer (such as rail pads or under sleeper pads) allows for lower deterioration of the track without producing a significant increase in rail deflection.

Nonetheless, despite these results, further works are required for the optimisation of railway track behaviour. In this sense, the development of theoretical-numerical approaches could provide the simulation of track response under different configurations, carrying out a sensitivity analysis in comparison with the results shown in the present paper.

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Dear Mr. Pirozolo
Reference: **MC-048-16**
Title: **EVALUATION OF BITUMINOUS SUBBALAST MANUFACTURED AT LOW TEMPERATURES AS AN ALTERNATIVE FOR THE CONSTRUCTION OF MORE SUSTAINABLE RAILWAY STRUCTURES**
We are pleased to inform you that your manuscript has been accepted for publication in **Materiales de Construcción**. You will be receiving the proofs shortly.
Yours faithfully,

Prof. Francisca Puertas
Eduardo Torroja Institute for Construction Sciences (IETcc-CSIC)
Editor-In-Chief of "Materiales de Construcción" Journal (JCR- 2015; I.F.: 0.960)

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