Pavement Selection Strategies using Life-Cycle Cost Analysis

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ABSTRACT: Building and maintaining a road network involves the expenditure of large budgets and therefore, 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 the investments in road construction and maintenance. The issues involved in life-cycle cost analysis of different paving solutions will vary from region to region, depending on local factors such as environmental conditions and availability of materials and technologies.

This paper presents a study that is being carried out in Portugal, concerning the life-cycle cost analysis of different paving alternatives. The analysis is carried out using actual data on construction costs of typical pavement structures in Portugal and taking into consideration appropriate performance models for each type of structure being selected. The models are calibrated using results from long term performance studies and the maintenance strategies considered take into account the current practice in the Portuguese main road network.

1 BACKGROUND

A big proportion of the Portuguese main road network has flexible pavements, comprising asphalt and unbound granular layers placed on top of the capping layer, although the pavement design guide issued by the Road Administration presents a pavement catalogue that includes flexible, semi-rigid and rigid pavements. The fact that the adoption of semi-rigid and rigid pavements corresponds in many cases to higher construction costs is one of the main reasons for this situation.

Building and maintaining a road network involves the expenditure of large budgets and therefore, 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 construction and maintenance. Life-cycle cost analysis (LCCA) during the design phase is one of the key instruments for the optimization of expenditures in road construction and maintenance.

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 and environmental costs should also be taken into account when selecting a pavement solution for a particular road.

This paper presents a study concerning the LCCA of different paving alternatives, with the objective of contributing for a better support in the decision process when designing new pavement structures.

2 METHODOLOGY

In order to perform LCCA to different pavement structure alternatives, there are a number of issues that must be selected, taking into account the objectives of the study, such as:

- The analysis period, which should be long enough to reflect long-term costs associated with each of the design alternatives, for reasonable maintenance and rehabilitation strategies (ACPA, 2002). A total analysis period of 35 years was selected for this study. This is the minimum analysis period generally recommended for this purpose (Walls & Smith, 1998).
- 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. Since benefits are very difficult to quantify, the selected indicator was the NPV.
- The performance models that are used to evaluate pavement distresses over the analysis period, as well as the Maintenance and Rehabilitation (M&R) strategies associated with each performance indicator. The models used in this project were primarily derived from long term performance studies performed in Portugal and in other European countries (Antunes, 2005; Quaresma, 2001a, b; Sweere *et al*, 1998). The M&R strategies were established taking into account the current practice by the Portuguese Road Administration and the private motorway concessionaires.

The costs associated with different construction, maintenance and rehabilitation works were collected from the Portuguese Road Administration database, which contains statistics of the unit costs of paving works performed throughout the country. Additional information was gathered among Portuguese road contractors.

The total costs supported by the Administration were calculated by adding the NPV corresponding to 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 Administration, there are other elements that should be included in LCCA, such as user costs and external costs like environmental costs. The main difference in user costs for different paving solutions will be the ones associated with M&R workzones. The number of workdays necessary to perform each M&R on 10 km of road was selected as an indicator for user costs. As for environmental costs, the indicator selected is related to the quantities of material expenditure and deposited in landfills associated with construction, maintenance and rehabilitation. A multi-criteria analysis was performed in order to compare LCC of different solutions, taking into account user or environmental costs.

The main activities performed in the framework of this study are summarized in Figure 1.

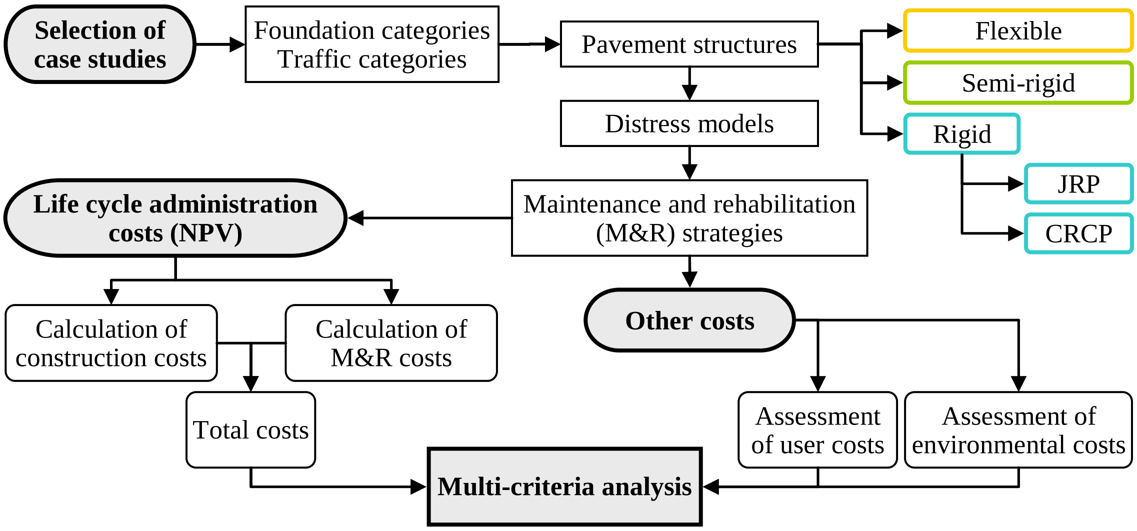

Figure 1. Flowchart of main activities performed

3 PAVEMENT STRUCTURES FOR ANALYSIS

3.1 *Selection of structures*

The pavement structures selected for this study are representative of the Portuguese situation in terms of 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 annual Average Daily Truck Traffic (ADTT), traffic growth rate (t) and Cumulative Number of Standard Axle Load of 130 kN (CESAL) for a design life of 35 years.

Table 1. Traffic categories.

Traffic categories	ADTT	t	$\text{CESAL}_{130\text{kN, 35YEARS}}$	
	max	%	Flexible	Rigid or semi-rigid
T1	2000	5	5,3E+07	6,6E+07
T5	300	3	2,6E+06	4,0E+06

The Portuguese Road Administration pavement design guide considerers 4 types of road foundation, which are characterized by a design stiffness modulus (E) within a given range. However, when the subgrade soil is relatively weak, it is generally recommended to improve the existing foundation, especially for heavy traffic roads. For this reason, 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, and their main elements are presented in Table 2.

Table 2. Flexible and semi-rigid pavement structures

Pavement ID	Surface layer				Base layer				Subbase layer			
	Material	h	E	ν	Material	h	E	ν	Material	h	E	ν
		cm	MPa			cm	MPa			cm	MPa	
FL5.T5.F3	AC	18	5200	0.35	GB	20	400	0.35	GSb	20	200	0.35
FL7.T5.F3	AC	14	5000	0.35					GSb	20	200	0.35
FL9.T5.F3	AC	12	4900	0.35					GSb	20	1000	0.30
SR4.T5.F3	AC	13	5000	0.35	LC	23	20000	0.25	GSb	15	200	0.35
SR4.T5.F3.AF												
SR6.T5.F3	AC	13	5000	0.35	LC	21	20000	0.25	SC	15	1000	0.30
SR6.T5.F3.AF												
FL4.T1.F3	OTAC	28	5500	0.35	GB	20	400	0.35	GSb	20	200	0.35
FL6.T1.F3	OTAC	23	5300	0.35					GSb	20	200	0.35
FL8.T1.F3	OTAC	24	5400	0.35					SC	20	1000	0.30
SR3.T1.F3	OTAC	19	5200	0.35	LC	25	20000	0.25	GSb	15	200	0.35
SR3.T1.F3.AF												
SR5.T1.F3	OTAC	19	5200	0.35	LC	23	20000	0.25	SC	15	1000	0.30
SR5.T1.F3.AF												

Key: FL = flexible; SR = semi-rigid; AF = with anti-reflective cracking treatment; T1 & T5 = traffic categories as defined in Table 1; F3 = subgrade type (E=100MPa ν = 0.35); h = thickness; E = stiffness modulus; ν = Poisson ratio; AC = asphalt concrete; OTAC = open texture asphalt concrete; GB = granular base; GSb = granular subbase; SC = soil cement subbase; LC = lean concrete.

3.2 *Calculation of design life*

The 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, using the design criteria commonly used in Portugal, which aim at the limitation of bottom-up fatigue cracking of asphalt layers and cement treated layers and the limitation of permanent deformation originated in the subgrade (Antunes *et al*, 2008). The stresses and strains induced by the 130 kN standard axle load were calculated using multi-layer linear elastic analysis. The results are summarized in Table 3.

Table 3. Design life of pavement structures

Pavement ID	Stresses and Strains				Design criteria		$CESAL_{130}$	Design life
	ε_t	ε_c	σ_t	σ_t / σ_R	CESAL Fatigue	CESAL Perm. Deform.		
			MPa					years
FL5.T5.F3	171	-434			1,84E+06	2,95E+06	1,84E+06	27,6
FL7.T5.F3	181	-363			1,49E+06	6,05E+06	1,49E+06	23,8
FL9.T5.F3	130	-487			8,00E+06	1,87E+06	1,87E+06	27,9
SR4.T5.F3 SR4.T5.F3.AF	-	-115	0,685	0,46	unlimited	6,09E+08	6,09E+08	>35
SR6.T5.F3 SR6.T5.F3.AF	-	-129	0,746	0,50	unlimited	3,80E+08	3,80E+08	>35
FL4.T1.F3	92	-235			3,62E+07	3,47E+07	3,47E+07	28,3
FL6.T1.F3	101	-223			2,50E+06	4,23E+06	2,50E+06	23,4
FL8.T1.F3	71	-256			1,37E+08	2,46E+07	2,46E+07	23,2
SR3.T1.F3 SR3.T1.F3.AF	-	-82	0,585	0,39	unlimited	2,30E+09	2,30E+09	>35
SR5.T1.F3 SR5.T1.F3.AF	-	-94	0,565	0,38	unlimited	1,33E+09	1,33E+09	>35

Key: ε_t = maximum horizontal tensile strain; ε_c = maximum vertical compression strain; σ_t = maximum horizontal tensile stress.

4 DISTRESS MODELS

4.1 *Introduction*

Pavement condition changes throughout its life cycle, as a consequence of traffic, climatic conditions and other environmental effects. There are a number of distress mechanisms, not directly related to the conventional pavement design criteria mentioned in the previous section, which may condition the need to perform maintenance activities. Some of these distresses, such as ravelling or rutting of the wearing course, are mainly attributed to the use of inappropriate materials and therefore, they were not considered for LCCA. Roughness was also not considered, since excessive roughness does not normally occur when adequate construction materials and techniques are used.

The following distress mechanisms were taken into account in this study for flexible and semi-rigid pavements:

- Fatigue cracking originated in the bituminous and cement-bound layers (considered in the calculation of the design life).
- Surface cracking, predominantly in the wheel path.
- Reflective cracking on semi-rigid pavements.

- Permanent deformation of structural origin (also considered in the calculation of the design life).
- Deterioration of skid resistance.

The models for prediction of structural distresses (fatigue cracking and permanent deformation) were already presented in 3.2. The models used to predict surface cracking and reflective cracking were derived from long term performance studies. These models considered two phases: crack initiation and crack propagation. The models for crack initiation, with the exception of reflective cracking, were derived from the PARIS project (Sweere *et al*, 1998), which used Long Term Pavement Performance (LTPP) data acquired throughout Europe. The remaining models for cracking were derived from LTPP data from Portuguese test sections.

There were no models for the evolution of skid resistance. Therefore, the maintenance strategies considered with respect to lack of skid resistance were defined on the basis of the current practice in motorways and other primary roads.

4.2 *Models for flexible pavements*

Cracking in flexible pavements was expressed in terms of a cracking index, CI, defined in the PARIS project as a combination of longitudinal, transverse and alligator cracking per each 100 m section. This index varies from 0 to a maximum value of 400. The model for crack initiation on flexible pavements derived from the PARIS project is given by equation (1) (Sweere et al 1998):

$$N_{10} = 10^{\left[7{,}169 - 0{,}0074\cdot(SCI_{300}) - 2899829\cdot\left(\frac{1}{SCI_{300}\cdot N_{10}Y}\right)\right]} \qquad (1)$$

where:

N_{10}	Cumulative number of 100 kN ESAL until crack initiation;
SCI_{300}	Surface Curvature Index corresponding to a 50 kN load applied by a FWD.
$N_{10}Y$	Average annual number of 100 kN ESAL.

In order to convert the number of 130kN ESAL used in the present study into 100 kN ESAL, the fourth power law was used.

After cracking has been initiated, the following equation (2) was used for the prediction of crack propagation:

$$CI_n = CI_{n-1} + t \times N_{130}^{n} \qquad (2)$$

where:

CI_n	Cracking Index in year n
CI_{n-1}	Cracking Index in the previous year
t	Crack increasing rate
N_{130}^{n}	Number of ESAL occurred in year n.

For flexible pavements, the following value of t was used, taking into account LTPP studies on flexible pavements (Antunes 2005): $t = 3 \times 10^{-5}$.

4.3 *Models for semi-rigid pavements*

The LTPP database on reflective cracking of semi-rigid pavements monitored in Portugal for more than 10 years (Quaresma, 2001a, b) included 4 test sections whose design was comparable to the structures analysed in this study. Two of these sections had no anti-reflective cracking measures (SRRef), one of them had a geotextile SAMI (SRG) and the other had been pre-cracked before application of the asphalt layers (SRIC). Figure 2 presents the evolution of the number of equivalent full-width reflective cracks derived from the data observed in these for sections.

If 20 equivalent full-width cracks per km is considered as the threshold for crack sealing interventions, it can be see concluded, from the Figure presented above, that this threshold is 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.

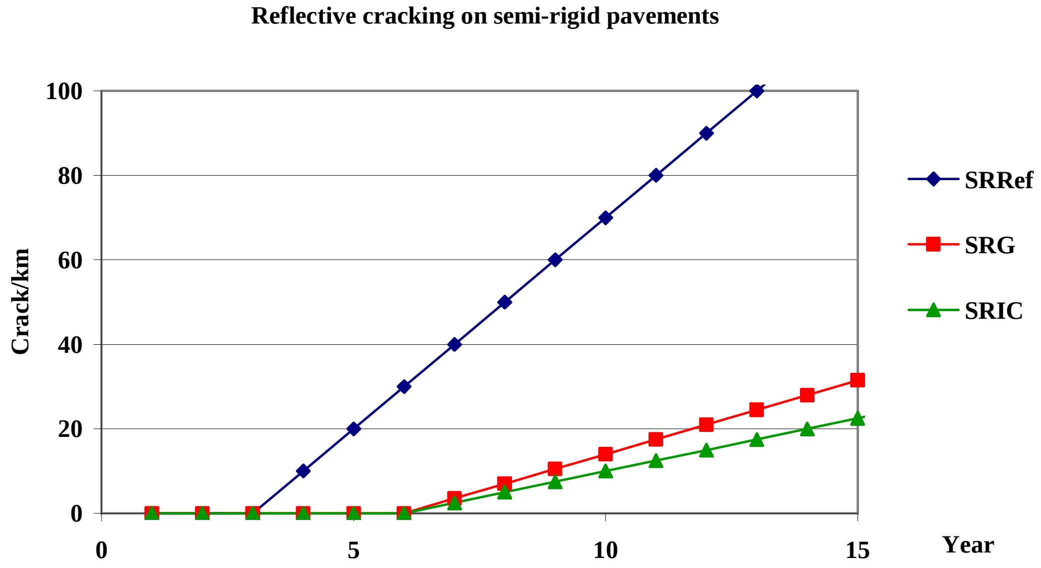

Figure 2. Reflective cracking in semi-rigid test sections.

The models used for crack initiation and crack propagation prediction were similar to the ones presented for flexible pavements. The model for crack initiation is given by equation (3):

$$N_{10} = 10^{\left[7{,}05 - 0{,}006 \cdot (SCI_{900}) - 2496877 \cdot \left(\frac{1}{SCI_{900} \cdot N_{10} Y}\right)\right]} \tag{3}$$

where:

SCI$_{900}$ Base Curvature Index corresponding to a 50 kN load applied by a FWD.

5 MAINTENANCE AND REHABILITATION STRATEGIES

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 type of pavement. Table 4 summarises the type of maintenance measures considered throughout the life cycle of each structure.

Table 4. Maintenance thresholds and types of maintenance measures.

Type of pavement	Distress type	Indicator	Maint. threshold	Maint. measures	Comments
Flexible	Surface cracking	CI	CI > 150	SuR	-
	Fatigue damage	% damage fatigue (D_f)	$D_f > 80\%$	StR	-
	Permanent def. damage	% damage perm.def. (D_{pd})	$D_{pd} > 80\%$	StR	-
	Lack of skid resistance	Age / traffic	12 years / T1 15 years / T5	SuR	Based in current practice
Semi-rigid	Surface cracking	CI	CI > 150	SuR	-
	Reflective cracking	Crack/km (N)	N > 20	CS or SuR	-
	Fatigue damage	% damage fatigue	$D_f > 80\%$	StR	The threshold is not reached within the analysis period
	Permanent def. damage	% damage perm.def.	$D_{pd} > 80\%$	StR	The threshold is not reached within the analysis period
	Lack of skid resistance	Age / traffic	12 years / T1 15 years / T5	SuR	Based in current practice

Key: S_uR = surface rehabilitation; StR = structure rehabilitation; CS = crack sealing.

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. Note that for residual life calculation only structural rehabilitation maintenance tasks were taking into account.

Table 5. Maintenance treatments.

Measure ID	Maintenance measure type	Measurement treatments	
		Task	Quantity
1	SuR	milling and replacing (5cm) asphalt concrete surface (5 cm)	20% area 100% area
2	SuR	milling and replacing (5cm) thin open texture asphalt concrete surface (4cm)	20% area 100% area
3	StR	milling and replacing (5cm) asphalt concrete binder course (8 cm) asphalt concrete surface (5 cm)	30% area 100% area 100% area
5	StR	milling and replacing (5cm) asphalt concrete base course (8 cm) thin open texture asphalt concrete surface (4cm)	30% area 100% area 100% area
8	CS	cleaning and sealing transversal cracks	20 cracks /km

Table 6. Maintenance schedules.

Pavement ID	Design life	Maintenance and reabilitation schedule					Residual life
	years	YS / MT	YS / MT	YS / MT	YS / MT	YS / MT	years
FL5.T5.F3	25	15 / 1	30 / 3				15
FL7.T5.F3	20	17 / 3	32 / 1				2
FL9.T5.F3	25	15 / 1	30 / 3				10
SR4.T5.F3	> 35	6 / 8	12 / 1	18 / 8	24 / 1	30 / 8	0
SR4.T5.F3.AF	> 35	12 / 1	24 / 1				0
SR6.T5.F3	> 35	6 / 8	12 / 1	18 / 8	24 / 1	30 / 8	0
SR6.T5.F3.AF	> 35	12 / 1	24 / 1				0
FL4.T1.F3	25	10 / 2	20 / 5	30 / 2			5
FL6.T1.F3	20	10 / 2	20 / 5	30 / 2			5
FL8.T1.F3	20	10 / 2	20 / 5	30 / 2			5
SR3.T1.F3	> 35	6 / 8	12 / 2	18 / 8	24 / 2	30 / 8	0
SR3.T1.F3.AF	> 35	12 / 2	24 / 2				0
SR5.T1.F3	> 35	6 / 8	12 / 2	18 / 8	24 / 2	30 / 8	0
SR5.T1.F3.AF	> 35	12 / 2	24 / 2				0

YS = year in service; MT = Maintenance treatment as defined in Table 5

6 LIFE-CYCLE COST ANALYSIS

The information on costs of pavement construction and maintenance works was gathered from the Road Administration 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 analysed using Net Present Values (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 a negative value, 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) (AASHTO, 2004). For the pavement structures that had no structural rehabilitation during the analysis period, the residual value was 0. Figures 3 and 4 present 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 Figures 3 and 4 show that, for this particular case study, the life-cycle costs of flexible structures supported by the Administration 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.

Finally, 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 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).

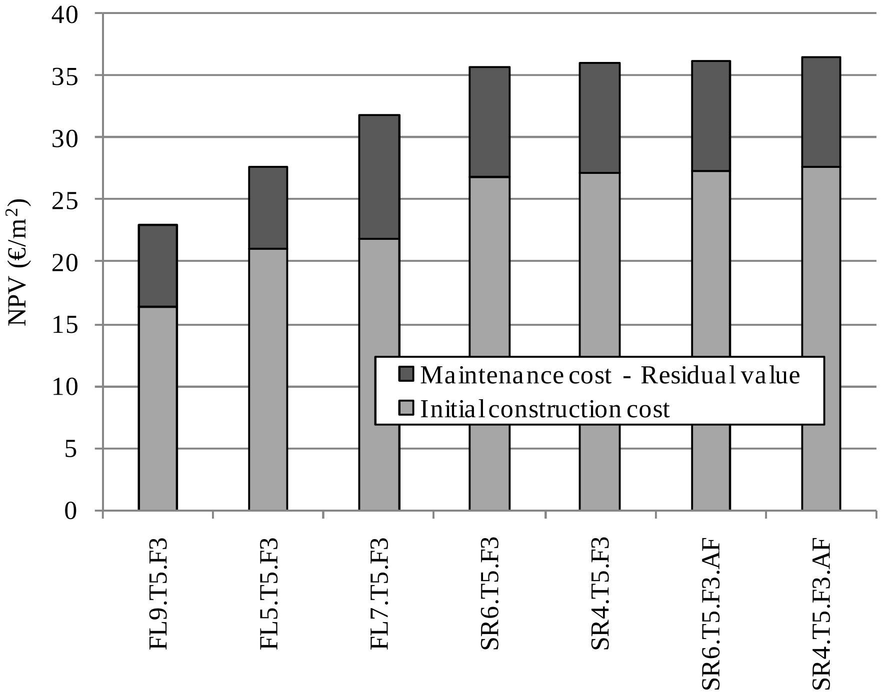

Figure 3. Total NPV associated with pavement structures for traffic T5.

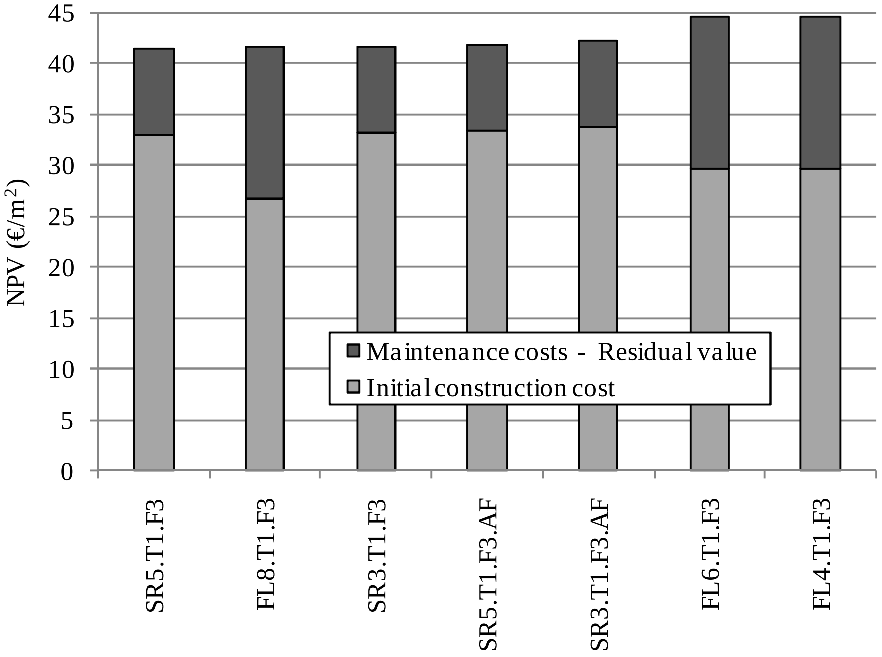

Figure 4. Total NPV associated with pavement structures for traffic T1.

The results presented above are restricted to costs directly supported by the Road Administration. They may be complemented with data from user costs due to traffic constrains during maintenance, and environmental costs corresponding to the use of raw materials or CO_2 emissions due to paving works. Although user costs and environmental costs are not easily quantifiable, some indicators, like duration of road works or volume of materials used and deposited due to road works, can be used as inputs for multi-criteria analysis of different paving solutions. In this case, the NPV values calculated for different alternatives are also one of the inputs for the analysis.

7 FINAL REMARKS

The work presented in this paper was part of a broader project that is being carried out, concerning the life-cycle cost analysis of different paving alternatives included in the Portuguese Road Administration pavement design catalogue. The analysis was carried out using actual data on construction costs of typical flexible and semi-rigid pavement structures in Portugal and taking into consideration performance models that were derived from long term performance studies performed in Portuguese pavement sections. Information on maintenance strategies adopted on pavement structures in the main road network was also taken into account. The life-cycle costs were analysed in terms of Net Present Values.

The results obtained show that 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. The results also show that, for the same traffic volume and foundation category, pavement structures with soil-cement sub-bases are generally more economic then the ones with granular sub-bases.

Apart from the comparisons between life-cycle costs supported by the Administration presented herein, the NPV values calculated for different alternatives can be used as one of the inputs for multi-criteria analysis of different paving solutions, taking into account user costs associated with the application of maintenance treatments and environmental costs.

8 REFERENCES

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