# Assessment of Top-Down Cracking Causes in Asphalt Pavements

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ABSTRACT: Cracks observed at the surface may have several origins and causes. A crack may either begin at the bottom or at the top of an asphalt layer. Cracking originated at the top of asphalt layers (top-down cracking) observed in temperate-climate countries is a degradation mechanism which has not been fully researched. In order to access this "new" degradation in Portugal, a sampling plan has been set in a high thickness pavement, including the extraction of cylindrical cores and slabs. Cracks were carefully identified and several laboratory tests were performed on grading, bitumen content and air voids, fatigue strength and stiffness. Pavement bearing capacity was also measured. The assessment and comparison of the results show, in a first approach, that all cracks are surface-originated and top layers contains excessive fine aggregates and voids. A second approach concerning modulus, fatigue strength and bearing capacity is less conclusive, which leaves a long way to go. Nevertheless, it seems that construction quality continues to be the most probable cause of top-down cracking.

KEY WORDS: Top-down cracking, modulus, fatigue, deflection, construction quality.

## 1. INTRODUCTION

Top-down cracking (TDC) is a deterioration mechanism that has been identified in temperate-climate countries. However, it is far from being completely controlled. Its causes are not sufficiently known, and studies undertaken until now do not converge. Climatic conditions, traffic, ageing, structure and construction quality are the main causes pointed out for the initiation and propagation of TDC.

This paper describes phase two of a study that intends to characterize the initiation and the progression of TDC on a thick, highly trafficked road in the north of Portugal. Phase one provided detailed characterisation of this kind of cracking, and researched the cause-effect relations between material physical properties, traffic and TDC. This phase was aimed at researching cause-effect relations between TDC and layers modulus, fatigue cracking. In addition, one had to verify whether TDC influences deflection basins and, consequently, global strength.

Differences between modulus either between layers do not seem to be a cause in this mechanism.

It is shown that TDC does not decrease global strength, but there is still the possibility of the deflection basin being responsible for crack progression, since fatigue does not seem to be a cause of the initiation mechanism.

As results are not conclusive, more research must be done, based on accelerated loading tests, where construction quality parameters regarding grading, aggregate type, voids content, amongst others, may be controlled to better understand isolated effects. Ageing is another possible cause that should be studied. Numerical simulations should also be performed in order to study the combined effect of each cause.

## 2. BACKGROUNG

### 2.1. Top-down cracking location

TDC has been recorded on roads with a wide range of thickness and age, under diverse climatic conditions, such as hot or high rainfall areas, subjected to intense heavy vehicle volume roads.

It may be found either in the wheel path (Matsuno et al., 1992) or out of it (Svasdisant et al., 2002). Its initiation age has been registered at 1 to 5 years in Japan, 3 to 5 years in France, 3 to 8 years in Washington State, 5 to 10 years in Florida and 10 years in the United Kingdom (Matsuno et al., 1992; Myers, 2000, Uhlmeyer et al., 2000).

### 2.2. Top-down cracking initiation and progression mechanisms

According to Svasdisant et al. (2002), initiation and progression of TDC follows three stages. The first stage consists of a single short longitudinal crack appearing just outside the wheel path. Over time, sister cracks develop 0.3 to 1 m parallel to the original crack. Finally, cracking evolves into a third stage, where the parallel cracks are connected via short transversal cracks.

Firstly, researchers claimed that high tensile contact stresses generated on the road surface close to the tyre edges, cause the appearance of small cracks. Before ageing, some of these small cracks may disappear by the kneading action of the tyres and the healing effect of asphalt, while surface stiffness is low as a result of high temperature. When temperature decreases (daily or seasonally), the surface contracts and the remaining cracks set, thus becoming top-down cracking (Matsuno et al., 1992).

Some laboratory tests were also undertaken by CROW and LCPC. The first sustains that only a combination of high dissipation energy at the surface, shear stresses, temperature induced stresses and residual stresses could cause cracking at the surface (CROW, 1990). The second relates the TDC evolution rate with factors that promote asphalt ageing (high temperature, high voids rate and low binder content) and bitumen fragility, contraction and fatigue (low temperature, high daily temperature amplitude) (LCPC, 1999).

The latest studies indicate that construction quality regarding gradation, segregation, compaction and mixture spreading contribute considerably the initiation of TDC (Uhlmeyer et al., 2000; Myers et al., 2001; Freitas et al., 2002 and Svasdisant et al., 2002).

According to Matsuno et al. (1992), TDC progression relies on traffic stresses distribution inside pavements, which is significantly important at crack tips, when temperature is high or stiffness is low.

Groenendijk (1998) argues that crack propagation of surface cracks will occur mainly in shear mode. Yielding due to shear stresses (with all principal stresses being compressive, although not of equal magnitude) could result in shearing cracks (yield planes), as a consequence of the introduction of secondary tensile stresses.

Matsuno's theory was developed by Myers (2000), who has concentrated his research on load spectra (magnitude and position) and stiffness gradient, either due to differential temperature or ageing (Figure 1).

At about the same time, Merril demonstrated numerically that the mechanism of thermal contraction could propagate a crack more deeply into the asphalt layer than tyre stresses alone, considering the temperature range between -20ºC and +40ºC (Merril, 2000).

Recently, Svasdisant et al. (2002) assembles these theories and adds a new factor. This author defends that TDC is caused by high tensile stresses due to traffic loading, temperature gradients, binder ageing and construction quality (materials, compaction and paving).

Early, many of the pointed causes have been addressed by Alim et al. (1996), such as relative rigidity, compaction and thermal stresses, which also includes road geometry as a factor that intervenes in cracking shape and pattern.

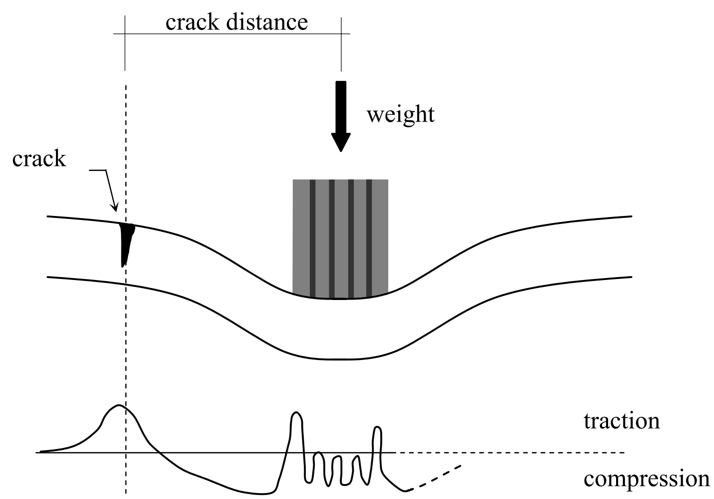


Figure 1: Structure bending due to traffic weight and resulting stresses (adapted from Myers, 2000)

## 2.3. Top-down crack characterization

Top-down cracks may be characterized according to location, depth, direction and speed propagation.

Top-down type cracking may be longitudinal, transversal, oblique, star shaped, in block or even alligator cracking and may be found either in or out of the wheel path (Freitas et al., 2002). Crack depth ranges from a few millimetres to the total thickness (Myers, 2000 and Uhlmeyer et al., 2000). Theoretically, progression stops at a 15 cm depth (Merril, 2000) for pavements with 19 cm of bituminous layers. However, deeper cracks (19 cm) have been found in pavements with a higher total thickness of bituminous layers (Freitas et al., 2002).

Cracks propagate perpendicularly to principal stresses. For short cracks, propagation is driven purely by tension and they progress straight down into the pavement. At intermediate depths, cracks change direction, since the state of stress in the asphalt layer change with depth (Myers, 2000).

Progression speed depends on crack length, asphalt layer thickness and grading. Progression speed is very slow when crack lengths range between 0,625mm and 18,750 cm (Myers, 2000). It increases with pavement thickness (Myers et al., 2001) and with course grading (Komoriya et al., 2001).

## 3. CASE STUDY

### 3.1. Procedure

In order to undertaken research regarding the TDC phenomenon in flexible pavements, in Portugal, a sampling plan was set up on a 7 km stretch of a 20 km motorway, aged 9 years. The asphalt layer depth is 30 cm (6+6+9+9). Forty-five cylindrical cores were extracted from cracked areas both in and out of the wheel path. Eight 80×80 cm slabs were extracted, six of these as near as possible from areas revealing longitudinal, transversal and oblique cracks and two (slab 4 and 6) from undamaged areas. Crack position, lengths and orientation were measured.

As far as the wearing course and base layer are concerned, several laboratory tests were performed on fatigue strength, stiffness, grading, bitumen content and air voids. In addition, the pavement bearing capacity was measured at 100 metre intervals.

This procedure will allow for the identification of cracking origin as well as the establishment of relations between traffic, crack length and location.

The assessment and comparison of each asphalt layer strength, as well as global strength, characterized by bearing capacity, will allow for the research of a restricted group of causes.

### 3.2. Visual characterization (surface and cracks)

After thoroughly surveying surface and cores, some points can be highlighted (Figure 2):

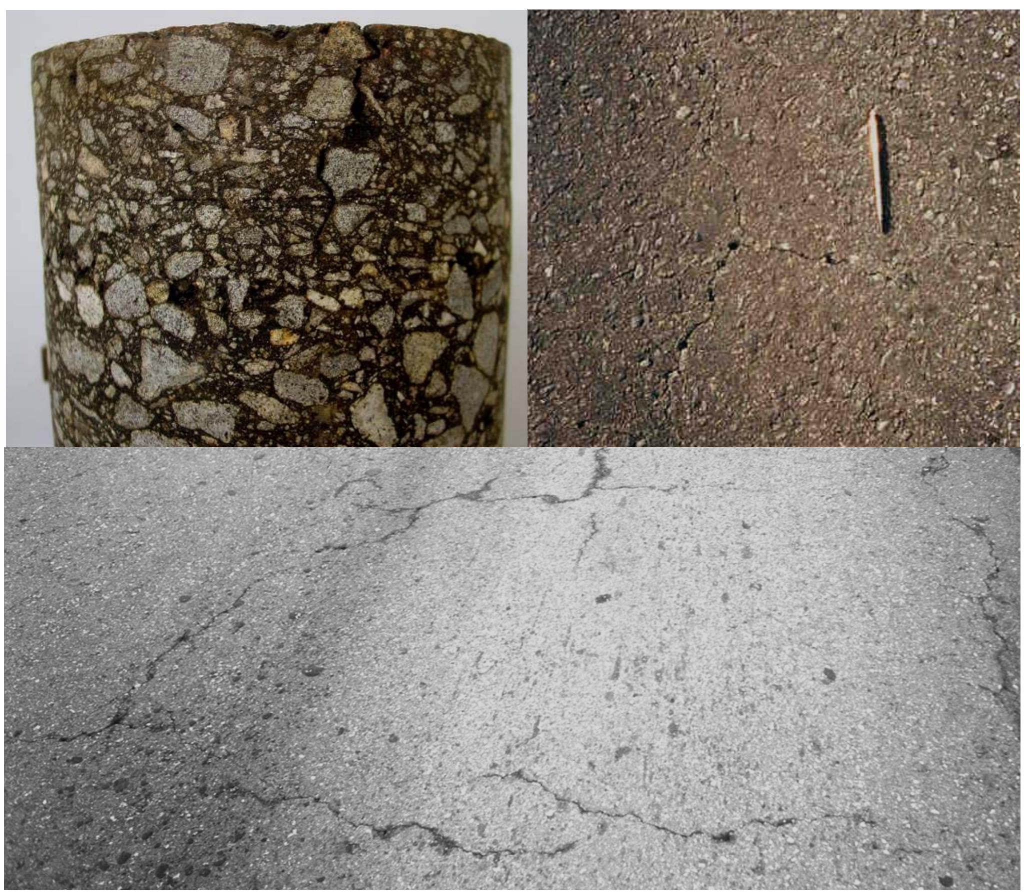

Figure 2: Different views of top-down cracking (Freitas, 2002)

i) TDC is the main degradation;
ii) cracked areas are rougher due to segregation as a result of deficient mixtures spreading;
iii) course aggregate stripping might initiate “star” cracking;
iv) TDC and segregation (high rate voids) seem to have a direct relation, since all cores exhibit this flaw either in the wearing course, or in the binder layer;
v) crack length ranges from 0 to 19 cm, but is generally less than 11 cm;
vi) crack direction is mainly vertical and follows course aggregates;
vii) no relation was found between crack location, direction and depth; thus traffic does not seem to be the main cause of cracking progression.

### 3.3. Physical properties

In order to verify if there is any relation between material physical properties and TDC, tests were performed to determine density, binder content, voids content and grading, on at least three cores extracted from all layers of the eight slabs.

Except for grading, average values in each layer are very similar and within standard values. However, extreme values are too low or too high, namely the voids content in the wearing and binder layers (Table 1). Unexpectedly, slabs 4 and 6, chosen as control slabs, did not show significant differences from the others. The main difference was the lack of flaws in the wearing course and in the binder layer.

Regarding grading curves, a tendency to exceed the superior limit of the grading envelope (lowest sieves) was observed.

Table 1: Asphalt layers physical properties (Freitas, 2002)

| Slab | | Wearing course | | | Binder layer | | | Base layer 1 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Density ($g/cm^3$) | Binder content (%) | Voids content (%) | Density ($g/cm^3$) | Binder content (%) | Voids content (%) | Density ($g/cm^3$) | Binder content (%) | Voids content (%) |
| 1 | Average | 2.36 | 6.23 | 4.23 | 2.35 | 7.67 | 2.35 | 2.43 | 7.59 | 3.02 |
| | Max-Min | 0.05 | 1.83 | 1.21 | 0.04 | 1.39 | 0.04 | 0.02 | 1.16 | 1.65 |
| 2 | Average | 2.35 | 6.83 | 3.77 | 2.30 | 6.07 | 2.30 | 2.44 | 5.64 | 5.94 |
| | Max-Min | 0.15 | 1.38 | 6.13 | 0.04 | 1.19 | 0.04 | 0.08 | 1.28 | 1.64 |
| 3 | Average | 2.35 | 6.43 | 4.15 | 2.33 | 6.89 | 2.33 | 2.46 | 6.47 | 5.00 |
| | Max-Min | 0.16 | 0.34 | 6.52 | 0.03 | 0.28 | 0.03 | 0.01 | 0.24 | 1.22 |
| 4 | Average | 2.31 | 6.82 | 5.48 | 2.34 | 7.60 | 2.34 | 2.43 | 7.09 | 3.82 |
| | Max-Min | 0.03 | 0.48 | 1.23 | 0.01 | 0.39 | 0.01 | 0.02 | 0.34 | 0.41 |
| 5 | Average | 2.39 | 6.85 | 1.19 | 2.38 | 6.85 | 2.38 | 2.44 | 6.43 | 2.46 |
| | Max-Min | 0.01 | 0.60 | 0.41 | 0.00 | 0.29 | 0.00 | 0.00 | 0.25 | 0.00 |
| 6 | Average | 2.34 | 6.50 | 3.92 | – | 6.67 | – | 2.42 | 6.28 | – |
| | Max-Min | 0.03 | 0.27 | 1.23 | – | 0.05 | – | 0.02 | 0.04 | – |
| 7 | Average | 2.35 | 6.18 | 4.29 | 2.40 | 7.34 | 2.40 | 2.43 | 6.87 | 1.10 |
| | Max-Min | 0.05 | 0.86 | 2.04 | 0.04 | 1.46 | 0.04 | 0.02 | 1.27 | 1.65 |
| 8 | Average | 2.36 | 6.80 | 2.59 | 2.41 | 7.63 | 2.41 | 2.42 | 7.12 | 0.21 |
| | Max-Min | 0.02 | 0.17 | 0.83 | 0.00 | 0.15 | 0.00 | 0.01 | 0.13 | 0.00 |

## 4. STIFFNESS CHARACTERIZATION

Four point bending tests were performed to measure the stiffness modulus at 20ºC. Three cores from each slab were submitted to a sinusoidal loading corresponding to a maximum strain at the base of 100 μdef, in the following decreasing order of frequency: 10, 5, 2, 0.5, 0.2, and 0.1 Hz.

Figures 3 and 4 respectively show the average modulus and the phase angle. The former is, in general, high and similar, except for base layer 2 concerning slab 6. Exceptionally in this slab, this layer is characterized by excessive voids and segregation.

Modulus spectra amplitude, as well as phase angle spectra amplitude, indicates a relative sensitivity of each slab and layer to speed. Wearing course shows narrower amplitude spectra in both cases and lower phase angle values (less than 30º), probably due to ageing.

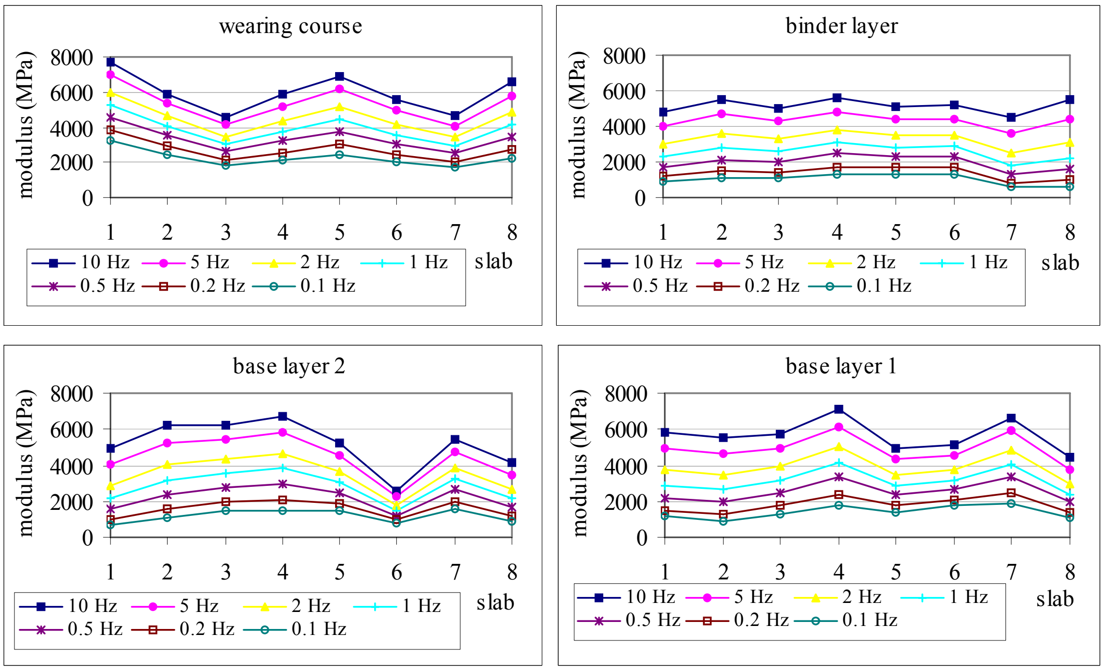


Figure 3: Bituminous layers stiffness

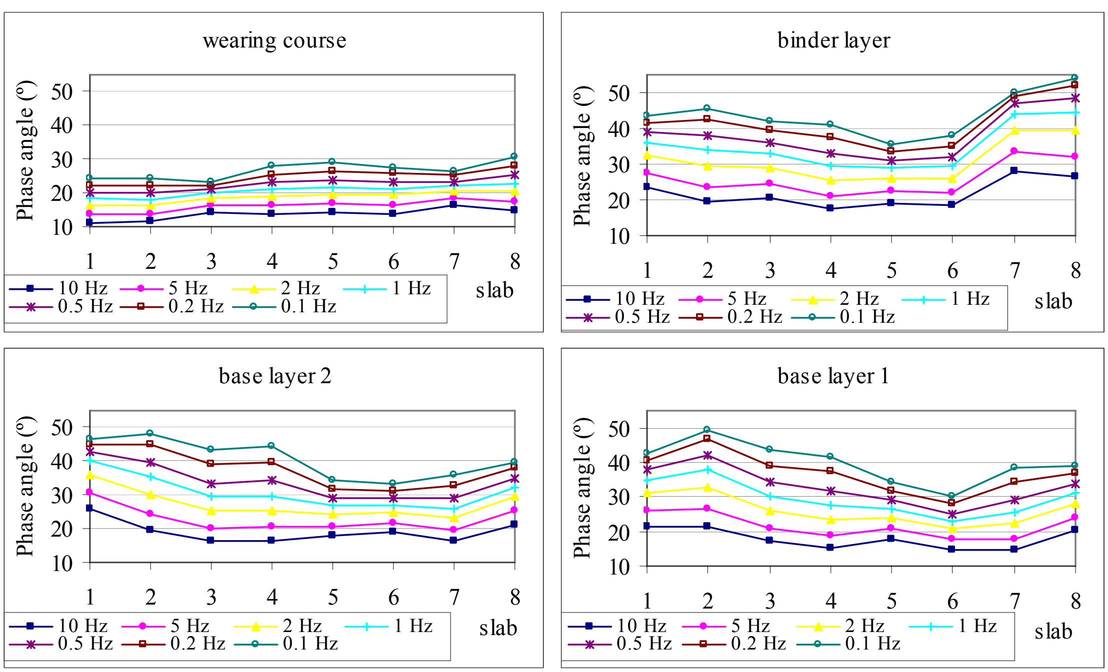


Figure 4: Bituminous layers phase angle

Both the modulus and the phase angle do not allow one to distinguishing control areas from damaged areas.

Phase angle indicates that ageing may be an important factor contributing to TDC.

## 5. FATIGUE CHARACTERIZATION

In order to verify if surface bending could be a TDC cause, four point bending tests were performed, either on the wearing course or on the base layer to measure fatigue strength. Nine cores from each slab were subjected to a sinusoidal loading, without a rest period, under strain control, applying the following strain levels: 200 µdef, 400 µdef and 800 µdef, at 20ºC in temperature.

Fatigue life has been determined by extrapolation of the curve that best fits the corresponding point sets. Figure 5 presents the obtained point sets and the corresponding fatigue curves that have the following form:

$$\varepsilon_t = aN^b \qquad (1)$$

where:

$\varepsilon_t$ = Tensile strain;

N = cycles number;

a, b = material parameters.

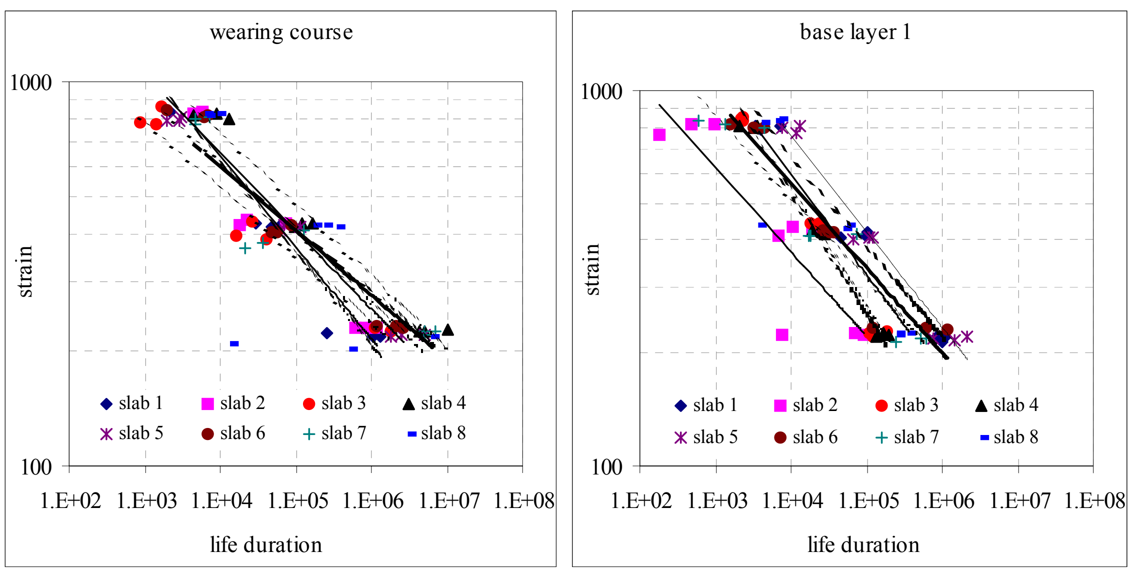


Figure 5: Wearing course and base layer 1 fatigue curves

In this figure results dispersion is highlighted. This is conditioned by the high variations in the binder and voids content, which have a stronger effect on the base layer 1. Since wearing course fatigue curves are crossed, different behaviour to loading weight is expected, probably due to the diversified exposition to sunlight, which results in different ageing degrees.

In general, the fatigue life of bituminous mixtures for wearing courses is higher than other bituminous mixtures. In fact, more bitumen content and less void content drive fatigue behaviour in that sense. Considering this, and in order to support this statement a conventional fatigue life strain of 100 µdef was used in the calculations, both in the wearing course and in the base layer.

Results show that wearing course fatigue life is generally much higher than base layer fatigue life (Table 2). On the other hand, tensile strains in wearing courses are expected to be much lower (or inexistent) than 100 μdef.

An immediate conclusion (but probably not correct) may be drawn from this: fatigue does not cause crack initiation at the top. If surface service strain level is proved to be higher than the pointed level, then another conclusion may be drawn: fatigue life will greatly decrease and may still be a TDC cause.

To reach a definite conclusion, numerical simulations based on advanced models must be performed in order to analyse surface strains accurately.

Table 2: Fatigue law parameters and life

| parameter | slab | wearing course | base layer 1 | slab | wearing course | base layer 1 |
|---|---|---|---|---|---|---|
| a | 1 | 5639 | 5876 | 5 | 3314 | 8087 |
| b | | -0.2397 | -0.2375 | | -0.1828 | -0.2564 |
| $r^2$ | | 0.95 | 0.98 | | 0.99 | 0.97 |
| $N_{100}$ | | 20.22E+06 | 28.10E+06 | | 208.50E+06 | 27.58E+06 |
| a | 2 | 5764 | 2944 | 6 | 4204 | 4531 |
| b | | -0.2382 | -0.2247 | | -0.2025 | -0.2259 |
| $r^2$ | | 0.93 | 0.77 | | 0.96 | 0.92 |
| $N_{100}$ | | 24.65E+06 | 3.45E+06 | | 104.25E+06 | 21.45E+06 |
| a | 3 | 2667 | 9998 | 7 | 2809 | 3814 |
| b | | -0.1757 | -0.3191 | | -0.166 | -0.2174 |
| $r^2$ | | 0.96 | 0.99 | | 0.87 | 0.93 |
| $N_{100}$ | | 131.69E+06 | 1.85E+06 | | 532.37E+06 | 18.80E+06 |
| a | 4 | 4215 | 9573 | 8 | 2808 | 7241 |
| b | | -0.189 | -0.3113 | | -0.1674 | -0.2174 |
| $r^2$ | | 0.97 | 0.99 | | 0.46 | 0.93 |
| $N_{100}$ | | 395.20E+06 | 2.31E+06 | | 449.07E+06 | 359.70E+06 |

## 6. BEARING CAPACITY

Bearing capacity is an indicator of the global strength of pavements, generally used at the project level to analyse whether a road needs to be submitted to maintenance. In this context, Falling Wight Deflectometer (FWD) tests have been performed, at a 100 m interval, covering total extension (20 km), before and after milling top-down cracked surface areas. The corresponding deflection basins were obtained for air temperature, ranging from 15 to 19ºC in the first case and from 18 to 25ºC in the second case (Figures 6 and 7).

In both cases, deflection may be generally classified as excellent and good and no significant differences exist, though under diverse climatic conditions. Load spreading is generally very good. Thus, surface cracking does not appear to interfere with global strength.

Deflection basins could also be used as a means to facilitate the calculation of the real surface strains due to vertical loading and to accomplish fatigue study.

To achieve this, back analysis should be the next step to be performed in order to use layer modulus as seeds in a FEM model, thus allowing for accurate surface calculations.

## 7. CONCLUSIONS

Top-down cracking in Portugal, as in many others temperate-climate countries, is an important degradation mechanism, as far as thick pavements are concerned.

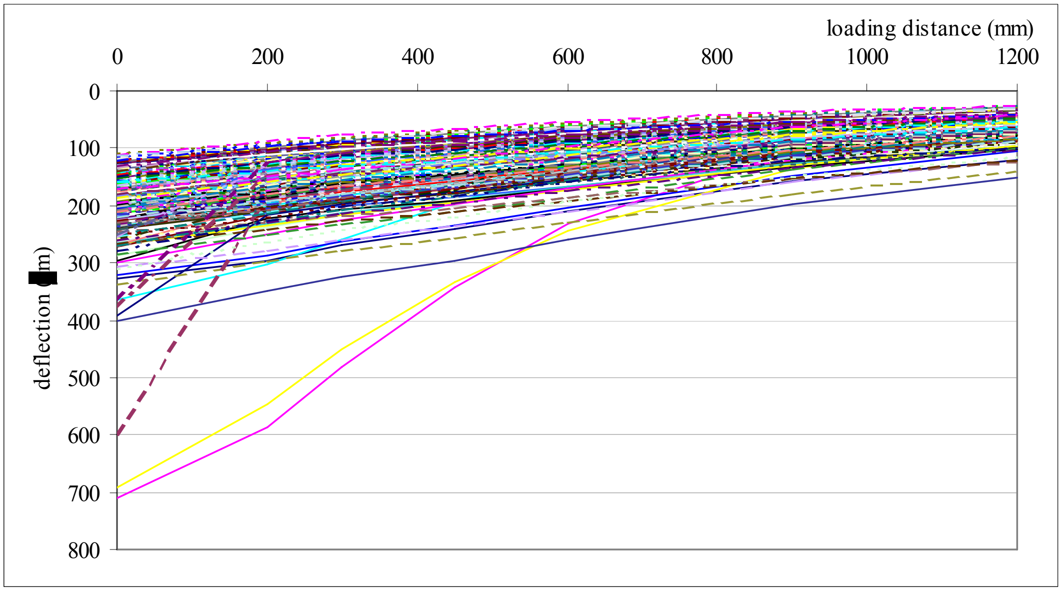


Figure 6: Deflection basins before maintenance

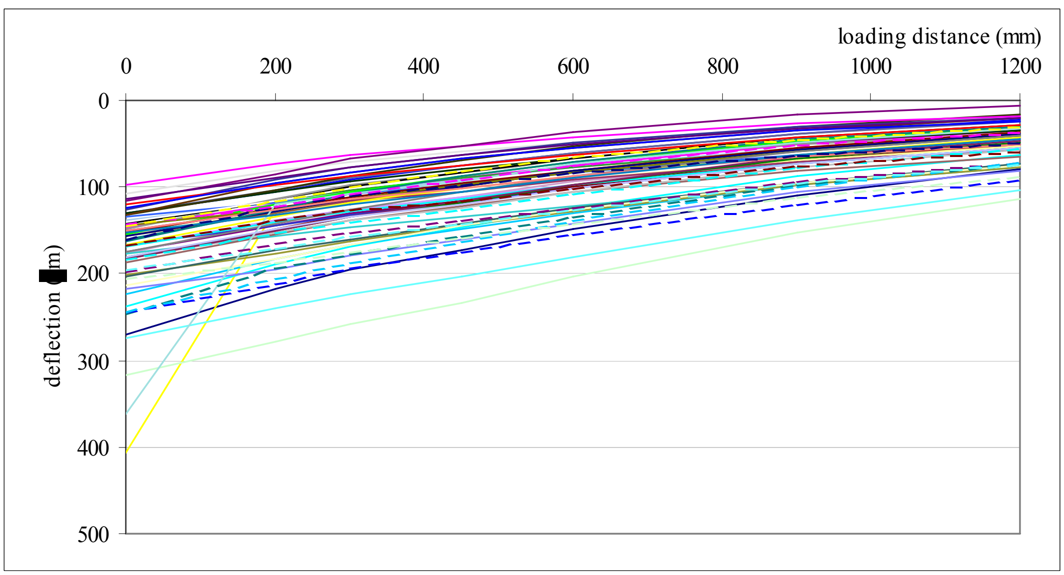


Figure 7: Deflection basins after maintenance

From the literature review there seem to be five main factors that contribute to the appearance and to the progression of TDC (climatic conditions, traffic, ageing, structure and construction quality). However, their study has been largely based on computer simulations and simplified traffic loading models. Nevertheless, by means of field and laboratory research, it is possible to understand TDC mechanism better, as well as to improve both.

In order to assess TDC causes, a sampling plan was set up on a pavement in service, as a first research phase. A second phase consisting of laboratory and field tests was undertaken.

First phase findings indicate construction quality as a strong cause of TDC. It can also be stated that traffic does not seem to be one of the main responsible factor in crack progression.

The second phase comprised stiffness and fatigue tests, as well as deflection tests. As far as the stiffness modulus is concerned, no significant differences were found between control

slabs (4 and 6) and slabs extracted from cracked areas. The phase angle analysis indicates ageing as an important cause in TDC mechanism.

A first sight, fatigue does not seem to cause top-down cracks. However, it may contribute to crack progression. Deflection basin analysis is a possible way of clarifying the phenomenon.

Future research should comprise accelerated loading tests to improve understanding of how construction quality parameters affect TDC. The determination of bitumen aging and fatigue influence on TDC, using deflection basin analysis, will also be one of the primary objectives of research. This complementary research aims to sustain the modelisation of TDC on flexible pavements.

## REFERENCES


CROW, 1990. *Surface Cracking in Asphalt Layers*. Report of the Working Group "Surface Cracking in Asphalt Layers". Centre for Research and Contract Standardization in Civil Traffic Engineering. Netherlands.

Freitas E., Pereira, P. and Picado-Santos, L., 2002. *Estudo do Fendilhamento com Origem na Superfície*. 2.º Congresso Rodoviário Português. Laboratório Nacional de Engenharia Civil, Lisboa, Novembro.

Groenendijk, J., 1998. *Accelerated Testing and Surface Cracking of Asphaltic Concrete Pavements*. PhD Thesis. Delft.

Halim, A.O.A., Nabi, R.M.A., Aleem, A.A., Easa, S.M. and haas R., 1996. *Effect of Highway Geometry and Construction Equipment on the Problem of Reflection Cracks*. Reflective Cracking in Pavements. Design and Performance of Overlay Systems. Proceedings of the Third International RILEM Conference. Netherlands.

Komoriya, K., Yoshida, T. and Nitta, H., 2001. *WA-DA-CHI-WA-RE - Surface Longitudinal Cracks on Asphalt Concrete Pavement*. Transportation Research Board 80th Annual Meeting. Proceedings CD Rom. Washington. D.C..

LCPC, 1999. *Étude de la Fissuration par le Haut des Bétons Bitumineux*. Études et Recherches des Laboratoires des Ponts et Chaussées, Paris, Octobre.

Matsuno, S. and Nishizawa, T., 1992. *Mechanism of Longitudinal Surface Cracking in Asphalt Pavement*. 7th International Conference on Asphalt Pavements. University of Nottingham. Vol. 2.

Merrill, D.B., 2000. *Investigating the Causes of Surface Cracking in Flexible Pavements Using Improved Mathematical Models*. PhD. Thesis. Department of Civil Engineering. University of Wales Swansea. Wales.

Myers, L.N., 2000. *Development and Propagation of Surface Initiated Longitudinal Wheel Path Cracks in Flexible Highway Pavements*. PhD Thesis. University of Florida. Florida.

Myers, L.N., Roque, R. and Birgisson, B., 2001. *Propagation Mechanisms for Surface-Initiated Longitudinal Wheel Path Cracks*. Transportation Research Record N.º 1778. Transportation Research Board. Washington D.C..

Svasdisant, T., Achorsch, M., Baladi, G.Y. and Pinyosunun, S., 2002. *Mechanistic Analysis of Top-Down Cracking in Asphalt Pavements*. 81st Transportation Research Board Annual Meeting. Proceedings CD-Room. Washington D.C..

Uhlmeyer, J.S., Willoughby, K. Pierce, L.M. and Mahoney, J.P., 2000. *Top-Down Cracking in Washington State Asphalt Concrete Wearing Courses*. Issues in Pavement Design and Rehabilitation. Transportation Research Record No. 1730. Transportation Research Board. Washington D.C..