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Eco-friendly materials for a new concept of asphalt pavement

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Abstract

It is estimated that more than 90% of the 5.2 million kilometers of European paved roads and highways are surfaced with asphalt. Also, about 44% of goods are transported by road in the EU; maintaining their condition whilst in transit is crucial for the economy.

The construction of a new road has a number of implications for the environment, consuming large amount of materials and energy. Also, the price of crude oil, which is the major source of bituminous binder, has significantly increased in recent years (the most noticeably in 2001–2008). This has led to an increase in the total price of asphalt mixtures.

In order to promote sustainable practices and to combat price increase, measures with sound sustainability credentials need to be widely implemented. Developing novel materials and technologies to integrate greener material, waste and recycled materials into the production cycle of asphalt mixtures is a solution that improves both sustainability and cost-efficiency of the asphalt pavement industry.

The main concept presented in this paper is the application of an eco-innovative asphalt pavement designed through partial substitution of greener materials into asphalt mixtures: reclaimed asphalt pavement (RAP), construction and demolition waste (C&DW), lignin (by-product of 2nd generation bioethanol processing) and bio-binder from vegetable oil. This paper discusses

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a new concept of an asphalt pavement structure with ecologically oriented attributes, achieved whilst maintaining a level of long term performance comparable or greater than that of conventional pavement structures.

The two main components of asphalt mixture – bitumen and aggregates – are focused upon. In relation to bitumen, two methods to ‘green’ the fresh binder fraction are explored: The first investigates bio-fluxing bitumen, which enables part of the petro-chemical binder to be replaced with bio-based products; the second uses a specific industrial waste, also bio-derived, to replace the crude-oil derived polymer in modified bitumen. In relation to aggregates, two different approaches are also explored: The use of high rates of reclaimed asphalt pavement (RAP) in new hot asphalt mixtures, thanks to the addition of bio-fluxing agents which will allow working at lower temperatures, and the use of construction and demolition waste (C&DW). Optimal integration of C&DW as raw material will be established using a selective process for the separation of C&DW to increase the overall quality of the recycled aggregates.

Considering the full pavement structure, the main innovations can be summarized as follows: (A) in surface course is the introduction of green bitumen modifier, derived from recovered waste bioethanol production as an alternative to the traditional additives used for polymer modification; (B) in binder and base course, bio-fluxing agents allow for the integration of higher percentage of reclaimed asphalt; and (C) the lower layers (sub-base and subgrade) are mainly composed of materials derived from construction and demolition waste.

This paper describes the systematic approach for selecting the right combination of these main pavement components in the design of asphalt mixtures, from laboratory tests to real applications. This approach has been developed by a consortium of partners in the FP7 funded *Asphalt Pavements for a Sustainable Environment (APSE)* project.

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Keywords: asphalt; pavement; recycling; road; environment;

1. Introduction

It is estimated that in excess of 90% of the 5.2 million kilometers of European paved roads and highways are surfaced with asphalt. Also, about 44% of goods are transported by road in the EU, therefore maintaining the condition of highways, to ensure effective transit of goods, is crucial to the economy.

The construction of a new road has a number of implications for the environment, consuming large amounts of materials and energy. Also, the price of crude oil, which is the major source of asphalt binder, has significantly increased in recent years (the most noticeably in 2001–2008). This has led to an increase in the total price of asphalt mixtures.

In order to promote sustainable practices and to combat price increase, measures with sound sustainability credentials need to be widely implemented. Developing novel materials and technologies to integrate greener material, waste and recycled materials into the production cycle of asphalt mixtures is a solution that improves both sustainability and cost-efficiency of the asphalt pavement industry. It can be noticed that application of RAP in asphalt mixture production is growing; another word-noticeable trend is a continuous development of warm mix asphalt (WMA) technology and addition of bio-origin components in production of materials for road construction (Fini et al. 2012).

Nomenclature

AC	Asphalt Concrete	C&DW	Construction and Demolition Waste
PMB	Polymer Modified Bitumen	RAP	Reclaimed Asphalt Pavement
RBT	Ring and Ball Test	RTFOT	Rolling Thin Film Oven Test
SBS	Styrene-butadiene-styrene	APSE	Asphalt Pavements for a Sustainable Environment
GA	Graded Aggregate or granular material	E	Subgrade

2. Research approach

The main concept presented in this paper is the application of an eco-innovative asphalt pavement designed through partial substitution of greener materials into asphalt mixtures: RAP, C&DW, lignin (by-product of 2nd generation bioethanol processing) and bio-binder from vegetable oil. This paper discusses a new concept of an asphalt pavement structure with ecologically oriented attributes, achieved whilst maintaining a level of long term performance comparable or greater than that of conventional pavement structures.

The two main components of asphalt mixture – bitumen and aggregates – are focused upon. In relation to bitumen, two methods to ‘green’ the fresh binder fraction are explored: The first investigates bio-fluxing bitumen, which enables part of the petro-chemical binder to be replaced with bio-based products; the second uses a specific industrial waste, also bio-derived, to replace the crude-oil derived polymer in modified bitumen. In relation to aggregates, two different approaches are also explored: The use of high rates of RAP in new hot asphalt mixtures, thanks to the addition of bio-fluxing agents which will allow working at lower temperatures, and the use of C&DW. Optimal integration of C&DW as raw material will be established using a selective process for the separation of C&DW to increase the overall quality of the recycled aggregates.

This paper describes the systematic approach for selecting the right combination of main pavement components in the design of base and asphalt mixtures. This approach has been developed by a consortium of partners in the FP7 funded APSE project.

3. Eco-friendly concept of asphalt pavement

Considering the full pavement structure, the proposed concept of eco-friendly asphalt pavement can be summarized as follows (see Fig. 1):

- in surface course is the introduction of green bitumen modifier, derived from recovered waste bioethanol production as an alternative to the traditional additives used for bitumen production,
- in binder and base course, bio-fluxing agents allow for the integration of higher percentage of reclaimed asphalt,
- the lower layers (sub-base and subgrade) are mainly composed of materials derived from construction and demolition waste.

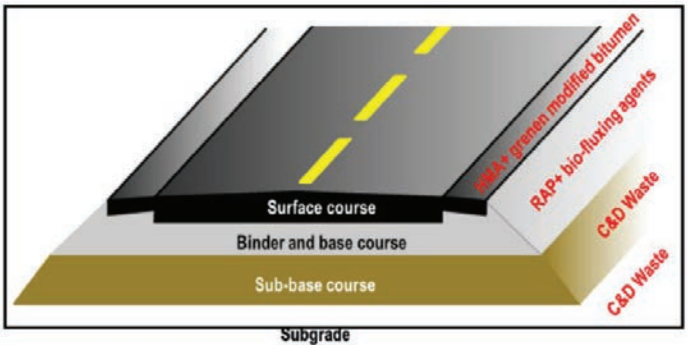


Fig. 1. Eco-innovative asphalt pavement structure.

3.1. Applications of Construction and Demolition Waste in road construction

C&DW material composition and characterization according to EN 933-11 shows that, in order to obtain high grade recycled aggregates applicable in building products applications, there is a need to sort out a number of contaminant components such as calorific fractions, gypsum and the non-concrete stony fraction.

In the actual market there is no complete advanced recycling concept available from input of raw (stony) C&DW to the dispatch of pure high-grade recycled concrete aggregates. Therefore an advanced processing concept was developed under the name “Stone Recycling”. This concept is a flexible solution to rather complex questions on how to obtain pure aggregates from raw C&DW. The Stone Recycling concept is conceived in two major parts, which can be operated separately, or in one line depending on the required outcome and product quality. In order to obtain high-grade recycled aggregates the complete processing concept is needed.

The processing concept consists of very well-known processing steps in the C&DW recycling industry such as primary crushing and sieving, wind shifting and the sorting out of ferric and non-ferric parts. Next to those the Stone Recycling processing concept is built around the purification of the material in terms of sorting out unwanted components such as gypsum by using Near-Infrared (NIR) technology and the separation of the non-concrete fraction from the concrete fraction using colour-sorting equipment.

Finally the pure concrete aggregates resulting from the processing concept are brought to the right size fraction by crushing and sieving. These resultant high-grade recycled aggregates are applicable in both the bound and unbound application for road construction.

In the study of C&DW recycled aggregates for road applications, two different applications were evaluated: C&DW for asphalt mixtures applications and C&DW for sub-grade and sub-base applications.

In case of asphalt mixture applications, three different asphalt mixtures were designed and characterized: AC-22 Reference, AC-22 with 15% C&DW and AC-22 with 25% C&DW. The results obtained showed that most properties are similar to the reference asphalt mixture and fulfil the standards. When 25% C&DW is added to the asphalt mixture the water sensitivity value is lower than required according to the standards, which means that quantities above 15% are not recommended. The addition of cohesion additives could increase the total amount of C&DW.

In the case of sub-grade and sub-base applications, different tests have been performed in order to determine if C&DW can be used as a substitute of contribution soil for sub-grade applications (Tab. 1). The material was subjected to the same test that soil must comply with as specified in the Spanish PG3. According to the results obtained, it is possible to use C&DW instead of a suitable soil. In addition, different types of stabilizers were added and it was demonstrated that is was also possible to improve its bearing strength and to perform as a selected soil. C&DW is also suitable for application in sub-base road applications for medium trafficked roads T2 to T4 (range between 5 and 800 heavy vehicles per day, according to Spanish category’s), as a replacement of virgin graded aggregates, as long as proper sieving and crushing operations are carried out before its use.

Table 1. Summary of C&DW results obtained.

Parameter	Limits established by Standards	Results
Total sulfur content (EN 1744-1)	< 0.5% < 1.0%	0.0%
Sand equivalent (EN 933-8)	T00-T1: EA>40 T2-T4 & shoulders: EA>35 Shoulders T3-T4: EA>30	34
Methylene blue test (EN 933-9)	If sand equivalent does not occur: >10	1.5
Plasticity (EN 103103 & EN 103104)	No plasticity	No plasticity
Resistance to fragmentation (Los Angeles loss, EN 1097-2)	T00-T2: < 30 T3, T4 and shoulders: <35	35
Shape (form coefficient, EN 933-3)	<35	7
Angular shape (EN 933-5)	T00-T0: 100% T1-T2 & shoulders: 75% Other cases: 50%	98%

3.2. Bio-fluxed bitumen for asphalt mixtures containing reclaimed asphalt pavement

The main objective of the research programme was to increase amount of RAP in asphalt mixtures without compromising technical properties. In such mixtures, aged bitumen may require rejuvenation and, during production, the mixture may require higher temperatures due to viscosity changes in aged bitumen. A possible solution is to apply fluxed bitumen with bio-agent, to facilitate a production temperature decrease. Moreover, chemical reactions occurring in fluxed bitumen in time rebuilds properties of binder (Antoine and Marcilloux, 2000). Bio-fluxed binders shows decreased consistency and then, due to the sycativation process, consistency increases (Wexler, 1964). This hardening is not associated with emission of volatile organic compounds (VOC) (Gaweł et al. 2010).

During research, road bitumen 50/70 was modified with a 10% addition of bio-flux (obtained from rapeseed oil methyl ester). Two different procedures were utilized: (A) with addition of cobalt catalyzer (0.1%), heating to 90 °C and oxidation for 1h and (B) with addition of cobalt catalyzer (0.1%) and cumene hydroperoxide (1%) and oxidation for 2 h at 20 °C.

Samples of the modified bitumen were conditioned at room temperature in a thin (1 mm) layer prior to testing at 1, 3, 7 and 14 days post-modification. Then samples were tested for softening temperature and viscosity according to EN specifications. Based on the changes in bitumen softening temperature (shown in Fig. 2) it can be stated, that both modification methods cause similar increment in consistency after 14 days (about of 5 °C).

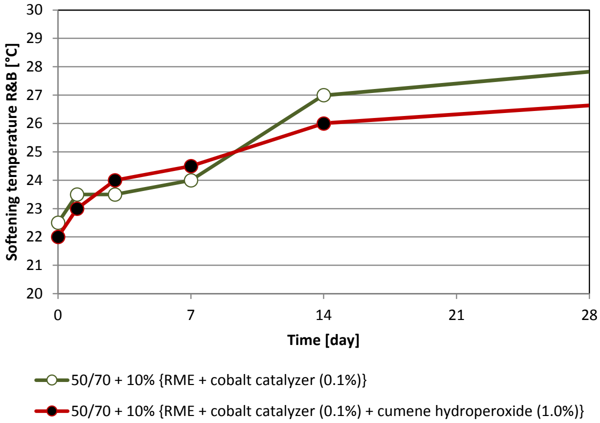


Fig. 2. Increase in softening temperature of bio-fluxed bitumen.

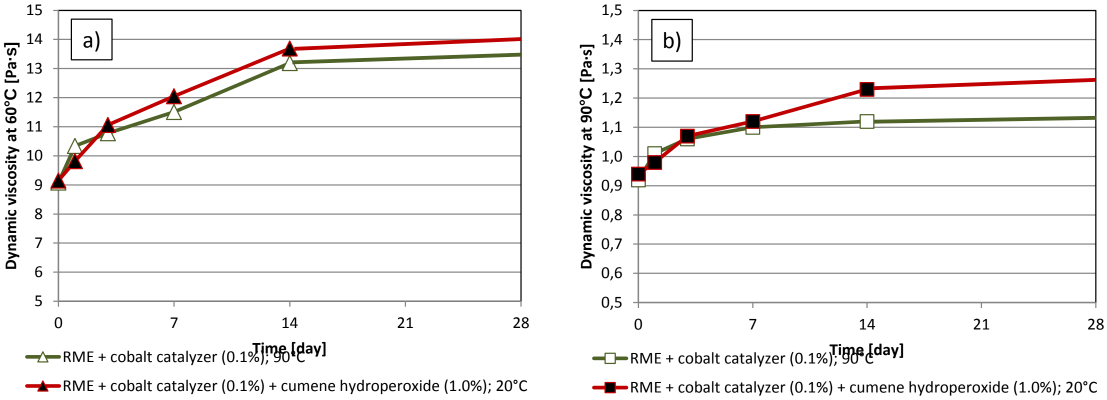


Fig. 3. Increase in dynamic viscosity of bio-fluxed bitumen: a) at 60 °C, b) at 90 °C.

Based on the viscosity testing (Fig. 3), a consistency increase can also be observed. An increase in consistency of fluxed bitumen's can be observed in viscosity tests conducted during the first 14 days. When results for viscosity at 60 °C (Fig. 3-a) and 90 °C (Fig. 3-b) are compared, it can be observed that agents obtained in both procedures (A and B) provides similar increase in consistency. After 14 days, a viscosity increase of about 5 kP·s when tested at 60 °C and of 0.5 kP·s when tested at 90 °C.

Based on other tests conducted, not provided here due to space limitation, it can be concluded that both fluxing bio-agents show a similar impact on bitumen properties. Selection of the optimal agent for industrial-scale production should therefore be based on other factors such as economic and environmental perspectives (that will be explored later in the APSE project).

As implied by Gaweł et al. (2010), most of binder hardening occurs within first 14 days and then polymerization reaction gradually stops. It can be concluded that binder is temporarily (and reversibly) fluidized, and this is very beneficial for technological process. Moreover, bio-agent works as a rejuvenator in asphalt mixture with RAP. During first 14 days of exposure of the aged bitumen to the bio-agent, chemical changes are induced in the bitumen that rebuild its fluidized consistency without over stiffening the mixture in time.

3.3. Bio-binders for asphalt surface layer

The aim of this work was to obtain, at laboratory scale, modified bitumen with properties at least comparable to a PMB 45/80-60, using a reduced amount of polymer. In order to reach this objective, an SBS composed of residue from the production of bioethanol with high lignin content were used as modifying agents.

In second generation bioethanol production, agricultural waste products such as wheat straw, corn stover, and sugarcane bagasse are utilised to produce bioethanol. Since the feedstocks are typically lignocellulosic biomasses containing a significant amount of lignin (20–30%), utilization of this fraction is usually required to reach a profitable process. Currently, this is often done by pressing lignin into pellets for burning in power plants or for producing heat for the process itself.

Lignin varies in purity depending on the process conditions and feedstock used in the process. Hydrolysis lignin generally contains a residue of carbohydrates, since they are not fully hydrolyzed by the enzymes in the reaction time available, but also due to the presence of lignin carbohydrate complexes in the material. These impurities, along with mineral impurities can constitute over 30% of the mass in standard hydrolysis lignin. In Table 2, the composition of two un-treated lignin samples were presented and compared to organosolv lignin, which is a pure lignin product originating from ethanol extraction from wood. The two different Inbicon lignin residues were produced at pilot and demonstration scale, respectively, with similar process conditions and hence yield-comparable lignin purities.

Table 2. Composition of un-treated lignin.

	Inbicon lignin	Inbicon lignin	Organosolv lignin
Scale (lignin production)	Pilot	Demonstration (41.8 tons/day)	-
Lignin	52.8%	53.8%	89.5%
Cellulose	21.7%	17.5%	0.11%
Hemicellulose	6.36%	5.08%	0.24%
H	5.04%	5.37%	5.12%
C	45.8%	49.9%	61.0%
N	1.17%	1.59%	1.89%
Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe	5.79%	7.62%	0.06%
Estimated ash	11.1%	14.4%	0.10%

The types of Inbicon lignin used in this study were: (1) non treated lignin (at it comes from the process itself); (2) treated lignin (more pure); (3) untreated lignin from a different batch production. The optimal lignin for this research was the non-treated one, wherein the real content of lignin is 52 to 54% approximately.

Regarding base bitumen, three main types of penetration grade bitumen, with penetration comprised between 50 and 150, have been used. More than 25 binary mixes (bitumen/SBS) were prepared by varying base bitumen, SBS type and concentration. Additionally, processing conditions were also studied: processing time ranged from 45 min to 120 min, use of Silverson L5M and IKA process plant as processing devices, 165–190 °C of processing temperature and a rotation speed of 6000–7700 rpm. Regarding base bitumen, both 70/100 and 50/70 can be potentially used to obtain a PMB 45/80-60. Nevertheless, 70/100 grade bitumen is preferred because it produces a higher softening point when it is mixed with the selected SBS and it presents a much higher initial penetration.

In the first stage, binary mixtures (Lignin + Bitumen) were used to analyze the influence of lignin particle size and concentration. Some different tests were performed in order to select the lignin-based granulometry to act as a modifying agent (<0.160 mm, >0.160 mm) with different lignin concentrations. The analysis has been accomplished using the penetration, softening point and storage stability tests according to EN specification. Results showed that bitumen/lignin blends reveal that particle sieving is not justified for industrial applications and also that due to sedimentation the concentration lignin is limited.

In a second stage, samples were analyzed to assess the effect of partial SBS substitution by lignin, especially in three areas: addition sequence of lignin and SBS, temperature during lignin addition and SBS concentration. A comprehensive modified binder characterization was conducted to determine its properties according to the standard EN 14023. Results from the optimum modified lignin bitumens, which meets the storage stability test requirements are shown in Table 3 and 4. All the obtained results comply with the Spanish Specifications for Road and Bridge Construction, also known as PG-3 (see Table 5).

Table 3. Ring and ball softening point and penetration for Bitumen/Lignin blends.

Sample	Lignin content	Penetration 25 °C (0.1 mm)	Softening point (°C)	Storage stability/Softening point		Storage stability Penetration	
				Top	Bottom	Top	Bottom
1	Low	73	51	50	51.4	61	56
2	Medium	63	52	51.4	56.6	57	43
3	High	59	52.4	49	50	55	32

Table 4. Results for optimum lignin modified bitumen.

Sample	Lignin content	Penetration 25 °C (0.1 mm)	Softening point (°C)	Elastic Recovery (%)	RTFOT		
					Retained penetration (%)	Increase in RBT (°C)	Mass loss (%)
Reference	Without	50	65	93	N/A	N/A	N/A
Reference aged		40	71	N/A	80	6	0.20
PMB	Medium	45	67.6	90	N/A	N/A	N/A
PMB aged		30	68.6	N/A	73	1	0.23

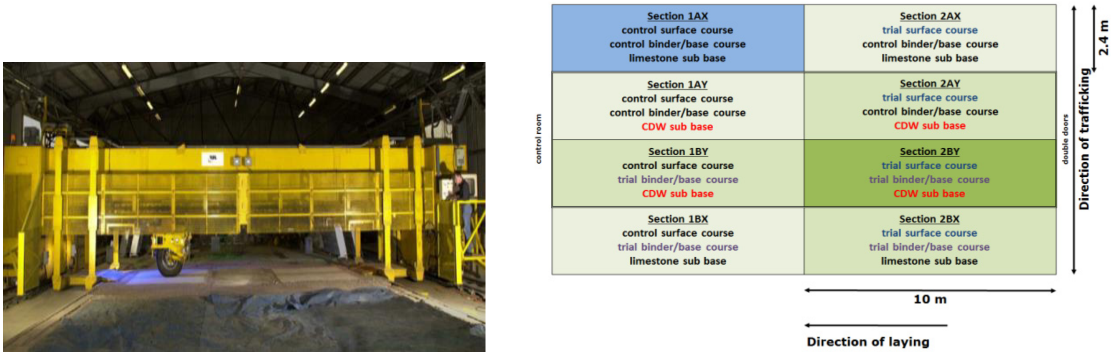
Table 5. Minimum acceptable values according to the Spanish Specifications (PG-3).

Test		EN Standards	Specification limits PMB 45/80-60
Penetration (0.1 mm)		1426	45-80
Softening Point (°C)		1427	≥ 60
Elastic recovery		13398	≥ 50
Storage stability	Softening Point difference (°C)	13399 + 1427	≤ 5
	Penetration difference (0.1 mm)	13399+1426	≤ 9
RTFOT	Change in mass (%)	12607-1	≤ 1.0
	Retained penetration (%)	1426	≥ 60
	Increase in softening point RB (°C)	1427	≤ 10

It can be concluded, that lignin can therefore be added to bitumen to partially replace the SBS polymer content. Taking into account that the price of SBS is far greater than the lignin, the replacement of SBS by lignin should entail an appreciable cost reduction in the final bitumen.

3.4. Accelerated testing

Accelerated testing in a controlled environment provides a convenient intermediate stage before full scale road trials are undertaken. The TRL Pavement Test Facility (PTF) is being used to test combinations of the materials being used in APSE in road pavement structures, in order to elicit any indication of variable performance, so that any issues can be addressed prior to use of use of the materials on the network. The TRL facility has long been established and is presented in Figure 4 along with a proposed layout for the trial sections.



Section 1AX control surface course control binder/base course limestone sub base	**Section 2AX** trial surface course control binder/base course limestone sub base
Section 1AY control surface course control binder/base course CDW sub base	**Section 2AY** trial surface course control binder/base course CDW sub base
Section 1BY control surface course trial binder/base course CDW sub base	**Section 2BY** trial surface course trial binder/base course CDW sub base
Section 1BX control surface course trial binder/base course limestone sub base	**Section 2BX** trial surface course trial binder/base course limestone sub base

Fig. 4. The TRL Pavement Test Facility and proposed layout of trial sections.

The PTF has many settings that can be adjusted to suit the specific nature the trial and produce a result within a given time period. Blackman, Halliday & Merrill (2000) provided a good overview of the facility and the adjustments that can be made to suit the specific nature of the trial including tyre type, load and number of passes; these have been matched to the exact requirements of the project when the project takes place, and are as follows:

- Test wheel load: between 40 kN (a standard axle); test wheel speed: approximately 2 ms^{-1},
- Test wheel type: Michelin Super Single XTE2 385/65 R22.5; test wheel tyre pressure: 621 kPa,
- Passes per hour: 750; Total passes per section: between 100,000 and 200,000.

The thicknesses of the pavement courses is set to achieve a failure within the given number of passes, in order to achieve a conclusive result that suggests the relative durability of the alternative pavement structures that utilize the following materials:

- A C&D sub-base or a conventional limestone alternative,
- Hot-mix base and binder courses with and without high RA contents facilitated by the addition of bio-flux,
- Hot-mix surface courses with and without the lignin polymer incorporated.

The hot-mix asphalts are all be plant mixed and machine laid. The performance of the sub-base materials is being tested according to a procedure for a trafficking trial for unbound sub-base (Clause 802.12-18 of the UK Specification for Highway Works (MCHW1)). The aim of this test is to investigate whether the properties of the C&D sub-base are broadly comparable to those of a conventional limestone and therefore whether this can be removed as a variable, thus requiring fewer pavement sections to be trafficked in total.

3.5. Structural analysis

The overall aim of this section is the analysis with a simulation tool of a typical pavement in order to optimize the structure and theoretically evaluate the APSE eco-innovative asphalt mixtures performance. The software ALIZE--LCPC developed by IFSTTAR was used for the analytic asphalt pavement design. The software is based on the analysis of stresses, strains and deformations produced within a defined pavement section to predict possible failures caused by the continuous action of traffic loads.

In order to calculate the pavement structure and determine its performance, five main parameters are required: stiffness modulus, fatigue law, Poisson ratio, layer thickness and equivalent standard axle (ESALS). Based on the initial analysis, the following hypotheses were considered:

- stiffness modulus. The test of APSE asphalt mixtures were performed on cylindrical Marshall specimens of 101 mm diameter at 20 °C; the stiffness modulus of APSE asphalt mixtures have been determined to be 30% lower that reference values, except in surface course where stiffness modulus slightly increases due to lignin content,
- stiffness modulus of sub-base and sub-grade are considered equal as reference values,
- fatigue law. To determine the fatigue properties, tests were carried out on 50 × 50 × 400 mm specimens at 20 °C and 30 Hz frequency,
- Poisson ratio is a fixed value and depends on materials and asphalt mixture used,
- layer thickness depends on the layer and pavement section chosen,
- equivalent standard axle (ESAL): in this case an ESAL defined as single axle of 128 kN with twin wheels (r=11.35 cm; P=0.8 MPa; d=37.5 cm) was chosen.

Two typical asphalt pavement sections, flexible and semi-rigid, were selected for analysis according to the Spanish standard Norma 6.1-IC (*catalogue of pavement sections for the design of pavement structures*). In the selected sections, the following parameters have been considered:

- Average Annual Daily Traffic (AADT) between 200–799 heavy vehicles,
- design period: 20 years and annual traffic increase and 1.44% constant during its service life,
- the flexible pavement is structured with 20 cm asphalts mixtures separated in three layers (surface, binder and base) and 25 cm of graded aggregate as sub-base layer,
- the section 232 is structured with 15 cm asphalt mixtures separated in three layers (surface, binder and base) and 20 cm of soil-cement as sub-base layer,
- in all cases, the subgrade layer considered is type E3 according to the Spanish standards. Subgrade layer Ev2 = 300 MPa considering E= Ev2.

Taking into account traffic parameters, the theoretical number of axles for the analysis period is: $0.9\cdot10^6$ ~ $3.75\cdot10^6$ ESALs for flexible pavement and $1.13\cdot10^6$~$4.51\cdot10^6$ ESALs for semi-rigid structure. Designed pavement sections complies with a value above the theoretical number equivalent of axles stipulated in road project. This number of theoretical equivalent axles is obtained according to the following equation (1):

$$N = IMD_p \cdot 365 \cdot CE \cdot \left[\frac{(1+c)^n - 1}{c}\right] \cdot \gamma_s \tag{1}$$

where: N = number of equivalent axles stipulated in the project (an equivalent axle corresponds to a 128 kN tandem axle); IMDP = Average Annual Daily Traffic; CE = equivalence factor; n = pavement service life; γs = load increase coefficient; and c = annual accumulative growth.

As is shown in Table 6 for flexible pavement, the section is oversized as the section is calculated to resist $6.49\cdot10^6$ equivalent axles, whereas the maximum indicated in the specification is $3.75\cdot10^6$. The APSE section is within the range of ESALS required for flexible design; although it is in the low range ($3.87\cdot10^6$ equivalent axles versus $3.75\cdot10^6$ in the project). As is shown in Table 7 for semi-rigid pavement, the section withstands $1.84\cdot10^6$ equivalent axles, while theoretical ESALS in the project are in the range of $1.13\cdot10^6$–$4.51\cdot10^6$ ESALS. Using APSE materials, the section resists $7.85\cdot10^5$equivalent axles, which means that this section is much over-designed and adjustment of layer thickness should be carried out in order to compensate for the shortcomings.

Table 6. Flexible pavement fatigue life.

Section	Reference			Innovative APSE		
Layer	Concept	Thickness (cm)	N (nº axles)	Concept	Thickness (cm)	N (nº axles)
Surface course	BBTM11B	3	$2.86 \cdot 10^{8}$	BBTM11B with lignin	3	$4.62 \cdot 10^{8}$
Binder course	AC 22 S	8	$3.48 \cdot 10^{8}$	AC 22 S+ RAP+ bioflux	8	$9.47 \cdot 10^{7}$
Base Course	AC 32 G	9	$6.49 \cdot 10^{6}$	AC 32 G+ RAP+ bioflux	9	$3.87 \cdot 10^{6}$
Sub base	GA	25	$8.40 \cdot 10^{7}$	C&DW	25	$6.83 \cdot 10^{7}$
Subgrade	E3	Inf.	$3.05 \cdot 10^{7}$	E3	Inf.	$2.49 \cdot 10^{7}$
		N (nº axles)	$6.49 \cdot 10^{6}$		N (nº axles)	$3.87 \cdot 10^{6}$

Table 7. Semi-flexible pavement fatigue life.

Section	Reference			Innovative APSE		
Layer	Concept	Thickness (cm)	N (nº axles)	Concept	Thickness (cm)	N (nº axles)
Surface course	AC 16 S	5	$6.44 \cdot 10^{11}$	AC 16 S	5	$1.44 \cdot 10^{12}$
Base Course	AC 32 S	10	$4.09 \cdot 10^{10}$	AC 32 G+ RAP+ bioflux	10	$3.65 \cdot 10^{11}$
Sub base	GA	20	$1.83 \cdot 10^{6}$	C&DW	20	$7.85 \cdot 10^{5}$
Subgrade	E3	Inf.	$4.97 \cdot 10^{8}$	E3	Inf	$3.75 \cdot 10^{8}$
		N (nº axles)	$1.83 \cdot 10^{6}$		N (nº axles)	$7.85 \cdot 10^{5}$

4. Conclusions and summary

Road construction is a sector where measures need to be taken in order to reduce the energy demand and environmental impact, and, in particular, to reduce the use of raw materials cost-effectively. The APSE project aims to contribute to sustainable development by adhering to relevant EU policies and reducing the environmental impact associated with the construction of roads. It aims to this by proving technologies that facilitate asphalt recycling, use of waste and novel greener binders, all integrated appropriately into optimal and eco-innovative designs of asphalt pavements, and thereby increasing their commercial viability. Based on the research conducted, it can be concluded that potential measures with sound sustainability credentials, including alternative binders and a wide use of recycled materials (including reclaimed asphalt and recycled materials derived from construction and demolition waste), can be adopted for widespread application in the right situations.

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