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Economic Sustainability of Concrete Pavements

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Abstract

Economic evaluation of transport infrastructure is as important as its technical and structural design: often only initial construction costs are calculated to evaluate economic project sustainability. Instead forgetting maintenance costs exposes society to unacceptable risks of expensive decisions. Road pavements design and construction solutions affect maintenance works during service life, which not only entail economical and financial expenditures but also damage service regularity for users. Distress pavement analysis can contribute to find the financially most advantageous solution. This paper shows a computer program defined to analyze structural, functional and financial characteristics of concrete pavements.

Keywords: concrete pavement; structural analysis; maintenance plan; Net Present Value.

1. Introduction

Evaluation of road concrete pavement level of service during design life is a very important aspect in the project phase: structural and functional performance verification affects pavement management system and its social and environmental costs [1] [2].

In this study, a design procedure for Joint Plain Concrete Pavement (JPCP) has been developed. This procedure involves the use of structural models to calculate pavement response and the implementation of distress predictive models. Pavement response, based on critical stresses due to repeated traffic and environmental loading, is evaluated by Kenslabs, a finite element software developed in Fortran 77. VBA code, named ESC (Economic Sustainability of Concrete pavement), has been implemented as input and output interface with Kenslabs: it can generate input data and read output files in order to extrapolate critical stresses in the mesh of the slab.

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Mechanistic and empirical pavement distress models, proposed by AASHTO Guide 2002 and SHRP, are used to evaluate pavement condition and define automatically maintenance and repair procedures. The examined distresses are: fatigue damage, transverse cracking, joint faulting and International Roughness Index (IRI).

Three JPCP highways concrete pavements listed in the Italian Pavement Design Catalogue [3] have been analyzed by ESC.

Critical stresses calculated by Kenslabs, structural, material and site-specific environmental data inputs are used to evaluate, year by year, pavement condition during service life. Maintenance plan is derived from international experience (scheduled and preventive maintenance) and effective condition (corrective maintenance).

Construction costs are calculated considering geometry inputs, while maintenance costs are derived from maintenance plan. Given the inflation rate and the discount rate, supposed both constant during pavement service life, ESC calculates the Net Present Value (NPV), synthetic evaluation methodology of economic and financial charges correlated to verified pavement.

2. Software design model

Factors influencing pavement design are: traffic, environmental conditions, subgrade bearing capacity and materials characteristics.

Default Microsoft Excel® worksheets are available to input design data. Construction and maintenance costs are derived from project geometrical characteristics, materials, labour, machinery and equipment unit costs. Joints, dowel bars and tie bars amount are automatically calculated by ESC. The most important parameter to determinate joints is its opening due to temperature change and drying shrinkage; it is expressed by (1) [4].

$$\Delta L = C \cdot L \cdot (\alpha_t \cdot \Delta T + \varepsilon) \tag{1}$$

where ΔL is the joint opening caused by temperature change and drying shrinkage of concrete; c is an adjustment factor due to slab-subbase friction; L is the joint spacing or slab length; αt is the coefficient of thermal expansion of concrete; ΔT is the temperature range; ε is the drying shrinkage coefficient of concrete.

Dowel bars at transverse joint are designed comparing bearing stress between dowel and concrete with allowable bearing stress, according to Friberg method [5].

Pavement bearing capacity is defined by modulus of reaction: this parameter depends on thickness and type of subbase layers (granular and/or cement treated subbase) and on modulus of subgrade reaction. The modulus of subbase reaction is automatically provided by ESC code, using Packard charts; maximum permitted modulus of reaction value is 130 MPa/m as recommended in the most of literature references [6].

Pavement thermal pattern, influenced by air temperature, sun's radiation, wind speed and thermal properties of concrete, is defined by Barber theory [7]; it is expressed by (2). The Barber formula to evaluate thermal gradients during the day and the night of all seasons is:

$$Tpav(z,t) = T_{ag} + r + \left(\frac{A_g}{2} + 3R \right) \cdot F \cdot \exp(-C \cdot z) \cdot \sin\left(0.262t - C \cdot z - \arctan \frac{C}{H + C} \right) \tag{2}$$

where Tpav(z,t) is the temperature of pavement at depth z at hour h in °C; Tag is the average seasonal daily air temperature in °C; R is calculated daily solar radiation contribution to air temperature in °C; it is expressed by (3):

$$R = \frac{2 \cdot b \cdot I}{3 \cdot 24 \cdot h} \tag{3}$$

Ag is the excursion daily average air in °C; b is the surface absorptivity to the total solar radiation (dimensionless); I is the daily solar radiation in kcal/day; h is expressed by (4):

$$h = 4.882 \cdot \left(1.3 + 0.4332 \cdot v^{0.75}\right) \tag{4}$$

v is the average wind speed in m/s; h is the heat transfer coefficient in kcal/m2 h °C; F is expressed by (5); H is expressed by (6) and C is expressed by (7):

$$F = \frac{H}{\sqrt{(H+C)^2 + C^2}} \tag{5}$$

$$H = \frac{h}{k} \tag{6}$$

where k is thermal conductivity of concrete in kcal/m h °C

$$C = \frac{0.131 \cdot s \cdot \gamma}{k} \tag{7}$$

where s is specific heat of concrete in kcal/kg °C and γ is density of concrete in kg/m^3.

Daily thermal gradients derived by (2) has been modified to consider that in the night they are half of those ones during the day, as experimentally verified and exposed in literature [8]; [9]; [11]. Fig. 1 shows the thermal gradients in one day. User inputs thermal seasonal data, so for each 24 hours of the four season VBA code calculate thermal pavement conditions.

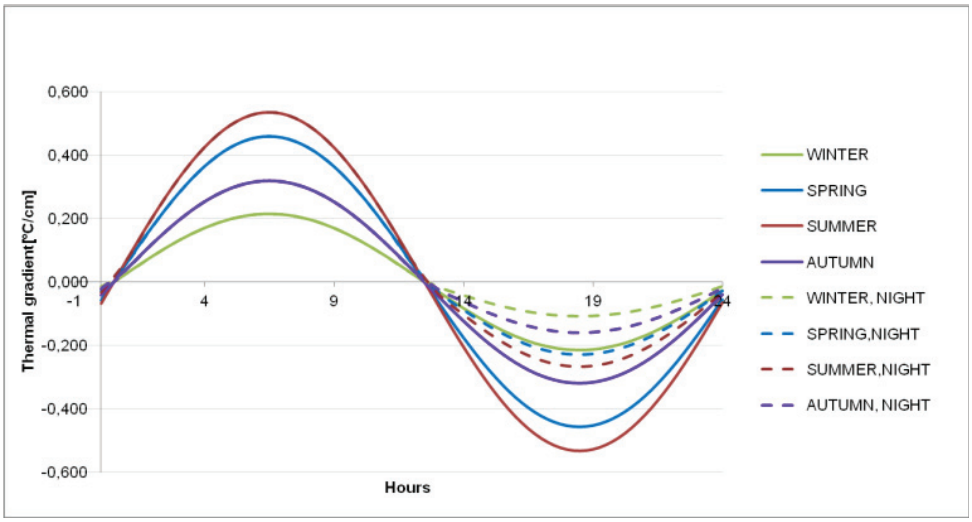

Fig. 1. Thermal gradient in concrete slab

In the computer code, datasheets are provided to input traffic level, establishing average daily heavy vehicles per lane at the road opening year, annual rate of traffic growth, pavement life, traffic spectrum and hourly distribution per vehicle type. ESC has defined in its datasheet all traffic spectra defined in the Italian Pavement Design Catalogue [12], but it allows defining any other traffic spectrum.

The combination of frequency between thermal gradients and different load configuration during day and night affects the number of repetitions for fatigue calculation in cracking model [10].

Materials amounts and characteristics are required as regard to composition of concrete mix (water, cement, sand, type of coarse aggregate, chemical admixtures), physical and thermal properties of concrete (density, coefficient of absorption of the solar radiation, specific heat, thermal conductivity, Poisson's ratio, cubic characteristic compressive strength of concrete) [13]. Elastic modulus is automatically deducted from compressive strength (R_{ck}).

Fig. 2 shows a finite element mesh of a three-slab model, and the configurations of traffic loads to calculate the most critical edge stress [14]. The image represented in Fig. 2 is half the total mesh area due to symmetry.

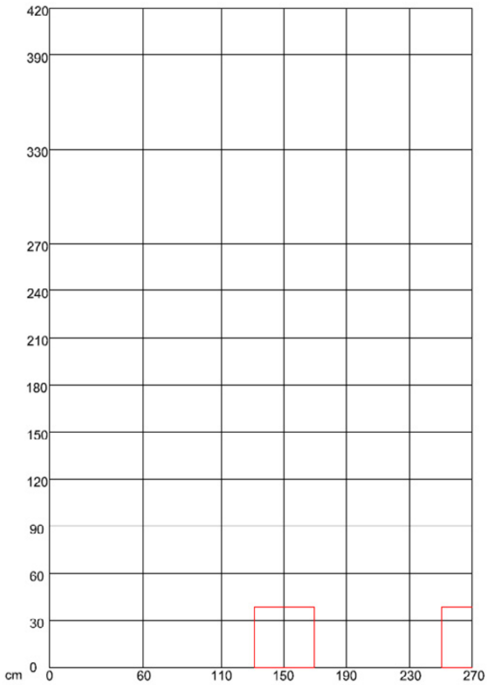

Fig. 2. Mesh size in JPCP model

After the input phase, Kenslabs runs and calculates stresses due to thermal and traffic condition on concrete slabs.

All output text files are stored and automatically examined by ESC. The code extrapolates stress in the critical node for each file, so it's possible to evaluate structural and functional level of service of concrete pavement hour by hour in the four season and year by year. Distress models used in this analysis are: cracking model by AASHTO Guide 2002, joint faulting model by SHRP model (that appear the most severe in literature) and IRI model by AASHTO Guide 2002. All indexes are calibrated to 90% of reliability. Fatigue damage is calculate year by year with Darter's and Miner's laws.

This analysis allows to define maintenance plan during the overall pavement service life and calculate discounted maintenance costs, assuming the inflation rate [15]. Strategies of preventive maintenance schedule joint sealing and full depth repair (to restore potholes). Rehabilitation strategies of corrective maintenance schedule diamond grinding to correct roughness and full depth repair to restore slabs cracked [16] [17].

Each maintenance work cost is discounted back to its present value (PV). Then their sum plus construction costs is the Net Present Value of project.

3. Case study

Three exposed aggregate JPCP highways concrete pavements listed in the Italian catalogue of road pavements has been verified. For each pavement type, concrete slabs 24 cm, 26 cm and 27 cm thick with double subbase, cement-treated layer 15 cm thick and unbonded granular mix layer 15 cm thick were analyzed; subgrade resilient modulus is equal to 90 MPa. Compressive R_{ck} is 55 MPa; modulus of rupture (MOR) is calculated with formula proposed in software package VENCON2.0; it's expressed by (8) [18].

$$MOR = 1.3 \cdot [(1600 - h)/1000] \cdot [1.05 + 0.05 \cdot (R_{ck} + 8)]/1.2 \tag{8}$$

where h is the thickness of the concrete slab in mm.

The annual increase of concrete strength during service life has been considered. Single concrete slabs were 540 cm long and 420 cm large. Pavement has 40-years design life.

All examined pavements are fatigue tested: fatigue damage (FD) is less than 1 at the end of service life, after 40 years, as can be seen in Table 2.

Table 1. Fatigue Damage

Slab thickness (cm)	FD (-)
24	1.77E-01
26	5.70E-01
27	2.70E-01

Table 2 shows transverse cracking, joint faulting and IRI thresholds.

Table 2. Threshold value distresses

Transverse cracking (%)	10
Joint faulting (mm)	4
IRI (m/km)	2.5

The AASHTO Guide 2002 equation has been used to calculate cracking [19]; the SHRP P-020 Faulting model for JPCP with dowels has been used to calculate joint faulting [20]; the AASHTO Guide 2002 equation has been used to calculate IRI [19].

Corrective maintenance results to be necessary at the years shown is Table 3, as it results in Fig. 3, 4 and 5.

Table 3. Year when threshold limit is achieved

Slab thickness (cm)	Year when threshold limit is achieved (year)		
	Transverse cracking	Joint faulting	IRI
24	13	31	>40
26	17	33	>40
27	25	36	>40

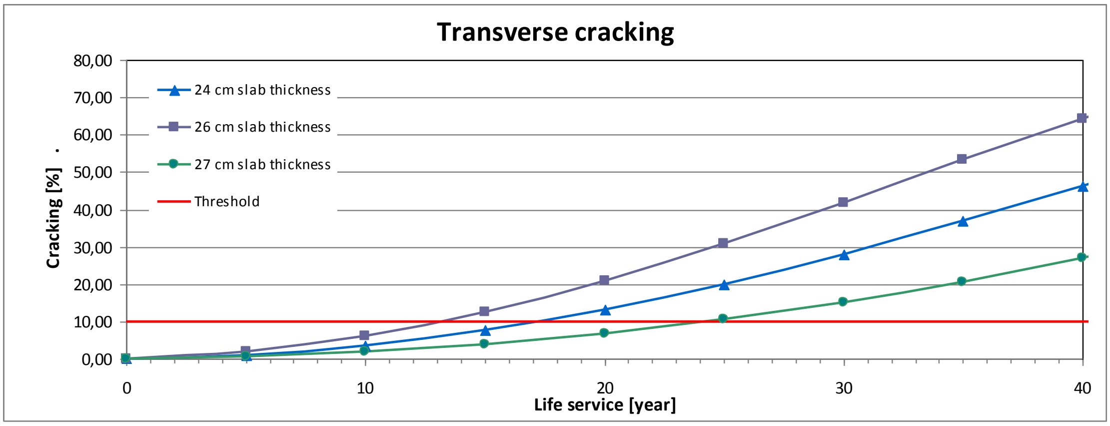

Fig. 3. Transverse cracking development

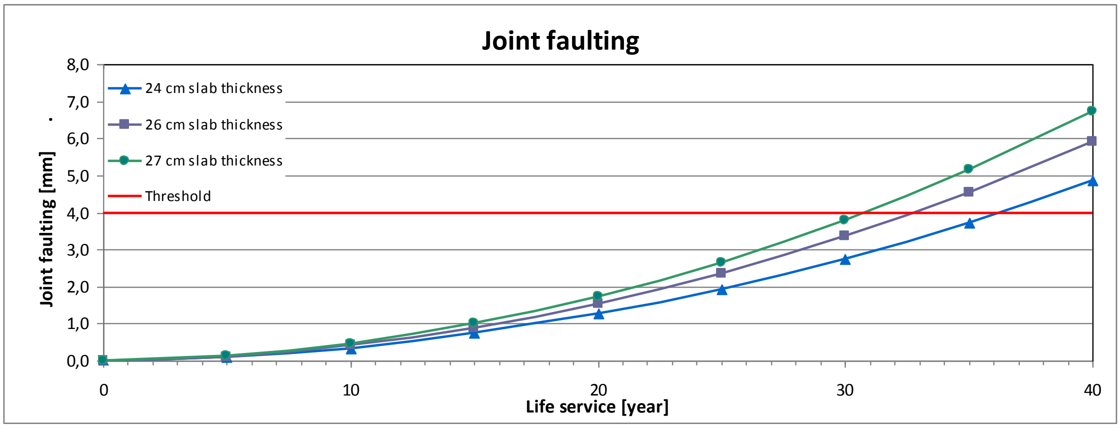

Fig. 4. Joint faulting development

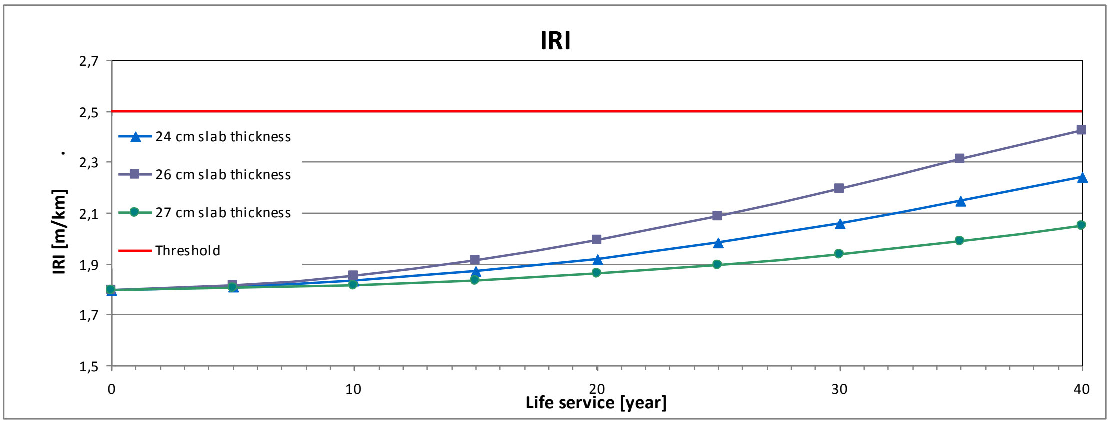

Fig. 5. IRI development

Construction costs are listed in Table 4.

Table 4 Construction costs (C_C)

Slab thickness (cm)	**CC (€/m^2)**
24	60.2
26	62.3
27	63.4

Maintenance strategies defined for these pavements are listed in Table 5. Preventive actions are carried out at a set time interval, as suggested in literature, while corrective actions are planned as calculated by ESC.

Table 5 Preventive (P) and corrective (C) maintenance

Type of maintenance	**Work**	**Year**	**Quantity**		**Slabs thickness (cm)**		
					24	**26**	**27**
P	Joint sealing	10	100%	Total joint length	X	X	X
P	Full depth patching	10	2%	Total area	X	X	X
C	Full depth patching	13	8%	Total area	X		
P	Joint sealing	15	60%	Total joint length	X	X	X
C	Full depth patching	17	8%	Total area		X	
P	Joint sealing	20	60%	Total joint length	X	X	X
P	Full depth patching	20	2%	Total area	X	X	X
C	Full depth patching	25	8%	Total area			X
P	Joint sealing	25	60%	Total joint length	X	X	X
P	Joint sealing	30	60%	Total joint length	X	X	X
P	Full depth patching	30	2%	Total area	X	X	X
C	Repair faulted joints	31	100%	Faulted joints	X		
C	Repair faulted joints	33	100%	Faulted joints		X	
P	Joint sealing	35	60%	Total joint length	X	X	X
C	Repair faulted joints	36	100%	Faulted joints			X

Nominal maintenance costs are calculated knowing type, extension and timetable of work, as expresses by (9).

$$C_x = C_0(1+i)^x \tag{9}$$

where C_x is the maintenance cost incurred in year x; C_0 is the maintenance cost at construction year; i is the annual inflation rate equal to 3%, average value of the eighteen last years in Italy [21]; x is the time in the future in years. Fig. 7. shows cumulated nominal costs during design life.

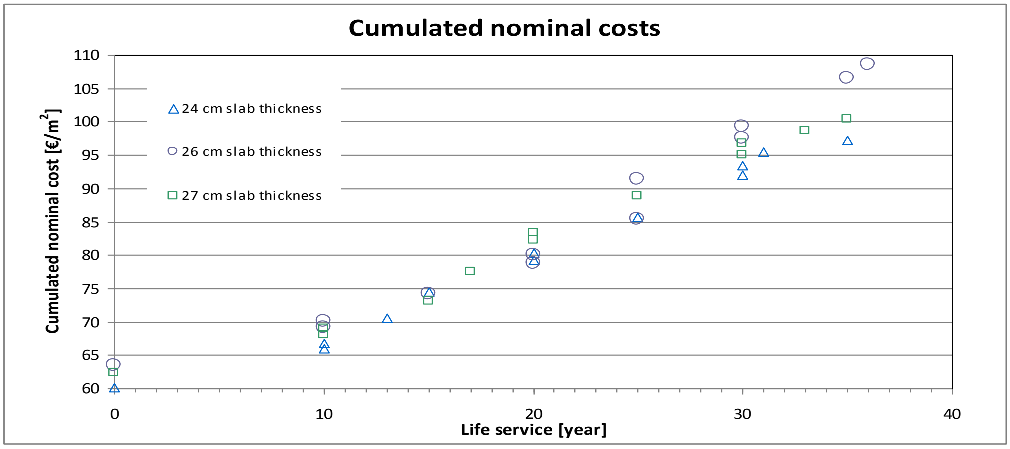

Fig. 6. Cumulated nominal costs

Actual maintenance costs are calculated as expressed by (10):

$$C_{A,x} = \frac{C_x}{(1+r)^x} \tag{10}$$

where C_A is the maintenance cost discounted at construction year x; r is the annual discount rate equal to 4% (the risk premium for the investment is equal to 1%) [22] and [23].

The Present Value of this series of costs is calculated as expressed by (11):

$$NPV = C_C + \sum_{x=1}^{N} C_{A,x} \tag{11}$$

where C_C is construction cost incurred in year 0 and N is the number of years in the analysis period.

Table 6 shows the NPV obtained, expressed in terms of euro/m^2.

Table 6 NPV of pavement investment

Slab thickness (cm)	NPV (€/m^2)
24	77.9
26	80.3
27	81.2

Results obtained are comparable with values in literature: concrete pavements are more expensive initially, but need limited work maintenance, so are economically competitive versus other solutions, as bituminous pavements.

4. Conclusions

The structural and functional characteristics of concrete pavements have been verified by automatic procedure implemented in VBA and using Kenslabs as solver software. The procedure defines pavement management system during service life and calculate the Net Present Value (NPV) of project solution. The foregoing discussion has attempted to make available a quick and user-friendly instrument to estimate total costs in concrete pavements: the procedure is a forward-looking decision framework that assess life time costs rather than only initial construction costs. The new approach should be used to evaluate economic and technical sustainability of JPCP and compare results with other types of pavement.

The current study has practical implications as well. The model is user-friendly and simple and it could be a valid tool for designers and decision-makers. The instruments allows to analyze life cycle cost of concrete pavements, an economic analysis procedure that compares alternative considering all construction, maintenance and rehabilitation costs.

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