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Evaluation and Modeling of Flexible Pavement Behavior in Morocco: Crack Initiation Model

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Abstract

The most common degradations encountered on the Moroccan network are cracking, rutting, longitudinal evenness, and stripping. Of these four degradations, the last three tend to develop progressively over time. For cracking, the situation is quite different. The first occurrence of this deterioration can only appear when the pavement has been in service for a certain number of years. In this initiation phase of deterioration, cracking first occurs at the bottom of the lower layers. Over time, fatigue cracks initiated below the bound layers propagate upward, and eventually become apparent on the pavement surface. Only from the above can they be observed during inspections. The purpose of this study is to propose a crack initiation model, in order to be aware of structural problems much earlier, and to prevent the crack from reaching the pavement surface.

Keywords

Pavement distress, Nanotechnologies, Cracking, Behavioral laws, Pavement maintenance

Introduction

Knowing the typical behavior of Moroccan pavements and their evolution over time, according to their structures, traffic, climate, and soil type is a fundamental data for the rational and objective management of the road network [1].

Indeed, the planning of the maintenance operations of this network and their investment needs which results from the technico-economic evolution of several maintenance scenarios and the choice of the best intervention strategy, requires a mastery of the laws of evolution of the Moroccan pavements deterioration [2].

Unfortunately, the techniques, materials and processes used in road construction today have certain limitations. Hence the need to develop innovative design techniques and use new materials incorporating nanotechnologies in order to develop processes that are not only more efficient and cost-effective, but also more sustainable.

The natural approach to define these behavioral laws is to choose a representative sample of new road sections and to follow the real evolution of distresses year by year until the final stage [3]. However, the urgent need to know, at least in an approximate way, a sketch of the evolution curves of the distresses led us to adopt a transversal approach.

The hypothesis of this approach is that sections with the same structure, on the same soil, in the same climate and with the same traffic should have the same behavior. Thus, it is possible to establish the representative curves of the evolution of the deterioration as a function of time, just by measuring the deterioration for all the sections in the same year. For this purpose, two approaches have been adopted: The first approach adopted for the monitoring of the control sections was based on a typology integrating the criteria of traffic, climate, and pavement type. However, the difficulty of understanding the behavior of pavements led us to adopt a second approach based on the same soil, in the same climate conditions and on which the same traffic circulates, should theoretically have the same behavior [4].

In this optic, we have established a sample of 80 control sections of 1km length each and an average width of 6m approximately, to follow the real evolution of the degradations according to their ages on the whole road network which constitutes a linear of 45,354 km.

Materials and Method

Statistical study

Pavement distresses are generally characterized by a condition indicator that evolves continuously over time. For example, the cracking rate for the variable crack. The present work consists in modeling this indicator, i.e., in identifying a mathematical, deterministic, or probabilistic relationship between the level of this indicator and the age of the pavement [5, 6]. The variables that condition the evolution of the deterioration, such as the climate, the nature of the soil, the volume, and the aggressiveness of the traffic [7], are known as explanatory variables and must be taken into account in the modeling. Figure 1 shows the general form of the development of cracking.

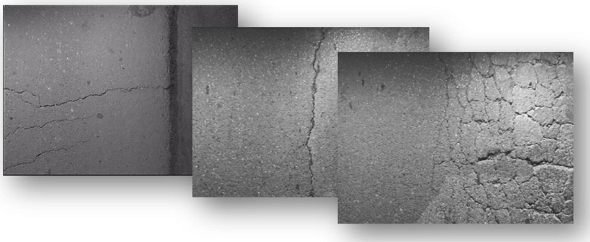

Figure 1: General form of crack development N1-140C.

The database

The database used in this study consists of annual damage records for each section of the roads considered in the sample [8]. We have a total of 80 sections. These sections are called Test Sections. These sections have a length of 1000 m and an average width of about 6 m.

It should be noted that the sections are chosen to cover the entire Moroccan road network according to climate, traffic class, soil type and pavement structure [9].

At the beginning of the selection, the climate criterion is set, i.e., arid, or non-arid zone. Once the zone is chosen, we consider the traffic class, i.e., heavy traffic, and then we consider the soil condition.

The 80 selected road sections were divided into the following main structure classes:

- BL + PC + RS + GNT + EB
- BL + PC + RS + GBB + EB
- BL + PC + RS +GNT + RS
- GNT + GBB + EB
- BL + PC + RS + EB
- BL + PC + RS
- GNT + RS

Where GNT (Untreated gravel), GBB (Gravel asphalt), EB (asphalt mix), RS (Superficial Coating), BL (Blocking), and PC (Broken stone) (Figure 2).

Figure 2: State of the deteriorations of Moroccan flexible road pavement, GNT + GBB + EB, GNT + RS.

Theoretical framework of the study

For this study, the statistical method for modeling pavement behavior is the statistical regression method [10, 11].

The regression method and the class method assume a priori that the state indicator follows a well-given functional form, and the validity of the functional form is obtained by determining the mean of the squares of the errors [12, 13]. Of these two assumptions, the one that best fits the data is the one with the smaller Mean. The determination of the functional form, is made under the following assumptions:

Regularity assumption

Let's ask:

$I_{j(t)}$: the value that the indicator takes on section j of a given structure at age **t**.
Id: the value of the indicator at construction.
If: the value of the indicator at the point of failure.

When the indicator reaches the value **If** we can consider that the pavement condition is bad.
The evolution law of cracking for pavement number j is given by the following relationship:

$$\mathbf{I_{j(t)} = Id + K_{j(t)} [If - Id]}$$

With **$K_{j(t)}$** an increasing function with values in the interval [0 ,1] called **"evolution coefficient".**

In order to know the evolution law, it is therefore necessary to estimate **$K_{j(t)}$**. Fortunately, there are many mathematical functions that verify the regularity hypothesis. Several studies have shown that the linear, exponential, and sigmoid functions are part of this set and are the most suitable for our study. The following table gives the mathematical formulation of **$K_{j(t)}$** (Table 1).

Table 1: Mathematical formulation without robustness assumption.

Model shape	Application cases	Mathematical formulation
Linear	Constant deterioration up to a time t_{dj} (possibly zero) and varying linearly thereafter.	$K_j(t) = \frac{1}{p_j * t_{dj}}(t - t_{dj})$ si $t \in [t_{dj}; t_{fj}]$ $K_j = 0$ si $t \le t_{dj}$ $K_j = 1$ si $t \ge t_{fj}$
Exponential	Deterioration equal during a certain time to a known value V_d then varying with a decreasing speed until a known value V_f towards which it tends asymptotically.	$K_j(t) = 0$ si $t < t_{dj}$ $K_j(t) = 1 - (\frac{t_{dj}}{t})^{p_j}$ si $t \ge t_{dj}$
Sigmoid	Deterioration varying from a known value, V_d, which it leaves at the time t = 0 with a zero speed, to a known value V_f towards which it tends asymptotically.	$K_j(t) = \frac{t^{p_j}}{t_m^{p_j} + t^{p_j}}$

Note: $\mathbf{t_{dj}}$ is the age of onset of degradation; in other words, it is the age at which the coefficient $\mathbf{K_j}$ begins to evolve. $\mathbf{t_{mj}}$ is the age at which $\mathbf{K_j}$ reaches the median value for sigmoid laws and $\mathbf{p_j}$ is a shape parameter of the evolution curve.

Robustness assumption

It says that when one section evolves faster than another at a specific age; it will continue to evolve faster than this one at later ages. This implies that $\mathbf{p_j}$ is a constant $\mathbf{p_0}$ for all sections.

Centering assumption

Let us consider all the pavements of a given structure. We call the **"average section with respect to indicator I"** the section such that on 50% of the sections of this structure the coefficient **K** evolves faster than on this average section.

Let $\mathbf{t_{dm}}$ be the age of onset of degradation for the average section and $\mathbf{t_{mm}}$ the age at which this section reaches an average evolution. Thus, we define the notion of robustness by the ratios in the second column of table 2.

Assuming that the law of evolution of the degradation is an exponential, we have:

$$Kj(t) = 1 - \frac{1}{q_{0j} * t^{p_{0j}}}$$

$$\mathbf{-log[1- Kj(t)] = log\, q_{0j} + p_{0j}\, log\, (t)}$$

Having at least three observations for each section; we use the Linear Regression option of SPSS software to determine

Table 2: Mathematical formulation with robustness assumption.

Model shape	Robustness of the Sj section	Mathematical formulation
Linear	$R_j = (\frac{t_{dj}}{t_{dm}}) = q_{0m} * t_{dj}$	$Kj(t) = \frac{q_{0m}}{p_0 R_j} t - \frac{1}{p_0}$ si $t \ge t_{dj}$ $Kj(t) = 0$ si $t \le t_{dj}$ $t_{dj} = (\frac{R_j}{q_{0m}})$
Exponential	$Kj(t) = 1 - \frac{R_j}{q_{0m} * t^{p}}$ si $t \ge t_{dj}$	$Kj(t) = 1 - \frac{R_j}{q_{0m} * t^{p}}$ si $t \ge t_{dj}$ $Kj(t) = 0$ si $t \le t_{dj}$ $t_{dj} = (\frac{R_j}{q_{0m}})^{\frac{1}{p}}$
Sigmoid	$R_j = (\frac{t_{mj}}{t_m})^{p_0} = \frac{(t_{mj})^{p_0}}{q_{0m}}$	$Kj(t) = \frac{t^{p}}{Rjq_0 t^{p}}$

the parameters $\mathbf{p_{0j}}$ and $\mathbf{q_{0j}}$.

If there are sections that have approximately the same coefficient p_{0j} then the robustness assumption is verified, and these sections then form a family. "A family is a set of sections that have virtually the same behavior under the influence of the same explanatory variables and verify the robustness and centering assumptions".

The inclusion of the explanatory variables is done under the assumption that the influence of the explanatory variables on the sections of the family is expressed through the coefficient $\mathbf{q_{0j}}$ by the following relation:

$$q_{0j} = e^{a0} \cdot \prod_{i=1}^{N} v_j^{\,a_i}$$

With $\mathbf{V_{ij}}$ the value that variable **i** takes for section **j**. N is the total number of explanatory variables.

Since we cannot identify all the explanatory variables, we are obliged to estimate the coefficients $\mathbf{q_{0j}}$ by the relation:

$$\log(q_{0j}) = a_0 + \sum_{i=1}^{n} a_i . \log(v_j) + \log(Q_j)$$

With log$(\mathbf{Q_j})$ the error committed in estimating the coefficients.

Once estimated the $\mathbf{q_j}$ and the $\mathbf{Q_j}$ the law of evolution of the degradation is summarized by the following model:

$$\mathrm{K_j(t) = 1 - \frac{R_j}{q_{0m}\, t^{p_0}}} \quad \text{Si} \quad \mathrm{t \geq t_{jd}}$$

$$\mathrm{K_j(t) = 0} \quad \text{si} \quad \mathrm{t \leq t_{jd}}$$

$$t_{jd} = \left(\frac{1}{q_{0j}}\right)^{\frac{1}{p_0}} \quad \text{et} \quad q_{0m} = e^{a_0} \prod_{i=1}^{n} v_{im}^{\;a}$$

$$R_j = R_j * R_{2j} \qquad R_{1j} = \prod_{i=1}^{n} \left(\frac{v_j}{v_{im}}\right)^{a_i} \quad \text{et} \quad R_{2j} = \frac{Q_j}{Q_m}$$

Results and Discussion

Modeling of cracking

Of the 80 Flexible Pavement sections, only 29 have at least three observations on cracking rates. For each section, we should normally have six readings [14]. Among these 29 considered pavements, we could not estimate the parameters $\mathbf{p_{0j}}$ and $\mathbf{q_{0j}}$ for 6 sections. The hypothesis of the nullity of the coefficients $\mathbf{p_{0j}}$ and $\mathbf{q_{0j}}$ being verified for the latter. The analysis was therefore carried out in 23 sections. On these sections we have distinguished 4 families, i.e., 4 groups within which the parameter p_{0j} is constant. We have considered 30% as the final value that the state indicator can take (**If = 30%**), and 0% for the value at construction (**Id = 0%**) (Table 3).

Table 3: Families obtained for cracking.

Family	P_0	Number of sections
A	0.032	3
B	0.024	2
C	0.056	4
D	0.112	4

$\mathbf{p_0}$ represents the average of the $\mathbf{p_{0j}}$ of the family. This average does not deviate too much from the $\mathbf{p_{0j}}$ since they are almost the same. The other sections have differently varying $\mathbf{p_{0j}}$ and were analyzed individually.

Sections of family A with $p_0 = 0.032$

All sections in family A are located in a non-arid zone. An application of the regression method with consideration of explanatory variables shows that structure does not explain cracking (Table 4).

Table 4: Sections of family A.

Section	Soil	Age of onset (years)	$K_{j(t)}$ after 10 years	Cracking rate
1	S1	5.07	0.0136	0.41%
2	S0	5.75	0.0176	0.53%
3	S0	0.3	0.1035	3.11%

After the analysis and the interpretation of the results, we noticed that the evolution curve highlights the age of appearance of the cracking and the parallelism of the curves confirms that these sections belong to the same family. We note that section n°3 evolves faster than the two others. The cracks on this section appear after one year of construction. The better the soil condition, the less quickly the cracking evolves.

Moreover, the truncation error Qj is practically equal to 1, which means that the explanatory variables retained are not very influential.

Sections of family B with $p_0 = 0.024$

Family B is composed of only 2 sections and for one of these sections, we do not have values on the structure index and the soil index.

We will, therefore, study these two structures without taking into account the explanatory variables, which have been found to have little influence in previous studies. The estimated parameters are given in table 5.

Table 5: Family B sections.

Section	Traffic	Age of onset (years)	$K_{j(t)}$ after 10 years	Cracking rate
1	T2	5.74	0.0134	0.40%
2	T4	2.27	0.0356	1.07%

We note that the cracking rate after ten years is 1.07% for section n°2 and 0.4% for section n°1. The age of appearance of cracks on the latter is less than the first. This could be explained by the fact that the second section has a high traffic volume while the first one has a medium traffic volume.

Sections of family C with p_0 = 0.056

There are four pavements in family C, three of which are in a non-arid zone. These are sections 1, 2 and 3. Only section 4 is in a dry zone. They are built on different soils. The analysis of the evolution curves showed that the parallelism of these curves only confirms the robustness hypothesis. The age of appearance of cracks on most pavements is about 7 years after construction. However, it is one year for section n°4 and the cracking evolves faster on this section than on the others. After ten years of use, the cracking rate on this section is 3.93% while it is less than 1% on the others.

And yet section 4 is built on better soil. This rapid evolution can be explained by the fact that the thickness given by the Structural Number (SN) is the lowest, namely 1.56.

After the analysis and interpretation of the results, we also noted that the curves of evolution of pavements 2 and 4 are the same, they are confused on the graph. However, these pavements have different thicknesses and do not support the same traffic. Note that they are located in the same non-arid climatic zone (Table 6).

Table 6: Sections of family C.

Section	Soil	Age of onset (years)	$K_{j(t)}$ after 10 years	Cracking rate
1	S2	6.39	0.0246	0.74%
2	S0	7.38	0.0324	0.97%
3	S3	1	0.1308	3.93%
4	S1	7.38	0.0323	0.97%

The truncation error Qj is practically equal to 1, which means that the explanatory variables selected are not very influential.

Sections of family D with p_0 = 0.112

The average section in family D is section n°3. The age of appearance of cracks on this section is one year after construction, it is the smallest. However, the cracks appear 8 years after the construction of the section n°4 and evolve very quickly. The table below shows us that only two years after this appearance, the cracking rate reaches 11.74% which is not at all negligible. This behavior can be explained by the fact that it is built on a bad soil. The other sections are located in the same climatic zone, i.e., a non-arid zone, therefore we can roughly consider that the influence of this variable is the same on these sections. The difference in age of onset and evolution of the crack would likely come from other explanatory variables. However, it should be noted that the variables we have at our disposal have little influence because the truncation error is 1. Finally, it should be noted that the cracking evolves very quickly in this family (Table 7).

Table 7: Family D sections.

Section	Soil	Age of onset (years)	$K_{j(t)}$ after 10 years	Cracking rate
1	S4	4.45	0.35	10.40%
2	S2	2.61	0.31	9.42%
3	S3	1	0.23	6.83%
4	S1	8.34	0.39	11.74%

Other sections

For the other sections, the robustness hypothesis is not verified. We have only taken into account the assumption of regularity. Obtained parameters are presented in table 8.

Table 8: Other sections cracking.

GNT + RS	q_{0j}	p_{0j}	Age of onset (years)
2	1	0.0005	0.07
5	0.81	0.1316	4.74
12	0.98	0.0253	2.21
15	1	0.0045	1
BL + PC + RS	p_{0j}	q_{0j}	t_{dj}
7	0.016	1	1
BL + PC + RS + EB	q_{0j}	p_{0j}	t_{dj}
1	0.20	0.55	18.69
4	0.0051	2.24	9.95
BL+PC+RS+GNT+RS	q_{0j}	p_{0j}	t_{dj}
7	0.15	1.05	5.93
2	1	0.82	1
1	1	0.0023	1

We calculated the average of the squares of the differences between the observations made on the sections and those estimated by the regression method considering the exponential form and we find 0.20%. Since the error is very small, we validated the exponential model.

Data analysis

The analysis of the evolution curves of the established cracks allows us to draw the main observations quoted in the table below concerning the age of appearance of the degradations and the % of the degradations after a few years of commissioning (Table 9).

The analysis of the different degradations observed on the sample of selected sections shows that, in general, their amplification is only noticed after **10** years of operation of the road.

Cracks, which are generally the consequence of a drop in the bearing capacity of the pavement or of its ageing, appear much more quickly for roads reinforced with GBB + EB.

Table 9: Evolution of cracks.

Families of pavement structures	Age of onset (years)	% Degradation after 8 years of operation
GNT + RS	2 years	4.79%
BL + PC + RS + GNT + RS	4 years old	0.23%
BL + RS + GNT + RS	6 years old	2.50%
BL + PC + RS + GBB + EB	3 years	8%
GNT + GBB + EB	2 years	6%
GNT + RS + EB	6 years old	0.17%
BL + PC + RS	3 years	0.24%

Table 10: Equations for the evolution of cracks.

Families of pavement structures	Mathematical equations for the evolution of cracks
GNT + RS	$Y = -0.003 X^4 + 0.066X^3 - 0.4327 X^2 + 1.5236 X - 1.7728$
BL + PC + RS + GNT + RS	$Y = 0.000166X^3 + 0.0076X^2 - 0.0532X + 0.08764$
BL + RS + GNT + RS	$Y = +0.0099X^3 - 0.114X^2 + 0.795X - 3.084$
BL + PC + RS + GBB + EB	$Y = 0.0446X^5 - 1.5398X^4 + 20.9605X^3 - 140.4128X^2 + 462.98X - 597.687$
GNT + GBB + EB	$Y = -0.128X^3 + 1.638X^2 - 3.028X + 4.531$
GNT + RS + EB	$Y = -0.0109X^4 + 0.3628X^3 - 4.4891X^2 + 24.491X - 49.585$
BL + PC + RS	$Y = -0.00011X^4 + 0.0027X^3 - 0.01259X^2 + 0.0123X + 0.0185$

The interpretation of the curves of evolution of the degradations also made it possible to bring out mathematical equations of polynomial form. The correlation coefficients (R^2) are higher than 96% for all the equations. These equations, for which 'X' indicates the number of years of service after the last intervention and 'Y' indicates the rate of degradation corresponding to the age X, are summarized in table 10.

Conclusions

The modelling of the cracks consisted in determining the time of appearance of the very first crack and also the evolution of this degradation in time. These parameters will be used for the calibration of the HDM4 model. From all the above, it was concluded that:

- In order to get good results, it is important to ensure that reliable data on good statistical variables are obtained. The relevance, accuracy and reliability of the model depend greatly on the characteristics of the database. The more accurate, rich, and representative the data and the more rigorous the analysis method, the more accurate and reliable the model will be.
- In addition, the approach used to monitor sections that include the structure does not provide a good understanding of pavement behavior. Indeed, the pavement behavior is largely explained by the last maintenance structure and not by the whole structure.
- We then recommend the following approach based on soil, climate, traffic and the last maintenance or reinforcement operation.
- The judicious application of nanotechnologies in roads and transport is currently proving very promising, with the potential to contribute to characterizing and improving the performance of road construction materials, which could ultimately lead to an extension of their life cycle and a significant improvement in their performance levels leading to greater resistance to permanent deformation [15, 16]. Not to mention the significant improvements in comfort, safety and economy that will make roads smarter, stronger, more durable and more efficient [17].

In sum, we can say that the statistical laws determined are only provisional, they would be definitive when the database is representative with many observations and enriched with explanatory variables. However, since the research is only at its beginning, it is necessary to continue the follow-up of the sections in order to be able to establish real and definitive laws of the evolution of their state according to time.

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Conflict of Interest

Authors declare no conflict of interest.

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