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A prediction model for top-down cracking in asphalt pavements with open-graded friction course

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Abstract

Thick asphalt pavements with open-graded friction course (OGFC) are subjected to top-down cracking (TDC), a distress consisting of cracks that initiate on the pavement surface close to the wheelpath and propagate downwards. However, road agencies do not yet have adequate tools to predict TDC. The objective of this study was to develop a practical and reliable model to predict TDC depth evolution in such pavements. The proposed model provides a maximum TDC depth that can potentially occur in a pavement characterized by certain mechanical properties and traffic at the time of interest. The model was calibrated and validated considering several Italian motorway pavements affected by TDC based on limited data, therefore more data should be collected in the future. This model can be used in a pavement management system (PMS) to plan timely surface maintenance against TDC.

Keywords: Thick asphalt pavement; open-graded friction course (OGFC); porous asphalt (PA); pavement management system (PMS); asset management system; resilient infrastructure.

1. Introduction

Top-down cracking (TDC) is a fatigue distress that affects asphalt pavements and consists of longitudinal cracks that initiate on the pavement surface and propagate downwards (Fig. 1). TDC is basically determined by the tire-pavement contact stresses, which cause the onset of tensile and shear stresses at or near the wheelpath (Canestrari and Ingrassia, 2020; Hu and Walubita, 2009; Luo et al., 2018).

In this regard, such distress is particularly critical for thick asphalt pavements presenting an open-graded friction course (OGFC), which are common on motorways. This type of high-speed roads requires thick pavement layers to

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ensure long-lasting bearing capacity against heavy traffic loadings and OGFC interconnected air voids to allow the surface water drainage. However, in the case of thick pavements, TDC generally precedes bottom-up cracking. At the same time, OGFCs are greatly exposed to TDC due to their high air void content and reduced mechanical properties (Canestrari and Ingrassia, 2020). This was demonstrated also by a survey of the Italian motorway network (Ingrassia et al., 2020a).

In the initial stage, longitudinal top-down cracks are usually isolated and can reach lengths of several hundred meters. Afterwards, parallel cracks appear (the so-called “sister cracks”), followed by short transverse cracks, finally leading to an alligator cracking-like pattern in the wheelpath area. The distress concurrently evolves in depth affecting increasing portions of the asphalt layers. Initially the crack evolves vertically, then it starts to deviate towards the centre of the wheelpath, and finally it propagates sub-horizontally. As a result, in advanced stages, if different cracks connect to each other, a generalized failure in the upper part of the pavement can occur. Consequently, the structural properties of the pavement worsen progressively, also due to rainwater seepage (Canestrari and Ingrassia, 2020, Canestrari et al., 2022).

Such detrimental consequences could be avoided through a timely identification of the distress and immediate surface repairs, which allow to preserve the pavement integrity by replacing few centimetres of asphalt concrete, thus minimizing also the maintenance costs (Canestrari and Ingrassia, 2020).

Nevertheless, the TDC issue is still little known to many road agencies (and practitioners), which do not have adequate tools to predict its evolution. In fact, the existing mechanistic (Ling et al., 2019; Roque et al., 2010) or statistical (Shen et al., 2016) TDC prediction models can be impractical for management and maintenance purposes. In addition, these models mainly focus on the longitudinal growth of TDC rather than on its depth evolution, which instead is more meaningful from the management and maintenance points of view in order to define a critical intervention depth.

Within this context, the objective of this study was to develop (and validate) a practical and reliable model to predict TDC depth evolution in thick asphalt pavements with OGFC. Specifically, the model focuses on the initial vertical evolution of the distress and provides a maximum TDC depth that can potentially occur in asphalt pavements characterized by certain mechanical properties and traffic at the time of interest. Even though the data considered for the model calibration and validation are limited, the proposed model has the potential to be used in a pavement management system (PMS) to counteract TDC.

Fig. 1. Typical top-down crack: (a) longitudinal view, (b) transverse view.

2. TDC prediction model

The prediction model was developed based on literature information, field observations and experimental evidence, taking into account the main factors that contribute to the TDC phenomenon (Canestrari et al., 2022). The general expression of the model is provided in Eqs. (1-3):

$$TDC = TDC_{max} e^{-\left(\frac{a}{n}\right)^{B}} \tag{1}$$

$$a = \alpha_1 - \alpha_2 \cdot (OGFC\ age) \tag{2}$$

$$B = \beta_1 - \beta_2 \cdot ITS \tag{3}$$

where TDC is the predicted depth (mm), TDCmax is the maximum depth (150 mm), n is the cumulative number of 12-ton equivalent single axle loads (ESALs) scaled by a factor equal to 108, a and B are respectively the translation factor and the shape parameter of the model, OGFC age (years) and ITS (MPa) are respectively the age and the indirect tensile strength of the OGFC mixture, the latter determined at 25°C with a displacement rate of 50 mm/min, $\alpha1$, $\alpha2$, $\beta1$ and $\beta2$ are the model parameters to be determined through the model calibration.

As can be seen from its definition, the model is sigmoidal with a maximum TDC depth equal to 150 mm and predicts the TDC depth as a function of the cumulative traffic loadings, the age and the mechanical properties of the OGFC mixture. The choice of a sigmoidal function was motivated by the fact that field observations indicate that the TDC depth usually does not exceed half the thickness of the asphalt layers (Roque et al., 2010) and other authors (Ling et al., 2019; Lytton et al., 2018) have already proposed a sigmoidal law to describe the longitudinal growth of TDC (which is strongly related to the depth evolution). The maximum TDC depth of 150 mm was chosen because, for a typical Italian motorway pavement, such depth corresponds to the binder-base interface (that may represent a structural discontinuity, facilitating the sub-horizontal propagation of TDC) and the total thickness of the asphalt layers is about 300 mm. The traffic loadings are expressed considering a 12-ton single axle with twin wheels as reference axle, whereas the mechanical properties of the OGFC mixture are expressed in terms of indirect tensile strength (ITS), which is correlated with the stiffness and the volumetrics of the mixture (Canestrari et al., 2022).

The model was calibrated considering pavements affected by TDC along the Italian motorway network (Canestrari et al., 2022). For these pavements, the information on the OGFC age and the traffic data during the OGFC in-service life were collected. The approach adopted for the computation of the ESAL values considered fatigue cracking as reference distress and allowed to take into account the effect of axle type, tire type and tire inflation pressure in the definition of the load equivalency factors (Evensen and Senstad, 1992; Ingrassia et al., 2020b). Moreover, some cores were taken along TDC isolated cracks in the wheelpath (cracked cores) and some cores were taken in the middle of the lane (intact cores). The cracked cores were examined to measure the TDC depth, whereas the intact cores were tested to determine the mechanical (and volumetric) properties of the OGFC mixture. The data used for the model calibration are summarized in Table 1. The TDC depth reported in the table is an average value measured on the cracked cores of each pavement.

It should be emphasized that the coring operations required the carriageway narrowing (i.e. reduction of the number of lanes available for the motorway traffic). Therefore, to minimize traffic inconvenience and also for safety reasons, all coring operations were carried out at night. Several other cores were also taken along the motorway network, leading to "false" TDC, i.e. longitudinal cracks attributable to construction joints and tire blowouts of heavy vehicles (Ingrassia et al., 2020a). In some cases, deep cracks were observed, i.e. reflective cracks and/or connection between top-down and bottom-up cracks (Canestrari et al., 2022). For the above-mentioned reasons, the data collected (even if limited) should be acknowledged as extremely valuable.

Table 1. Data used for the model calibration (Canestrari et al., 2022).

Pavement ID	OGFC age [years]	ESALs	TDC [mm]	ITS [MPa]
1	8	1.15E+08	80	0.69
2	10	8.70E+07	100	0.69
7	8	9.99E+07	79	1.00
8	13	1.70E+08	120	0.73
13	6	1.10E+08	67	0.71

The model was calibrated by minimizing the error between model and experimental data. Fig. 2 shows that the model prediction is good, as demonstrated by a determination coefficient R2 equal to 0.850. This result is promising, considering also that, in the pavements studied, the asphalt mixtures were characterized by different compositions. In the figure, the values of the calibrated model parameters α1, α2, β1 and β2 are also shown.

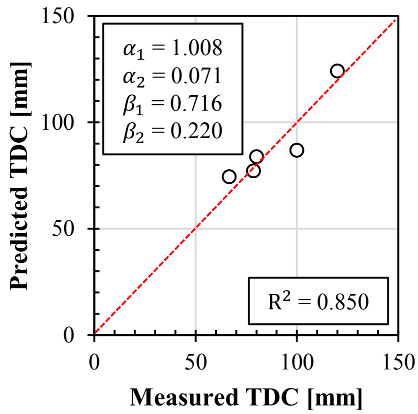

Fig. 2. Comparison between measured TDC and predicted TDC.

Therefore, the expressions of the translation factor a and the shape parameter B (Eqs. (2) and (3)) after the model calibration become the following:

$$a = 1.008 - 0.071 \cdot (OGFC\ age) \tag{4}$$

$$B = 0.716 - 0.220 \cdot ITS \tag{5}$$

Fig. 3 shows the sigmoids associated with the pavements studied (Table 1), considering the calibrated model.

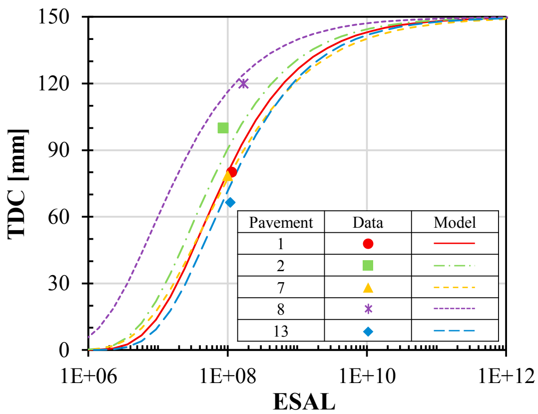

Fig. 3. Sigmoids associated with the pavements studied to calibrate the model.

Fig. 4(a) compares the sigmoids of two pavements (Pavement 1 and Pavement 7) with the same a parameter (i.e. same OGFC age, see Eq. (4)), whereas Fig. 4(b) compares the sigmoids of two pavements (Pavement 1 and Pavement 2) with the same B parameter (i.e. same ITS of the OGFC, see Eq. (5)).

From Fig. 4(a), it can be observed that, as the shape parameter B increases (i.e. ITS decreases), the sigmoid rotates anti-clockwise around a point with an abscissa corresponding to the value of the parameter a multiplied by 108. Such rotation implies a delay in the crack initiation, followed by a faster crack propagation. This is in agreement with the fact that stiffer materials are usually more brittle and thus prone to earlier crack initiation.

From Fig. 4(b), it can be noted that, as the translation factor a decreases (i.e. OGFC age increases), the sigmoid keeps the same shape but shifts to the left. This means that TDC initiation and propagation occur earlier for older mixtures, in agreement with the progressive reduction of the TDC resistance due to the mixture aging (Canestrari and Ingrassia, 2020; Luo et al., 2018). Such parametric analysis, performed considering actual data, supports the reliability of the model developed.

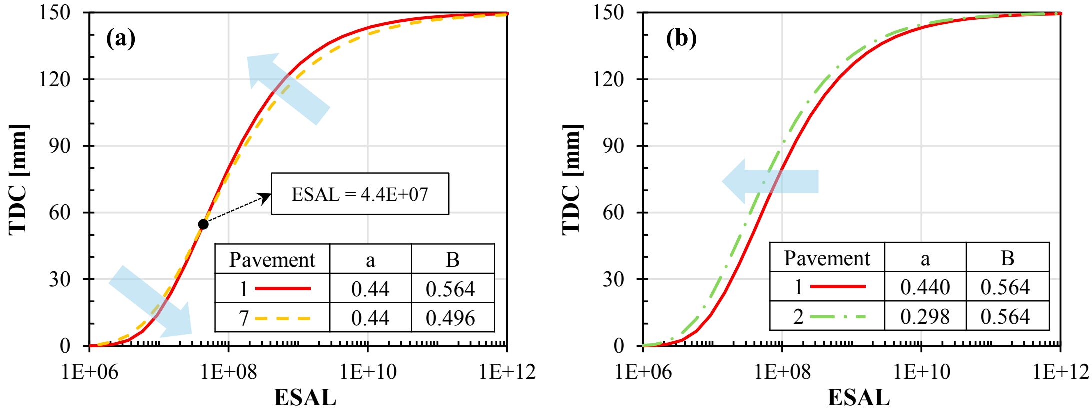

Fig. 4. Sigmoids associated with two pavements (a) with the same *a* parameter and (b) with the same *B* parameter.

The prediction model was validated considering other pavements affected by TDC along the Italian motorway network, which were recently surveyed. Table 2 summarizes the data used for the model validation (the TDC depth shown in the table is an average value measured on the cracked cores), whereas Fig. 5 shows the sigmoid functions associated with the pavements considered for the model validation. As can be seen from the figure, these additional data confirm the reliability of the proposed model.

Table 2. Data used for the model validation.

Pavement ID	OGFC age [years]	ESALs	TDC [mm]	ITS [MPa]
A	10	3.10E+07	66	0.83
B	11	5.32E+07	81	0.90

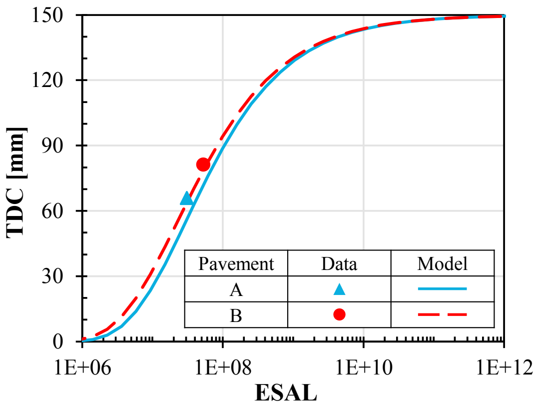

Fig. 5. Sigmoids associated with the pavements considered to validate the model.

3. TDC evolution according to the model

Fig. 6 shows an example (Pavement B, see Table 2) of the evolution of the TDC depth from the OGFC construction to a maximum of 13 years of in-service life, according to the prediction model. It is worth noting that the model developed is not applicable for OGFC ages greater than 14 years. In fact, the shape parameter a is zero for an OGFC age of about 14 years (Eq. (4)), meaning that the TDC depth is equal to TDCmax (Eq. (1)). This is due to the fact that the oldest OGFC mixture considered for the model calibration was 13 years old (Table 1). Nevertheless, this is not a shortcoming of the model, since most OGFCs are usually replaced before 13 years of in-service life due to ravelling and/or clogging. For simplicity, the annual traffic was calculated by dividing the ESALs cumulated during the in-service life by the OGFC age:

$$\text{Annual traffic} = \frac{\text{Cumulated ESALs}}{OGFC\ age} \tag{6}$$

It can be observed that the evolution of the distress as a function of the cumulative ESALs roughly follows a second order polynomial law. This relationship can be easily converted into a relation between years and TDC depth (as shown later in the paper) and depends only on the ITS of the OGFC mixture and the traffic level. Therefore, it can be used in a PMS to compare different pavements and define the maintenance priorities of the network.

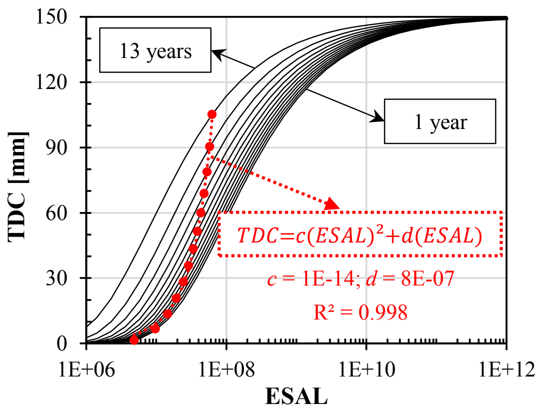

Fig. 6. Example of TDC evolution over time according to the prediction model (Pavement B).

Fig. 7 shows the comparison of the TDC evolution between Pavement 1 and Pavement 2 as a function of the cumulative ESALs (Fig. 7(a)) or the years (Fig. 7(b)). Both pavements are characterized by the same ITS value of the OGFC (0.69 MPa). The annual traffic of Pavement 1 (1.43·107 ESALs) is almost the double of that of Pavement 2 (8.70·106 ESALs). As can be seen from Fig. 7(b), the predicted TDC depth is always greater for the pavement affected by the higher traffic level, but the difference progressively decreases over the years.

Fig. 8 shows the opposite situation, namely it compares two pavements (Pavement 7 and Pavement 8) characterized by a similar annual traffic level (1.25÷1.30·107 ESALs) but different ITS values of the OGFC (1.00 MPa for Pavement 7 vs. 0.73 MPa for Pavement 8). In this case, the TDC depth for the two pavements remains comparable over time, as denoted also by the coefficients of the relationships between TDC depth and ESALs (Fig. 8(a)) and between TDC depth and years (Fig. 8(b)), which are almost identical. More in detail, for Pavement 8, the TDC depth is slightly lower in the first years and slightly higher after 4÷5 years as compared to Pavement 7. This confirms that a lower ITS implies a delayed crack initiation but also a faster crack propagation, as already discussed in Section 2.

Overall, this parametric analysis (performed with actual data) indicates that, according to the model, the effect of the traffic level on the evolution of TDC depth is stronger than the effect of the OGFC properties, which is consistent with the fact that traffic loadings are considered the main factor in TDC development (Canestrari and Ingrassia, 2020).

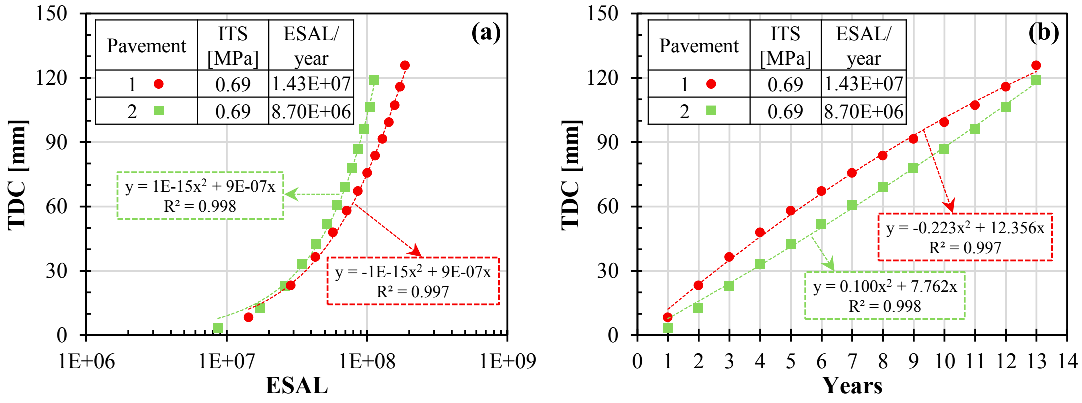

Fig. 7. Evolution of the TDC depth for two pavements with the same ITS: (a) as a function of the cumulative ESALs, (b) as a function of time.

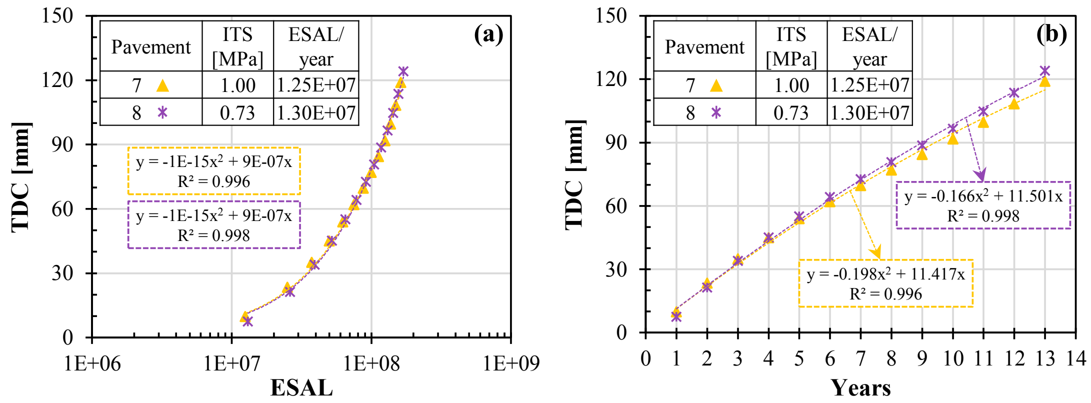

Fig. 8. Evolution of the TDC depth for two pavements with similar annual traffic: (a) as a function of the cumulative ESALs, (b) as a function of time.

4. Conclusions and future work

The objective of this study was to develop (and validate) a practical and reliable model to predict TDC depth evolution in thick asphalt pavements with OGFC, to be implemented in a PMS.

The proposed prediction model provides a maximum TDC depth that can potentially occur in a given pavement, characterized by certain mechanical properties and traffic, at the time of interest. The model is sigmoidal with a maximum TDC depth equal to 150 mm. The shape parameter and the translation factor of the sigmoidal function depend respectively on the ITS and on the age of the OGFC mixture.

Even though the model was preliminarily calibrated and validated considering several pavements affected by TDC along the Italian motorway network, the data available are still limited and the collection of more data is necessary to refine the model and obtain more accurate predictions of the TDC depth.

An automatic method for the recognition of TDC on the pavement is currently under development (Chiola et al., 2022). In the short term, the synergy between these two tools (automatic method for TDC recognition and mechanical model) can be useful to identify the pavements more likely affected by TDC and collect additional data. In the long term, such tools can be used in a PMS to plan timely surface repairs/maintenance against TDC, thus minimizing the pavement damage and the maintenance costs.

Finally, it is worth noting that the applicability of the model to pavements with different characteristics (e.g. thin asphalt pavements, dense-graded wearing layers) needs further study.

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