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DECISION TO PAVING SOLUTIONS IN ROAD INFRASTRUCTURES BASED ON LIFE-CYCLE ASSESSMENT

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Abstract. The construction and maintenance of a road network involve the expenditure of large budgets. In order to optimize the investments in road infrastructures, designers and decision makers should have the instruments to make the most suitable decision of paving solutions for each particular situation. The life-cycle assessment is an important tool of different road pavement solutions with this purpose. This paper presents a study concerning the life-cycle cost analysis of different flexible and semi-rigid paving alternatives, with the objective to contribute for a better support in the decision process when designing new pavement structures. The analysis was carried out using data on construction costs of certain typical pavement structures and taking into consideration appropriate performance models for each type of structure being selected. The models were calibrated using results from long term performance studies across Europe and the maintenance strategies considered have taken into account the current practice also found in the European context. Besides the life-cycle administration costs, the proposed methodology also deals with user and environmental costs through its inclusion in the decision process using multi-criteria analysis. It was demonstrated that this methodology could be a simple and useful tool in order to achieve the most adequate paving solutions of a road network, in terms of construction and maintenance activities, based simultaneously on technical, economic and environmental criteria.

Keywords: cost, construction, distress, life-cycle, maintenance, pavement, road.

1. Introduction

In general, the construction and maintenance of a road network involve the expenditure of large budgets. Therefore, it is important that designers and decision makers should have the instruments to make the most suitable choice of pavement solution for each particular situation, in order to optimize present and future investments in road infrastructures.

Life-cycle cost analysis (LCCA) during the design stage could be one of the key instruments for the optimization of expenditures in road construction and maintenance (Carlson 2011; Ferreira, Santos 2013; Haas *et al.* 1994; Mandapaka *et al.* 2012; Yu *et al.* 2015; Walls, Smith 1998). LCCA studies performed by Chenevière and Ramdas (2006) have demonstrated the interest of adopting long life pavements in the European context. The issues involved in LCCA of different paving solutions will vary from region to region, depending on local factors such as environmental conditions and availability of materials and technologies. The estimation of maintenance and rehabilitation costs throughout the pavement's life-cycle must be based on adequate pavement performance prediction models. Other aspects, such as road user costs (Hall *et al.* 2003) and environmental costs (Gschösser *et al.* 2012) should also be taken into account when selecting a pavement solution for a particular road.

Pavement condition changes throughout its life cycle, as a consequence of traffic loading, evolution of material's properties, climatic conditions and other environmental effects. Several distress mechanisms, related either with the pavement structure or with the subgrade soil, may occur and condition the need to perform maintenance activities. This issue has been addressed by several authors based on the observation of pavement performance (COST 1999; Merrill *et al.* 2006; Sivilevičius, Vansauskas 2013). Long Term Pavement Performance (LTPP) studies performed on test sections have demonstrated that the main deterioration mechanisms generally occurring in flexible and semi-rigid pavements before the end of the pavement's structural design life are cracking in the wheel

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path and reflective cracking (only for semi-rigid pavements) and loss of skid resistance. Raveling or rutting of the wearing course may occur, in specific sites where inappropriate materials were used in the surface course. Longitudinal unevenness is normally very low at the beginning of the pavement's service life, except when the layers are not compacted properly, and have shown a very little progression during the early service life on the pavements. It is assumed that surface unevenness occurring towards the end of the pavement's structural design period is indirectly accounted for in the models for limitation of permanent deformation in the subgrade.

Despite the diversity of approaches available for the main purpose of the present work, it was found that it is very important to develop a methodology based on life-cycle assessment with the objective to support the decision of paving solutions in road infrastructures. This methodology should be flexible enough to easily incorporate maintenance, user and environmental costs, along the pavement service life period, and the consideration of the most adequate construction technologies and materials available in the local or region. With this methodology it is also possible to choose the most convenient models for the pavement deteriorations, taking into account the traffic, the climatic conditions and other factors. The applicability of the methodology presented in this paper is demonstrated for flexible and semi-rigid pavement structures according to the Portuguese experience.

2. Methodology

In order to perform LCCA to different pavement structure alternatives, there are certain issues that must be addressed. The main activities performed in the framework of the proposed methodology are summarized in Fig. 1.

For reasonable analysis of maintenance and rehabilitation (M&R) strategies, the analysis period should be long enough to reflect the long-term costs associated with each of the design alternatives (ACPA 2002). An analysis period of 35 years is the minimum analysis period generally recommended for this purpose (Walls, Smith 1998).

The performance models that are used to evaluate pavement distresses over the analysis period are a key issue due to their relation to the resulting M&R strategies. So, taking into account the main conclusions from the LTPP studies, it could be concluded in general that the most important distress mechanisms in the case of flexible and semi-rigid pavements are: fatigue cracking originated in the bituminous and cement-bound layers; permanent deformation or rutting; surface cracking, predominantly in the wheel path; reflective cracking on semi-rigid pavements; deterioration of skid resistance. Fatigue and rutting are the most common distresses used in pavement design, because they are the primary modes of structural failure. Anyway, LCCA should be performed according the local experience in pavement modelling (region or country) where the different pavement solutions are intended to be used.

Distress models derived from LTPP studies performed on test sections in European countries are available in literature. Besides the most common models related to structural distresses used in pavement design – fatigue cracking and rutting (Shukla, Das 2008; Yang *et al.* 2009), other models are also important to predict surface cracking and reflective cracking (Sweere *et al.* 1998). For these distresses, the models consider two phases: crack initiation and crack propagation (Sweere *et al.* 1997, 1998). Deterioration of skid resistance is also important but there weren't found sound models for the evolution of this parameter. Therefore, the maintenance strategies considered with respect to the lack of skid resistance could be defined on the basis of the current practice in motorways and other primary roads.

Regarding the economic indicator used for the comparison of different alternatives, there are several approaches that can be used, such as the calculation of net present values (NPV), the uniform equivalent annual costs, which are derived from NPV, or cost/benefit ratios. For the purpose of straight comparisons between alternative

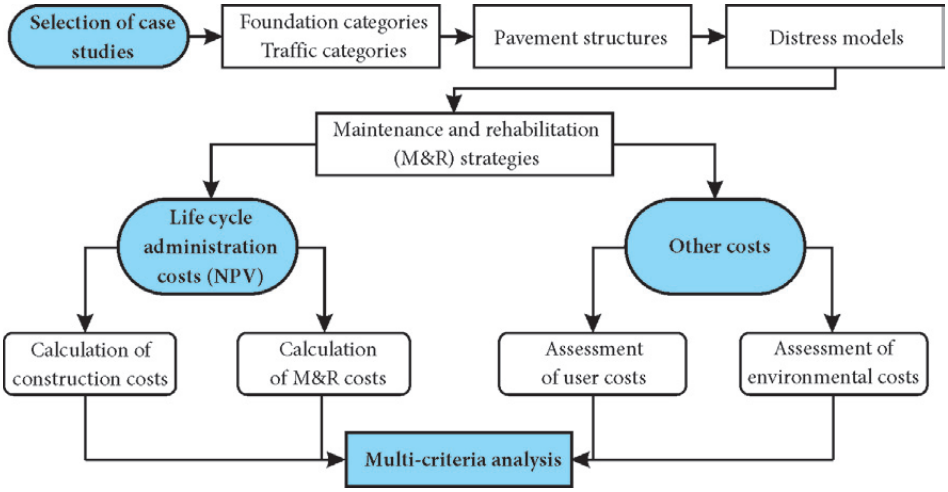

Fig. 1. Main activities of the proposed methodology

pavement design solutions, the use of cost benefit ratios is not generally recommended (Walls, Smith 1998). The selected indicator for this purpose was then the NPV. User costs were not directly considered for the calculation of this indicator, being its inclusion discussed later on.

The costs associated with different construction, maintenance and rehabilitation works can be collected from the road administrations or contractors' database containing statistics of the unit costs of paving works. The total costs supported by the road administration are calculated by adding the NPV corresponding to the initial construction, maintenance and rehabilitation and residual value. This last component is represented by a negative value. These costs did not include any activities that are not related to specific pavement structures, such as maintenance of drainage systems, since these will be similar for any paving solution.

Apart from the costs supported by the road agency, there are other elements that should be included in LCCA, such as user costs and external costs like environmental costs. However, the unavailability of accurate data in order to estimate these costs could compromise the possibility to compute them easily and correctly. Regarding vehicle operating costs (VOC) and for the pavement serviceability levels found in developed countries it is hard to believe that, for instance, quite different and significant roughness levels will appear in each pavement alternative taking to different VOC. In what it concerns to accidents costs, it is certainly unattainable to have an accident rate for each pavement type under normal operation conditions. Hence, in this context the users delay while travelling across a work zone, seems to be the main attribute that can achieve a major variability among different alternatives. In the absence of all the required data regarding the full description of work zones it was assumed that the duration of each activity is a reasonable indicator of the "cost" felt by the users. The number of workdays necessary to perform each M&R on 10 km of road was then selected as an indicator for user costs. For the environmental costs, an indicator was also selected and is related to the quantities of material expenditure and deposited in landfills associated with construction, maintenance and rehabilitation.

Finally, a multi-criteria analysis is performed in order to compare the life-cycle cost of different solutions, taking into account user or environmental costs.

3. Selection of case studies

3.1. Pavement structures, foundation and traffic categories

The pavement structures selected for this study are representative of the Portuguese situation in terms of the type of structure, type of materials and type of foundations. There are two groups of structures corresponding to two different traffic categories (*T1* and *T5*), which are characterized in Table 1 in terms of the Annual Average Daily Truck Traffic (*AADTT*), traffic growth rate (*t*) and Cumulative Number of Standard Axle Load of 130 kN (*CESAL*) for a design life of 35 years.

Although the pavement design guide from the Portuguese Road Agency (JAE 1995) considers 4 types of road foundation, it is generally recommended to improve the existing foundation when the subgrade soil is relatively weak, especially for heavy traffic roads. Hence, the comparison presented herein refers to pavement structures proposed in the design guide for a relatively good foundation, with a stiffness modulus E = 100 MPa. These structures are flexible and semi-rigid pavements with different options concerning the materials used in base and subbase layers. These options include issues such as the use of soil-cement subbases, instead of unbound granular materials or the use of anti-reflective cracking techniques for semi-rigid pavements. The type of surface layer considered was chosen depending on the traffic category, in order to reflect the current practice in Portugal: conventional asphalt concrete for low traffic volumes and open texture asphalt concrete using modified binders for high traffic volumes. The main elements of the selected pavement structures are presented in Table 2. For each layer of the pavement, it is indicated the type (according to the constituent material), the thickness, the stiffness modulus and the Poisson ratio. The values adopted for the stiffness modulus and the Poisson ratio are the suggested values from the Portuguese pavement design guide (JAE 1995) and also from authors' experience.

3.2. Distress models

3.2.1. Cracking

Cracking in flexible pavements is expressed in terms of a cracking index, *CI*, defined in the PARIS project as a combination of cracking indexes of longitudinal, transverse and alligator cracking per each 100 m section. This index varies from 0 to a maximum value of 400 and is given by the Eq (1).

$$CI = 2ACR + LCR + TCR, \quad (1)$$

where:

$$ACR = ACR_{low} + 1.5ACR_{moderate} + 2ACR_{high}, \quad (2)$$

$$LCR = LCR_{low} + 1.5LCR_{moderate} + 2LCR_{high}, \quad (3)$$

Table 1. Traffic categories

Traffic categories	*AADTT*max, veh	*t* %	$CESAL_{130\ \text{kN, 35 years}}$	
			Flexible pavement	Rigid or semi-rigid pavement
T1	2000	5	$53 \cdot 10^6$	$66 \cdot 10^6$
T5	300	3	$2.6 \cdot 10^6$	$4.0 \cdot 10^6$

Table 2. Pavement structures

Pavement ID	Surface layer				Base layer				Subbase layer			
	Type	*h*, cm	*E*, MPa	*v*	Type	*h*, cm	*E*, MPa	*v*	Type	*h*, cm	*E*, MPa	*v*
FL5.T5.F3	AC	18	5200	0.35	–	–	–	–	GSb	20	200	0.35
FL7.T5.F3	AC	14	5000	0.35	GB	20	400	0.35	GSb	20	200	0.35
FL9.T5.F3	AC	12	4900	0.35	–	–	–	–	SC	20	1000	0.30
SR4.T5.F3	AC	13	5000	0.35	LC	23	20 000	0.25	GSb	15	200	0.35
SR4.T5.F3.AF												
SR6.T5.F3	AC	13	5000	0.35	LC	21	20 000	0.25	SC	15	1000	0.30
SR6.T5.F3.AF												
FL4.T1.F3	AC*	28	5500	0.35	–	–	–	–	GSb	20	200	0.35
FL6.T1.F3	AC*	23	5300	0.35	GB	20	400	0.35	GSb	20	200	0.35
FL8.T1.F3	AC*	24	5400	0.35	–	–	–	–	SC	20	1000	0.30
SR3.T1.F3	AC*	19	5200	0.35	LC	25	20 000	0.25	GSb	15	200	0.35
SR3.T1.F3.AF												
SR5.T1.F3	AC*	19	5200	0.35	LC	23	20 000	0.25	SC	15	1000	0.30
SR5.T1.F3.AF												

Notes: FL, flexible; SR, semi-rigid; AF, with anti-reflective cracking treatment; T1 & T5, traffic categories (Table 1); F3, subgrade type (E = 100 MPa; v = 0.35); *h*, thickness; *E*, stiffness modulus; *v*, Poisson ratio; AC, asphalt concrete; AC*, AC including 3 cm of open texture asphalt concrete; GB, granular base; GSb, granular subbase; SC, soil cement subbase; LC, lean concrete.

$$TCR = TCR_{low} + 1.5TCR_{moderate} + 2TCR_{high}, \quad (4)$$

where *ACR*, *LCR*, *TCR* – cracking indexes of alligator cracking, longitudinal cracking and transverse cracking, respectively. Severity levels for the different crack types are low, moderate, high.

3.2.2. Crack initiation in the wheel path

The development of the models for crack initiation in the wheel path within the PARIS project is described in Sweere *et al.* (1997). The model for flexible and semi-rigid pavements is given by Eqs (5) and (6), respectively (Sweere *et al.* 1998).

$$N_{10} = 10^{\left[7.169 - 0.0074(SCI_{300}) - 2899829\left(\frac{1}{SCI_{300}N_{10}Y}\right)\right]}, \quad (5)$$

$$N_{10} = 10^{\left[7.05 - 0.006(SCI_{900}) - 2496877\left(\frac{1}{SCI_{900}N_{10}Y}\right)\right]}, \quad (6)$$

where N_{10} – the cumulative number Equivalent Single Axle Load (*ESAL*) of 100 kN until crack initiation; SCI_{300} and SCI_{900} – the surface and the base curvature index, respectively, corresponding to a 50 kN load applied by the Falling Weight Deflectometer (*FWD*); $N_{10}Y$ – the average annual number of 100 kN *ESAL*. In order to convert the number of 130 kN *ESAL*, used in this study, into 100 kN *ESAL*, the fourth power law was used.

3.2.3. Crack propagation in the wheel path

In the frame of the PARIS project, different functional forms were tested for the development of models for crack propagation in the wheel path, using full-scale accelerated load test results. It was found that linear models led to a good reproduction of the experimental data (Turtschy, Sweere 1999). Therefore, the Eq (7) is used for the prediction of crack propagation.

$$CI_n = CI_{n-1} + tN_{130}^{n}, \quad (7)$$

where CI_n – the cracking index in year n; CI_{n-1} – the cracking index in the previous year; t – the cracking rate; N_{130}^{n} – the number of *ESAL* occurred in year n. The following average value of t is derived from crack propagation monitored in LTPP studies on the Portuguese main network (Antunes 2005): $t = 3.0 \cdot 10^{-5}$, in the case of flexible pavements; $t = 8.2 \cdot 10^{-6}$, in the case of semi-rigid pavements.

3.2.4. Reflective cracking

The LTPP database on reflective cracking of semi-rigid pavements monitored in Portugal for more than 10 years (Quaresma *et al.* 2000) included test sections design of which was comparable to the structures analysed in this study. Some sections had no anti-reflective cracking measures, one of them had a geotextile SAMI and another one had been pre-cracked before the application of the asphalt layers. From the data observed in these sections, if 20 equivalent full-width cracks per km is considered as the threshold for crack sealing interventions, it can be concluded from those studies that this threshold was reached after 6 years since construction, for a pavement with no anti-reflective cracking measures, whereas for pavements with SAMI or with pre-cracking, the threshold will only be reached after more than 12 years.

3.3. Maintenance and rehabilitation strategies

The structural design life of the pavements presented above, expressed in terms of the cumulative number of 130 kN ESAL (*CESAL*), was determined though a mechanistic-empirical method which aim at the limitation of fatigue cracking in the asphalt layers (Eq (8)), the limitation of fatigue cracking in the cement bound layers (Eq (9)) and the limitation of permanent deformation originated in the subgrade (Eq (10)) (Antunes *et al.* 2008).

$$\varepsilon_t = \left(0.856V_b + 1.08\right)E^{-0.36}N^{-0.2}, \tag{8}$$

$$\frac{\sigma_t}{\sigma_r} = 1 - 0.08\log N, \tag{9}$$

$$\varepsilon_c = 1.8\cdot 10^{-2}N^{-0.25}, \tag{10}$$

where ε_t – the maximum tensile strain at the bottom of the asphalt layer; V_b – the volumetric binder content in the asphalt, %; E – the stiffness of the asphalt, Pa; N – the number of standard axle load repetitions; σ_t – the maximum horizontal tensile stress in the cement bound layers; σ_r – the bending tensile strength; ε_c – the maximum vertical compression strain at the top of subgrade.

The stresses and strains induced by the 130 kN standard axle load were calculated using multi-layer linear elastic analysis. Calculations were performed using input data from Table 2. The results are summarized in Table 3. The maintenance activities considered for LCCA of the pavement structures under study were selected taking into account the models presented above and the current practice in Portugal. Since the purpose of the study was to compare different pavement alternatives, there was no need to consider the maintenance activities that were not directly associated with the pavement. Table 4 summarizes the type of maintenance measures considered throughout the life cycle of each structure. The specific treatments applied within each type of maintenance measure were selected assuming that there were no restrictions associated with local conditions, such as limitations to the surface level. These treatments are shortly described in Table 5.

Whenever the timing for application of two different types of measures was close, these were combined, either by bringing forward one of them, or by delaying the other. The maintenance schedule considered for each pavement along with its residual life at the end of the design life is presented in Table 6. For the calculation of residual values at the end of the analysis period, only the residual life of structural rehabilitation treatments is taken into account.

From the results presented above, it can be seen that there is a significant difference in the total duration of road works (and therefore user costs) between flexible and semi-rigid pavements, for higher traffic volumes. For lower volumes, the influence of the type of structure is not so important, since distresses associated with ageing will be more critical then traffic associated distresses.

The volume of materials used and removed from the pavements during construction and maintenance of each

Table 3. Structural design life of pavement structures

Pavement ID	Stresses and strains				Design criteria (CESAL)			Design life, years
	ε_t	ε_c	σ_t, MPa	$\frac{\sigma_t}{\sigma_r}$	Fatigue $\cdot 10^6$	Perm. Deform. $\cdot 10^6$	130 kN $\cdot 10^6$	
FL5.T5.F3	171	–434	–	–	1.84	2.95	1.84	27.6
FL7.T5.F3	181	–363	–	–	1.49	6.05	1.49	23.8
FL9.T5.F3	130	–487	–	–	8.00	1.87	1.87	27.9
SR4.T5.F3	–	–115	0.685	0.46	unlimited	6.09E+08	6.09E+08	>35
SR4.T5.F3.AF								
SR6.T5.F3	–	–129	0.746	0.50	unlimited	380	380	>35
SR6.T5.F3.AF								
FL4.T1.F3	92	–235	–	–	36.2	34.7	34.7	28.3
FL6.T1.F3	101	–223	–	–	2.50	4.23	2.50	23.4
FL8.T1.F3	71	–256	–	–	137	24.6	24.6	23.2
SR3.T1.F3	–	–82	0.585	0.39	unlimited	2300	2300	>35
SR3.T1.F3.AF								
SR5.T1.F3	–	–94	0.565	0.38	unlimited	1330	1330	>35
SR5.T1.F3.AF								

Notes: ε_t – maximum horizontal tensile strain; ε_c – maximum vertical compression strain; σ_t – maximum horizontal tensile stress; σ_r – bending tensile strength.

Table 4. Maintenance thresholds and types of maintenance measures

Type of pavement	Distress type	Indicator	Maintenance threshold	Maintenance measures	Comments
Flexible	Surface cracking	CI	$CI > 150$	SuR	–
	Fatigue damage	RL_f	$RL_f < 20\%$	StR	–
	Permanent def. damage	RL_{pd}	$RL_{pd} < 20\%$	StR	–
	Lack of skid resistance	age / traffic	12 years/T1; 15 years/T5	SuR	Based on current practice
Semi-rigid	Surface cracking	CI	$CI > 150$	SuR	–
	Reflective cracking	crack/km, N	$N > 20$	CS or SuR	–
	Fatigue damage	RL_f	$RL_f < 20\%$	StR	The threshold is not reached within the analysis period
	Permanent def. damage	RL_{pd}	$RL_{pd} < 20\%$	StR	The threshold is not reached within the analysis period
	Lack of skid resistance	age / traffic	12 years/T1; 15 years/T5	SuR	Based on current practice

Notes: RL – structural residual life; SuR – surface rehabilitation; StR – structure rehabilitation; CS – crack sealing.

Table 5. Maintenance treatments

Measure ID	Measure type	Duration of road works, days	Measurement treatments	
			Task	Quantity
1	SuR	29	Milling and replacing, 5 cm	20% area
			Asphalt concrete surface, 5 cm	100% area
2	SuR	28	Milling and replacing, 5 cm	20% area
			Thin open texture asphalt concrete surface, 4 cm	100% area
3	StR	39	Milling and replacing, 5 cm	30% area
			Asphalt concrete binder course, 8 cm	100% area
			Asphalt concrete surface, 5 cm	100% area
5	StR	42	Milling and replacing, 5 cm	30% area
			Asphalt concrete base course, 8 cm	100% area
			Thin open texture asphalt concrete surface, 4 cm	100% area
8	CS	4	Cleaning and sealing transversal cracks	20 cracks /km

Table 6. Maintenance schedules and total duration of road works per 10 km lane during the analysis period

Pavement ID	Design life, years	Maintenance and rehabilitation schedule					Residual life, years	Duration of road works, days	Volume of materials used, m^3/m^2
		YS/MT	YS/MT	YS/MT	YS/MT	YS/MT			
FL5.T5.F3	25	15/ 1	30/ 3	– –	– –	– –	15	68	–
FL7.T5.F3	20	17/ 3	32/ 1	– –	– –	– –	2	68	–
FL9.T5.F3	25	15/ 1	30/ 3	– –	– –	– –	10	68	–
SR4.T5.F3	>35	6/ 8	12/ 1	18/ 8	24/ 1	30/ 8	0	69	–
SR4.T5.F3.AF	>35	12/ 1	24/ 1	– –	– –	– –	0	58	–
SR6.T5.F3	>35	6/ 8	12/ 1	18/ 8	24/ 1	30/ 8	0	69	–
SR6.T5.F3.AF	>35	12/ 1	24/ 1	– –	– –	– –	0	58	–
FL4.T1.F3	25	10/ 2	20/ 5	30/ 2	– –	– –	5	97	0.75
FL6.T1.F3	20	10/ 2	20/ 5	30/ 2	– –	– –	5	97	0.90
FL8.T1.F3	20	10/ 2	20/ 5	30/ 2	– –	–	5	97	0.71
SR3.T1.F3	>35	6/ 8	12/ 2	18/ 8	24/ 2	30/ 8	0	66	0.71
SR3.T1.F3.AF	>35	12/ 2	24/ 2	– –	– –	– –	0	55	0.71
SR5.T1.F3	>35	6/ 8	12/ 2	18/ 8	24/ 2	30/ 8	0	66	0.69
SR5.T1.F3.AF	>35	12/ 2	24/ 2	– –	– –	– –	0	55	0.69

Notes: *YS* – year in service; *MT* – maintenance treatment (Table 5).

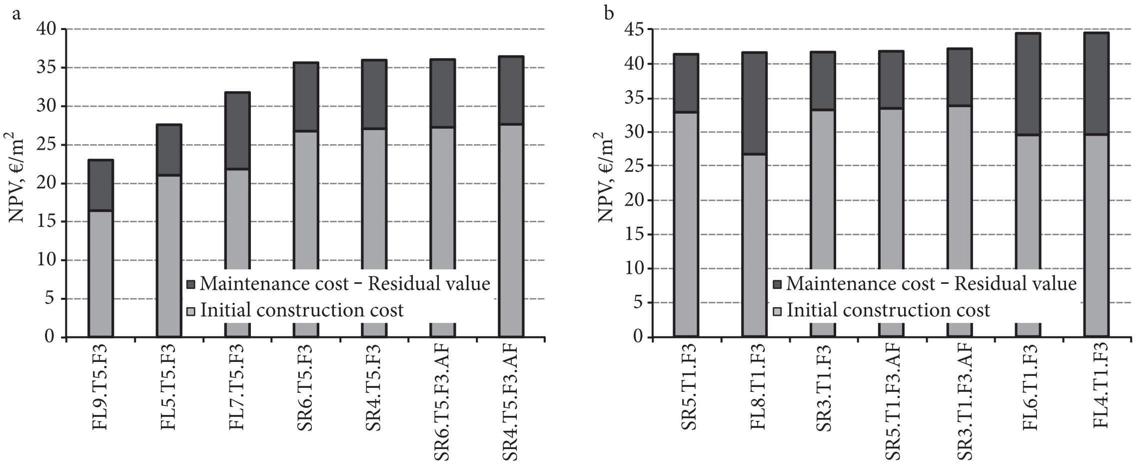

Fig. 2. Total NPV associated with pavement structures: a – traffic T5; b – traffic T1

pavement designed for the higher traffic category (T1) were also calculated, as the indicator of environmental costs.

4. Calculation and assessment of life-cycle costs

The information on costs of pavement construction and maintenance works was gathered from the Road Agency database concerning costs of paving works performed during the year of 2007 in Portugal. For each activity, the minimum, maximum and average unit costs were gathered. The life-cycle costs associated with each of the pavement alternatives considered were analyzed using NPV for an analysis period of 35 years and a 3% discount rate. The total NPV for each structure was the sum of three components: the initial construction cost, the total maintenance cost and the residual value at the end of the analysis period. The residual value is negative, which in the present study was estimated on the basis of the cost of the last structural rehabilitation, multiplied by its relative damage at the end of the analysis period (residual life divided by total design life) (NCHRP 2004). For the pavement structures that had no structural rehabilitation during the analysis period, the residual value was zero. Fig. 2 presents the total NPV of the selected structures, split into two components: initial construction costs; maintenance costs minus the respective residual values at the end of the analysis period.

The results presented in Fig. 2 show that, for this particular case study, the life-cycle costs of flexible structures are lower than the ones for semi-rigid structures, for the lower traffic category (T5). For higher traffic volumes (T1), semi-rigid structures are more economic in the long term, even if they have higher construction costs.

It can also be seen, in the examples presented in this paper, that the pavement structures that include a soil-cement sub-base – FL9 and SR6, for lighter traffic and FL8 and SR5 for the heavier traffic – are more economic than the corresponding structures with granular sub-bases. When we compare the life-cycle costs of semi-rigid pavements with anti-reflective cracking measures – referenced as AF – with the costs associated with similar structures without such measures, we conclude that the differences in the total life-cycle costs are insignificant. However, the use of anti-reflective cracking measures minimizes the need for crack sealing interventions and therefore, will result in lower user costs due to maintenance (Antunes *et al.* 2008).

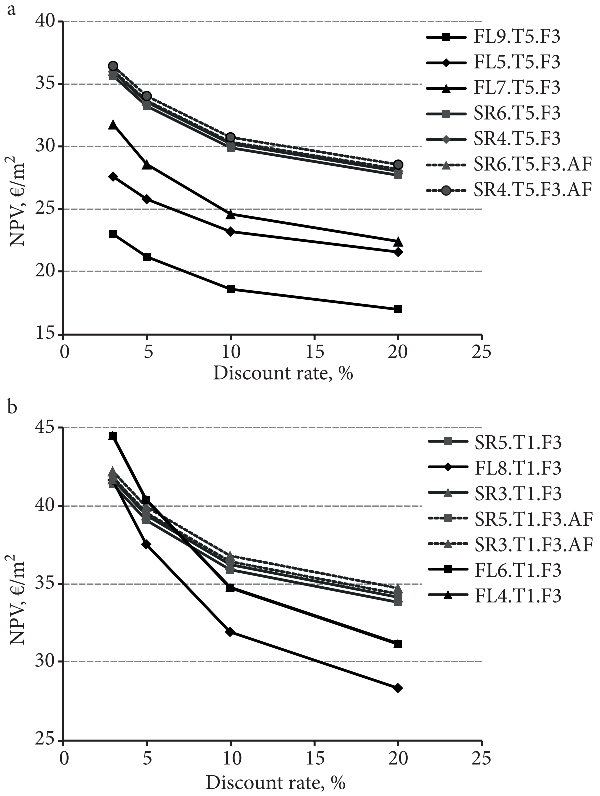

Fig. 3. Sensitivity analysis of the total NPV in relation to the discount rate: a – traffic T5; b – traffic T1

Finally, a sensitivity analysis of discount rate was performed in order to assess if it could influence significantly the previous mentioned results, using values from 3% to 20%. Fig. 3a shows that, for lighter traffic, the results are similar to the ones achieved with a 3% discount rate in terms of the most economical structures. However, for heavier traffic, if it were considered higher discount rates (over 8%) the flexible pavement structures are always preferable (Fig. 3b). The higher maintenance costs of flexible pavement structures contribute decisively to this fact.

The use of discount rate has the underlying assumption of equal inflation rates for all the materials used. In the presence of distinct materials such as asphalt and cement related product, the inflation rates for each case may be significantly different and affect the LCCA results (Mack 2012). However, based on the available data, this effect was not considered.

As referred, apart from the direct costs related to construction and maintenance directly supported by the road administration, there are other costs associated with pavement construction and maintenance that should be taken into account in LCCA studies, such as user costs due to traffic constrains during maintenance, or environmental costs corresponding to the use of raw materials and CO_2 emissions due to paving works. Although user costs and environmental costs are not easily quantifiable, specifically in a life cycle context, some indicators like the duration of road works or volume of materials used and deposited due to road works can be used for the purpose of comparing different solutions.

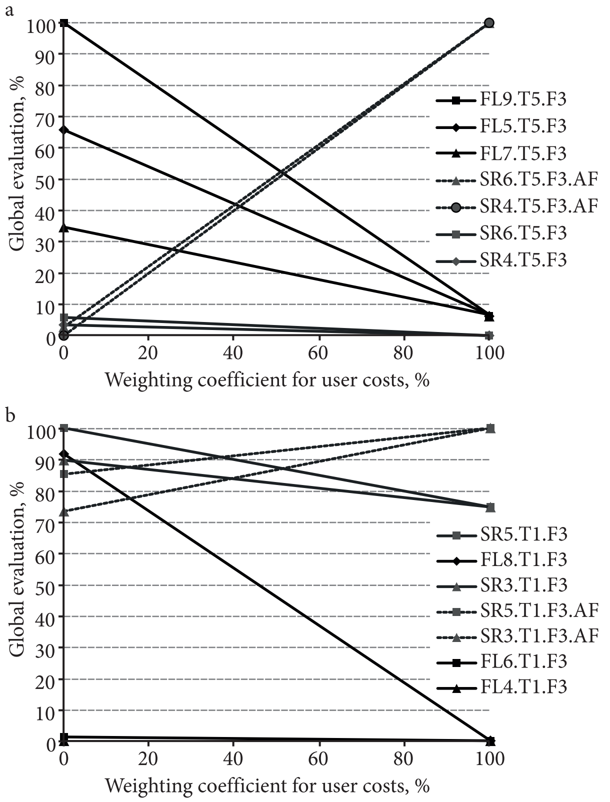

Fig. 4. Sensitivity analysis of the global evaluation in relation to the user costs: a – traffic T5; b – traffic T1

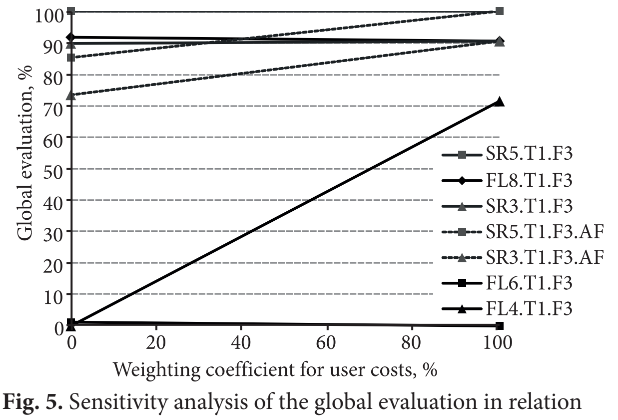

Fig. 5. Sensitivity analysis of the global evaluation in relation to the environmental costs (traffic T1)

The duration of maintenance works associated to each maintenance task considered in Table 5 were estimated from the database produced by COST 343 (COST 2003) and from interviews with road construction companies. The total durations of road works per 10 km lane associated with each treatment are presented in Table 5. The total duration of road works (excluding initial construction) associated with different pavement solutions during the analysis period was calculated (Table 6).

From the results presented above, it can be seen that there is a significant difference in the total duration of road works (and therefore user costs) between flexible and semi-rigid pavements, for higher traffic volumes. For lower volumes, the influence of the type of structure is not so important, since distresses associated with ageing will be more critical then traffic associated distresses. The volume of materials used and removed from the pavements during construction and maintenance of each pavement designed for the higher traffic category (T1) was also calculated, as an indicator of environmental costs associated with materials (Antunes *et al.* 2008).

5. Multi-criteria analysis

Using the NPV values calculated for different alternatives (administration costs), as well as the indicators presented above for user costs and environmental costs, a multi-criteria analysis can be performed for the comparison of different paving solutions. This analysis resulted from the combination of normalized costs, where for the worst solution, considered for each type of cost, was given the value of zero and for the best the value of one (Valadares *et al.* 1996).

In this context, the weighting coefficients, in percentage and assigned to each attribute, reflect the decision maker's preferences. In the absence of these weights, it is useful to perform a sensitivity analysis for both user and environmental costs weights in the alternative global evaluation. Regarding user costs, Fig. 4 shows the effect of user costs weighting coefficient in the global result (considering NPV and user costs). Fig. 5 shows the effect of environmental costs weighting coefficient for higher traffic structures (T1).

The results presented in Fig. 4 shows that, although flexible pavement structures for low traffic categories have lower NPV, semi-rigid structures with anti-reflective cracking measures will have a higher ranking when the weight assigned to user costs is higher, due to the lower need of future interventions. For higher traffic structures (T1), also due the lower maintenance needs, semi-rigid structures perform better when user costs are considered more important (Fig. 4). Figs 4 and 5 illustrate that semi-rigid pavement structures and flexible structures with soil-cement sub-bases have a better classification even when the relative weight assigned to user costs or environmental costs is modest.

These results were obtained following a deterministic approach. However, the pavement performance models are necessarily a source of variability regarding the prediction of long term future condition. Also the existing price volatility of pavement materials should guide further developments of LCCA studies to a stochastic approach (Pittenger *et al.* 2012).

6. Conclusions

1. The work presented in this paper concerns the life-cycle cost analysis of different flexible and semi-rigid paving alternatives and a new framework is described with the objective to contribute for a better support in the decision process when designing new pavement structures.

2. The performance models needed to the pavement distresses evaluation are a fundamental issue in the analysis due to their relation to the maintenance and rehabilitation strategies. The most important distress mechanisms in the case of flexible and semi-rigid pavements are: fatigue cracking originated in the bituminous and cement-bound layers; permanent deformation or rutting; surface cracking, predominantly in the wheel path; reflective cracking on semi-rigid pavements; deterioration of skid resistance. Both, the proposed models and the maintenance and rehabilitation strategies, have taken into consideration the results from long term performance studies and the best current practice in the European context.

3. The use of semi-rigid pavement structures is an interesting alternative to the more common flexible pavement structures, especially for roads with higher traffic volumes. For the same traffic volume and subgrade category, pavement structures with soil-cement sub-bases are generally more economic then the ones with granular sub-bases.

4. Net present values calculated for different alternatives are important inputs for multi-criteria analysis of different paving solutions, taking into account user costs associated with the application of maintenance treatments and environmental costs. Although user costs due to road works are difficult to quantify, it was demonstrated that the total duration of road works per 10 km lane could be used as a good indicator for the comparison of different pavement alternatives from this point of view. The total volume of materials involved in road building and maintenance operations can also be taken as an indicator for the environmental costs associated with raw materials expenditure and landfill volumes.

5. Using the above indicators together with the net present values, a multi-criteria analysis was proposed for the comparison of the different paving solutions. It was demonstrated that this methodology could be a simple and useful tool in order to achieve the most adequate paving solutions of a road network, in terms of construction and maintenance activities, based simultaneously on technical, economic and environmental criteria.

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