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Characterizing cracking and permanent deformation; an attempt for predicting the end of the structural pavement life

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Abstract

Durable, therefore sustainable, road needs to attain specific characteristics, among others, resistance to permanent deformation and cracking. Determining the development of both characteristics are important to be able to predict pavement life and performance. In this research, permanent deformation occurring in three pavement sections was measured by a transverse profilograph. The pavement sections were simple two layer structures consisting of a gravel asphalt concrete (GAC) layer on a sand subgrade. The length and the width of the section are 16 m and 4 m respectively. These three sections were tested by means of Lintrack, an Accelerated Pavement Test (APT) which allows large number of realistic wheel load applied in a limited period of time. The results of this measurements shows the development of permanent deformation, which is defined as 'rut depth', as function of the number of load repetitions. Using relation exists between the radius of curvature of a deflection profile and the tensile strain at the bottom of a slab, the creep/permanent strain as a result of permanent deformation was calculated. This paper is carried out to determine relations between the rut depth and the radius of curvature and between the rut depth and the creep/permanent strain. Also, cracking development was observed upon these three pavement section. The result shows that there is a rather good correlation between rut depth and permanent/creep strain which is independent of the layer thickness.

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Keywords: Permanent deformation; cracking; pavement

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1. Introduction

In 1990 the Road and Railroad Research Laboratory (RRRL) of the Delft University of Technology (DUT) built an accelerated pavement testing system (APT) called Lintrack which allows large number of realistic wheel loads to be applied in a limited period of time. Four pavement sections consisting of a gravel asphalt concrete (GAC) top layer on a sand subgrade were tested by means of the Lintrack [1-4].

These pavements had 16 m long and 4 m wide. After testing of lane I, it was decided to perform another test with the same loading condition but on a thinner construction. Therefore, the asphalt thickness of the second test lane (II) was reduced by milling it in May 1995 from 150 to 80 mm and the same was done for the third lane (III) in June 1996. These milled off sections with a thickness of 80 mm asphalt were called 'VA' and 'VB' respectively. Only pavement section I, VA and VB will be discussed in this paper. Table 1. provides the details of the thickness and the loading conditions of the three sections [1].

Table 1. Details of the three Lintrack sections

Section's name	Asphalt thickness [mm]	Load characteristic	Total number of wheel load applied
I	150 (80+70)	super single F = 75 kN, p = 950 kPa	4×10^6
II became V_A	150 became 80	super single F = 75 kN, p = 950 kPa	6.5×10^5
III became V_B	150 became 80	super single F = 50 kN, p = 700 kPa	1.7122×10^6

F = wheel load, p = tire pressure

During these tests, several parameters were measured such as strain at the bottom of the asphalt layer, temperature, transverse profile measurements to determine the amount of permanent deformation and surface cracking. This information provides a great opportunity to relate the development of the rut depth and the permanent/creep strain and further to evaluate its effect to the development of the surface cracking.

The World Bank's HDM III model shows that there is a relationship between the rut depth and the amount of cracking [5, 6]. In that model the average rut depth depends on the amount of cracking in the following way;

Average rut depth = f (% cracked area * mean monthly precipitation)

Since the Lintrack sections were covered, they were protected against the influence of precipitation making MMP (mean monthly precipitation) = 0. This implies that the HDM III model could not be used for the Lintrack sections to determine whether cracking would influence permanent deformation or vice versa. It is, however, very well possible that permanent deformation affects the occurrence of cracking because if a significant rut depth develops, significant curvature of the pavement occurs, which possibly cannot be followed by the asphalt layer without cracking. So cracking could develop as a result of creep.

Based on the huge number of information provided by the Lintrack sections, this paper attempt to determine to what extent the observed longitudinal cracks were a result of permanent deformation and their effect on the end of pavement life. This research is part of research performed on matching laboratory and field asphalt fatigue performance [7].

Before the existence of any relationship between permanent deformation and the structural pavement life (cracking) will be discussed, attention is called for the fact that all permanent deformation in each of the Lintrack pavement sections was caused by permanent deformations in the sand subgrade. Deformations in the asphalt layer itself made, if present, only a very small contribution to the total deformation.

2. Cracking and permanent deformation observed

2.1. Observed cracking

During the Lintrack tests the progression of the crack pattern at the surface was recorded using two techniques. The first one was by taking photographs of the test lane (regularly) and the second by drawing the cracks on transparent plastic sheets (regularly). The surface area of the Lintrack sections that was loaded was 12.8 m long and 2.4 m wide and on this area the crack observations at the end of the loading/testing were made, as shown in Figure 1 a, b and c [1, 2, 4].

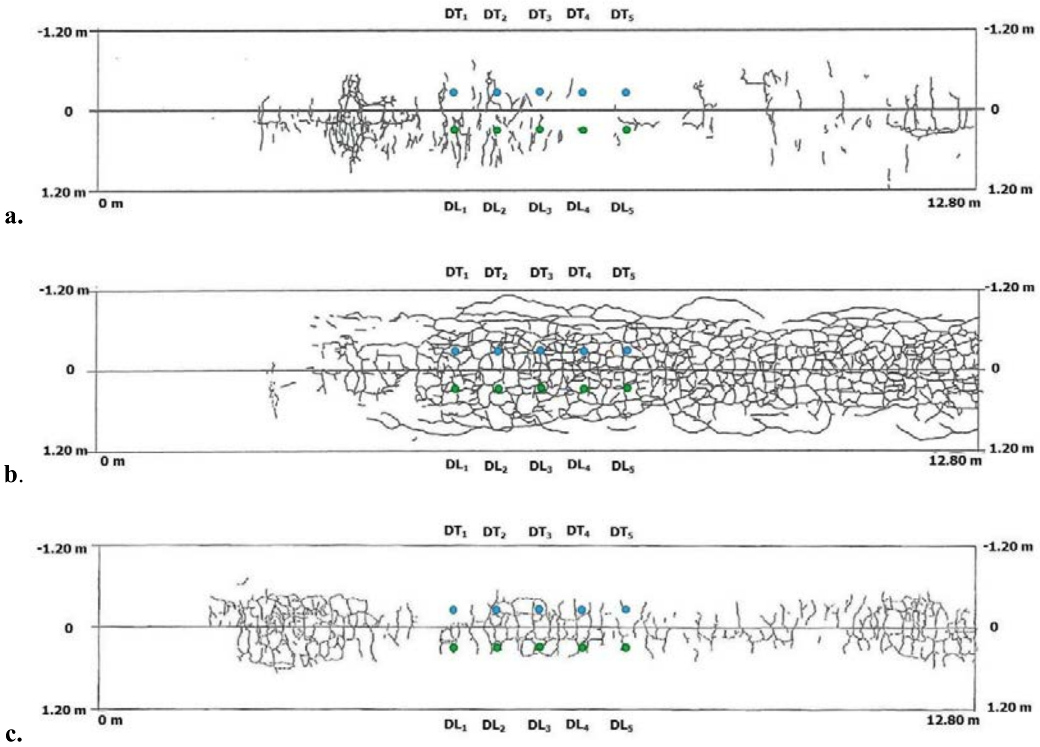


Fig.1. (a) Crack pattern of Lintrack section I after 4 Million cycles, wheel load 75 kN, 150 mm thickness. (b) section VA after 650 kilocycles, wheel load 75 kN, 80 mm thickness. (c) section VB after 1722 kilocycles, wheel load 50 kN, 80 mm thickness [1, 4]

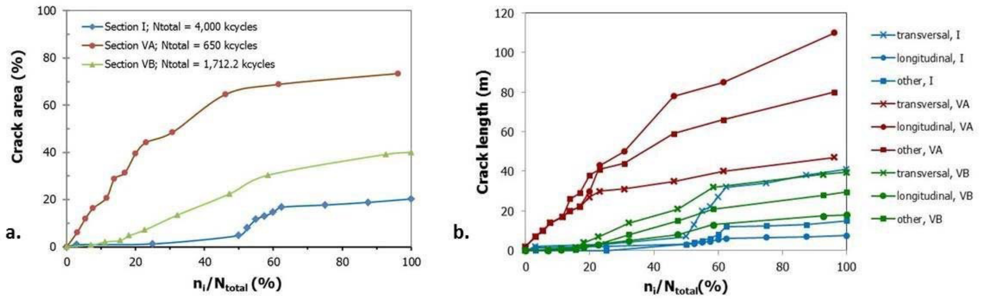


Fig. 2. (a) Development of the percentage cracked area on Lintrack sections I, VA, VB based on 100x100 grid size area (b) Development of crack length observed on Lintrack sections I, VA and VB (Pramesti [7] based on Groenendijk[1, 4] data)

The green and blue dots in Figure 1 describe the position of the five longitudinal and five transversal strain gauges respectively, which were placed close to the bottom of the asphalt layer. Figure 2 shows the development of the cracked area as a function of the number of load cycles applied which is shown as percentage of the total number of loads.

The amount of cracking was determined in the following way; an imaginary grid with cell sizes of 100 x 100 mm was laid over the travelled pavement surface. The percentage of the cells in which one or more cracks are visible is reported as the percentage cracked area. It should be kept in mind that the thinner VA and VB sections showed a denser crack pattern than the thicker section I and, therefore, showed a higher percentage cracked area at the end of the test than section I.

2.2. Observed permanent deformation

Permanent deformation occurring in the Lintrack sections was measured by a transverse profilograph comprising of an aluminium frame bridging the test lane and guiding the measuring wheel which travels across the pavement. Permanent deformation was defined as 'rut depth' and the results of the measurements are shown in Figure 3. The graph shows the development of permanent deformation as function of the number of load repetitions expressed as percentage of the total applied number of load repetitions. Section VA shows excessive permanent deformation development in the early stages of loading.

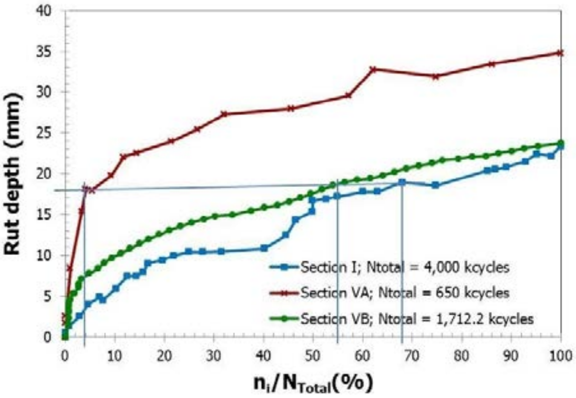


Fig. 3. Rutting of Lintrack sections I, VA and VB

According to the Dutch maintenance standard for motorways, maintenance action should be taken if the rutting depth reaches 18 mm. Based on this criterion, maintenance is supposed to be carried out at 4%, 55% and 68% of total loading for section VA, VB and I respectively. Figures 4.a. to 4.c. show the development of rut depth profiles on sections I, VA and VB.

3. Permanent strain and radius of curvature of the rut depth profile

From the theory of slabs it is known that a simple relation exists between the radius of curvature of a deflection profile and the tensile strain at the bottom of the slab [8].

$$M_{1x} = Eh^3 \frac{\left(\frac{1}{R_x} + \mu \frac{1}{R_y}\right)}{12\left(1-\mu^2\right)} \quad \text{and} \quad M_{1y} = Eh^3 \frac{\left(\frac{1}{R_y} + \mu \frac{1}{R_x}\right)}{12\left(1-\mu^2\right)} \qquad (1)$$

where:

M_{1x} = bending moment in the x direction,
M_{1y} = bending moment in the y direction,
R_x = radius of curvature in the x direction,
R_y = radius of curvature in the y direction,
E = elastic modulus of the slab,
h = thickness of the slab,

μ = Poisson's ratio.

The stresses can be calculated as:

$$\sigma_x = 6\frac{M_{1x}}{h^2} \quad \text{and} \quad \sigma_y = 6\frac{M_{1y}}{h^2} \tag{2}$$

If we are dealing with a circular load in the centre of a large slab,

$$R_x = R_y \quad \text{and} \quad \sigma_x = \sigma_y \tag{3}$$

Since:

$$\varepsilon_x = \frac{(\sigma_x - \mu\sigma_y)}{E} = \frac{(1-\mu)\sigma_x}{E} \tag{4}$$

we can develop a relation between the curvature and the tensile strain by substituting σ_x with Equation (2), we obtain:

$$\varepsilon_x = \frac{6(1-\mu)M_{1x}}{Eh^2} \tag{5}$$

Furthermore Equation (6) is developed by substituting M_{1x} in Equation (5) with Equation (1), where (ε_x) is the horizontal strain at the bottom, h is the thickness of the slab and (R_x) is the radius of curvature [8].

$$\varepsilon_x = \frac{h}{2R_x} \tag{6}$$

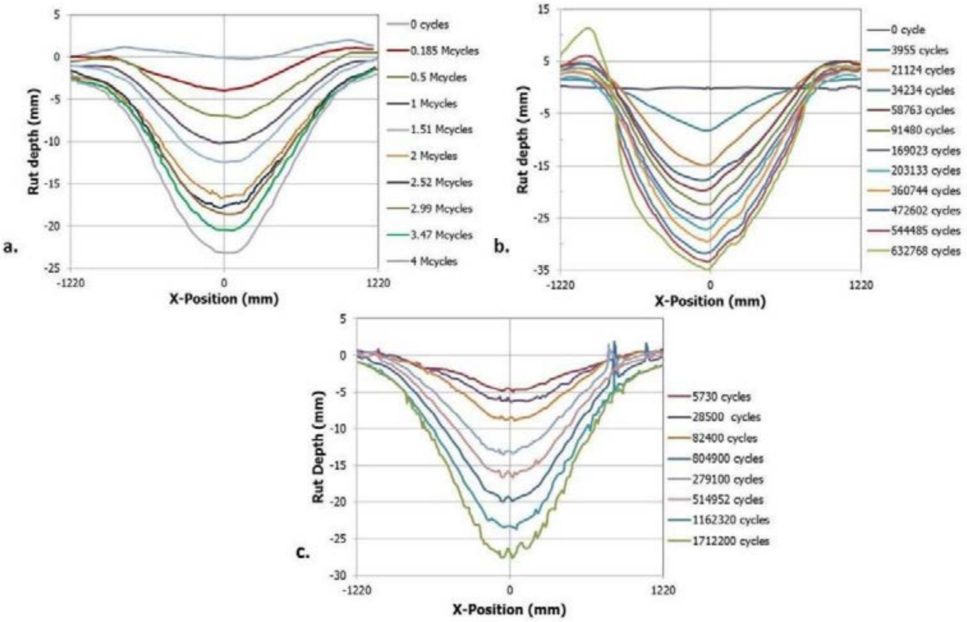
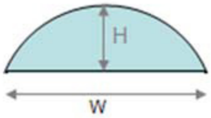


Fig. 4. Rut depth profile of each Lintrack section at several loading cycles [1, 4].
(a) Section I. (b) Section VA. (c) Section VB

In this study this relationship was used to calculate the creep/permanent strain as a result of permanent deformation. When a rut depth profile is modelled as an arc, with the length of the chord defining the base of the arc being W and the height measured at the midpoint of the arc's base is H, then the radius of this arc can be estimated using Equation (7).



$$\text{Radius} = \frac{H}{2} + \frac{W^2}{8H} \qquad (7)$$

When applying this principle on the curvature as a result of rut depth formation, then the challenge is to define H. This is because there is uncertainty of how big the arc should be. However some trials on the curvatures show that using H as 10.75% of the total rut depth will give the maximum strain [7]. Therefore, this 10.75% is used to make a consistent calculation in determining R.

Because of the irregular shape of the rut depth profiles, the W at a certain H could not be easily determined. Then, each rut depth profile was described using a polynomial function. They are shown in Figure 5 as dashed lines. These 'new' lines improved significantly the determination of the width of the arc (W) at a certain H value.

Based on the crack pattern shown in Figure 1.b, section VA is the only section that shows a significant amount of longitudinal cracking. The longitudinal cracking appears in the outer side of the wheel path. Figure 4.b. shows that at the outer sides of the wheel path also deformation in the shape of ridges developed (in the area from the -1220 to -800 and from 800 to 1220). Then, for this section, two deformations will be analysed which are the rut depth between -800 to 800 and the high ridge between -1220 to -800.

By using these new rut depth profiles, W was estimated. Hence the radii and the permanent strain could then be determined using Equation 7 and 6 consecutively.

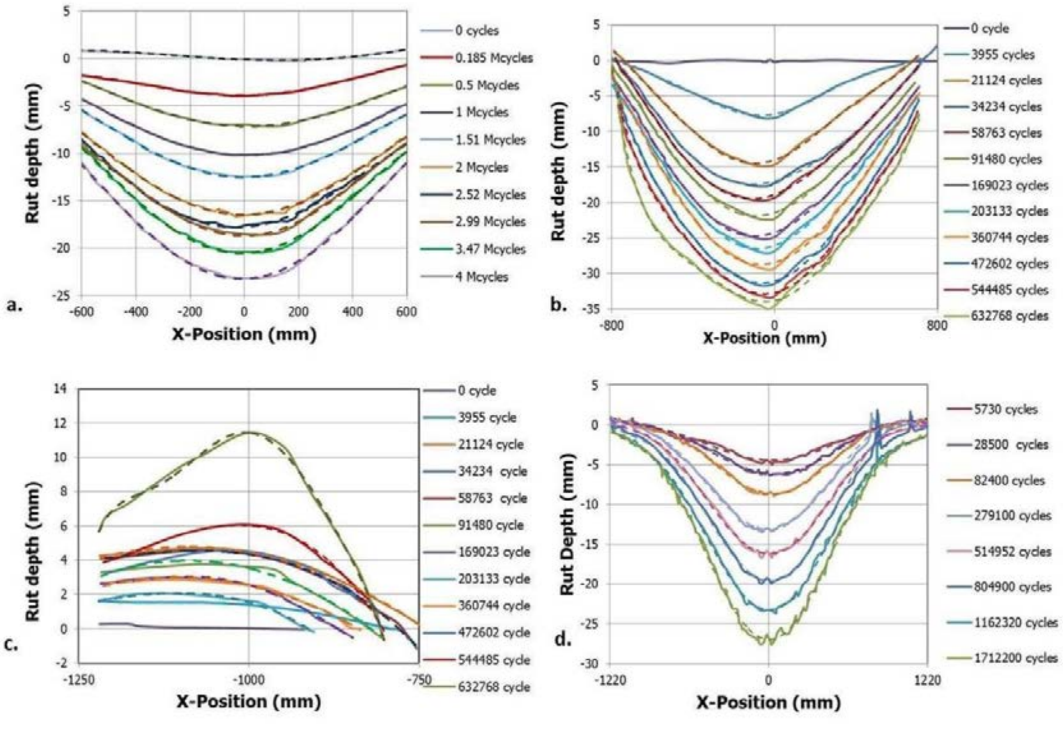


Fig. 5. Polynomial function of the rut profile (dashed line) at several loading cycles (a) section I. (b) section VA at the X-position from -800 mm to 800 mm. (c) Section VA at the X-position from -1220 mm to -800 mm. (d) Section VB

4. Relationship between the rut depth and the radius of curvature and between the rut depth and the permanent strain

The relation between the rut depth and radius and between rut depth and permanent strain as determined from the data obtained on the three sections are shown in Figure 6 and 7.

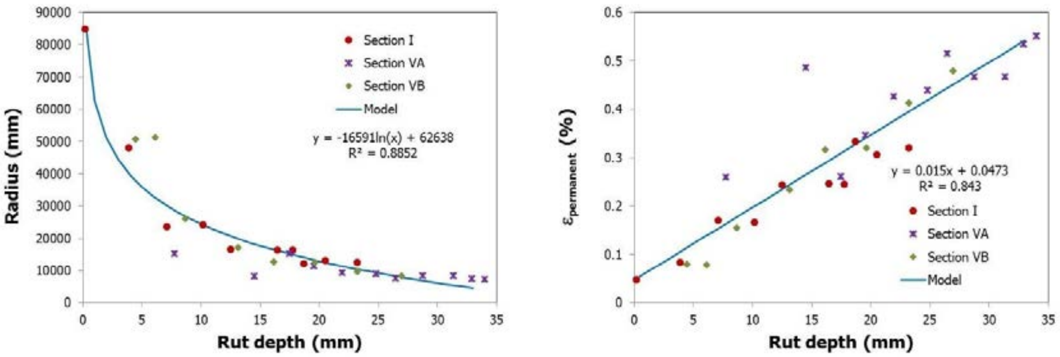


Fig. 6. Relation between (a) rut depth and radius of curvature and (b) rut depth and permanent/creep strain

Figure 6.a shows a nonlinear relation between the rut depth and the radius. However, the three sections show a similar pattern which can be represented by means of a logarithmic trend line. Meanwhile the relation between rut depth and permanent strain presented in Figure 6.b shows a linear relation between the rut depth and the permanent strain. Figure 6.b is an interesting one because it shows that there is a rather good correlation between rut depth and permanent strain which is independent of the layer thickness. This relationship, however, might be dependent on the amount of lateral wander.

5. Rut depth, permanent strain and cracking

The relationship that was developed between the number of load repetitions and the permanent strain of section I, VA and VB are shown as the blue line in Figure 7, 8, and 9 respectively (also the orange line in Figure 8 shows the development of the permanent strain of the ridge side of section VA). It is recalled that the permanent strain is acting at the bottom of the asphalt layer in the transversal direction and could, therefore, give rise to longitudinal cracking in the centre of the wheel path. Figures (a) and (b) show the development of the crack length and cracked area subsequently with respect to the number of load repetitions.

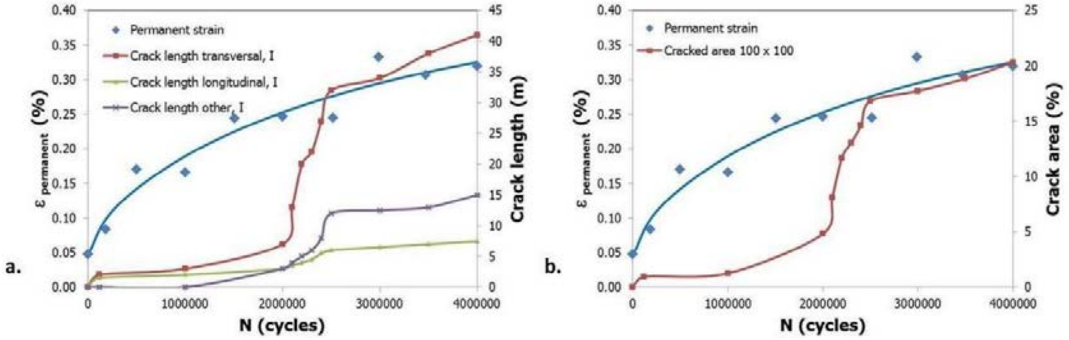


Fig. 7. Development of the permanent strain and crack length (a) and cracked area (b) of Section I

Figures 7 (a) and 7 (b) show that the crack development was rather slow until 2×10^6 load repetitions and that the crack lengths increased significantly after 2x10^6 cycles. At that number of load repetitions, the permanent strain value is around 0.25% and the rut depth around 17 mm (see also Figure 5.a.).

The blue line in Figure 8.a shows immediate and rapid increase of the permanent strain during the first 100,000 load repetitions while it developed at a much slower pace after 100,000 load repetitions. On the other hand the orange line, which represents the development of the permanent strain at the top of the ridge, shows that the permanent strain was rather constant at around 0.25% for a rather long period but increased dramatically after 500 kcycles. Figure 8 (a) and (b) show that cracking started immediately.

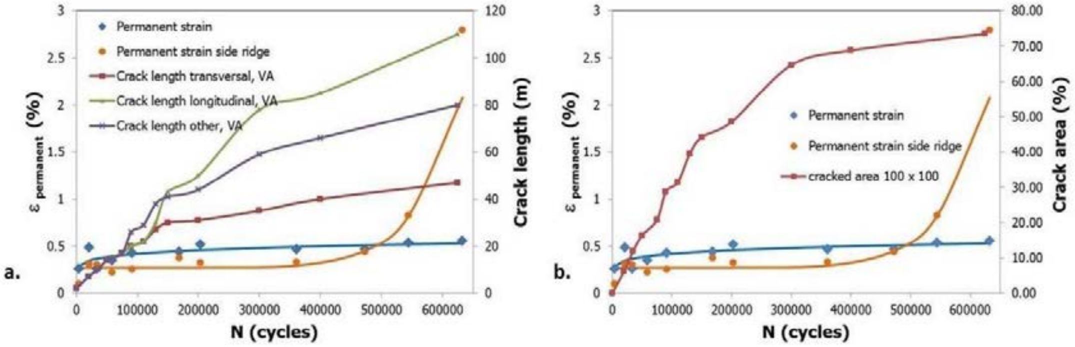


Fig. 8. Development of the permanent strain and crack length (a) and cracked area (b) of Section VA

Section VA is the section that shows quite a number of longitudinal cracks. This type of cracking was not only present in, or near, the centre of the wheel path, as was also the case in section I and VB, but many of these longitudinal cracks were also present at the edges of the rut profiles in section VA. These cracks were less present in Section VB and quite rare in Section I. From Figure 8 it can be concluded that after 75000 load repetitions, when the permanent strain had reached a value of 0.4%, the permanent strain is not increasing rapidly anymore. It seems as if the 0.4% strain is about the maximum the pavement can take. At that moment the rut depth is 22 mm and the cracked area is 20%.

The orange line in Figure 8 seems to indicate that a permanent strain of 0.4% is about the maximum the pavement can take because a very rapid increase in strain is observed after this strain level has been reached (at 450,000 load repetitions). Taking into consideration the size of the cracked area at that moment (see Figure 8.b) the pavement can be considered to be completely failed.

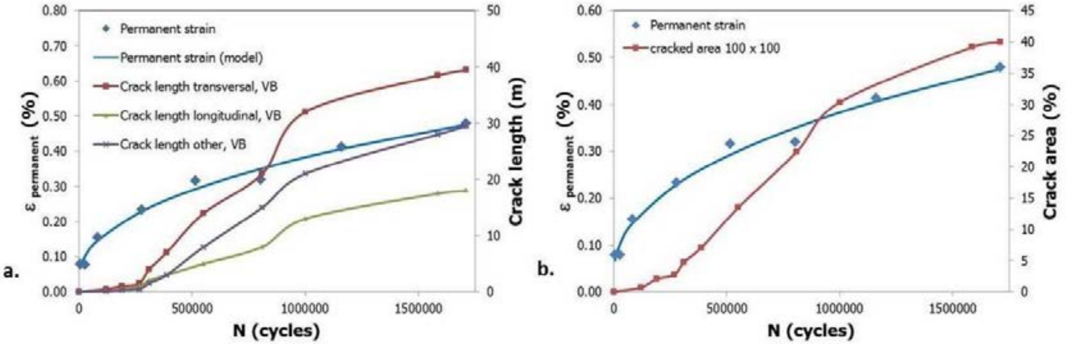


Fig. 9. Development of the permanent strain and crack length (a) and crack area (b) of Section VB

Figure 9(a) and (b) show that the cracks started to develop at around 278,000 cycles. At that point, the permanent strain is around 0.23% and the rut depth 13 mm. The 0.4% strain level is reached after approximately 1.1 million load repetitions and at that moment the cracked area amounts 32%. The rut depth at that moment was 22 mm.

6. Summary of findings with respect to the relationship between rut depth and cracking

The most important findings with respect to the relation between permanent deformation and cracking are summarized in Table 2.

Table 2. Summary of findings with respect to the relationship between rut depth and cracking.

Section	I	VA	VB
Nr of load repetitions at which cracking starts to increase	2,000,000		267,200
Permanent strain when cracking starts to increase	0.25%		0.23%
Rut depth when cracking starts to increase	16.6 mm		12.1 mm
Nr of load repetitions at which permanent strain equals 0.4%		75,000	1,000,000
Rut depth at a permanent strain of 0.4%		22 mm	22 mm
Cracked area when permanent strain equals 0.4%		20%	32%

From the results shown in Table 2 it appears that at a rut depth of around 15 mm, crack development starts to accelerate and that at a rut depth of 20 mm the sections can consider to be failed. It should be noticed that these findings are based on the performance of the Lintrack sections where permanent deformation was a result of deformation of the subgrade and NOT because of the asphalt layer. It is, however, noteworthy that these findings closely agree with the definitions of failure as used in the pavement evaluation and overlay design system as developed by the Transport and Road Research Laboratory in the UK which are shown in Table 3 [9].

Table 3. Classification of pavement condition according to Croney [9]

Classification	Visible evidence
Sound	No cracking. Rutting beneath 2-m straightedge less than 10 mm.
Critical	(a) No cracking. Rutting between 10 and 20 mm.
	(b) Cracking confined to a single crack in the wheel-track, with rutting less than 20 mm.
Failed	Cracking extending over the area of the wheel-track and/or rutting greater than 20 mm.

The results show that permanent deformation and structural performance were closely related in case of the Lintrack pavements. These findings also explain the cracking of the Lintrack sections is also caused by permanent deformation.

7. Conclusion

In this paper the surface cracking and permanent development of three accelerated pavement test sections (Lintrack 1990) was discussed. Parameters that were thought to be of importance for determining the pavement life were studied, being cracking (including crack length and cracked area) as well as permanent deformation.

This study showed that part of the observed longitudinal cracking in the Lintrack sections is quite strongly related to rutting. This statement is based on the following findings:

- Progressive development of cracking seemed to occur when the rut depth was around 15 mm or larger.
- The rut depth profile analyses showed that there is a rather good correlation between rut depth and permanent/creep strain which is independent of the layer thickness.
- It is clear that correlating the calculated pavement life to the cracked area is not recommended since quite some visible cracking, especially in VA and VB, must have been caused by rutting and some cracking must have been top down cracking initiated by compaction during construction. That permanent deformation did have an influence on the cracking performance was nicely shown when analysing the behaviour of Section VA. There it appeared that the ridge that developed next to the rut depth clearly corresponded with the longitudinal cracking observed in that area

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References

[1] J. Groenendijk, "Accelerated Testing and surface cracking of asphaltic concrete pavements," PhD, Delft University of Technology, Delft The Netherlands, 1998.
[2] P. D. Bhairo, "Comparison of the predicted and Observed Pavement Life of LINTRACK Test Lane Va," Delft University of Technology, Delft, The Netherlands, 1997.
[3] H. Sabha, "Estimation of Crack Growth Parameters and Fatigue Characteristics of Asphalt Mixes Using Simple Test," Delft University of Technology, Delft, The Netherlands, 1995.
[4] J. Groenendijk and C.H. Vogelzang, "Pavement Performance Under LINTRACK Accelerated Loading, Extending measurement report and interpretation report section Vb," Delft University of Technology, Delft, The Netherlands, 1998.
[5] W.D.O. Paterson, Road Deterioration and Maintenance Effects. Baltimore, U.S.A.: John Hopkins University Press, 1987.
[6] T. Watanatada, C. G. Harral, W. D. O. Paterson, A. M. Dhareshwar, A. Bhandari, and K. Tsunokawa, The Highway Design and Maintenance Standards Model: Description of the HDM-III model vol. 1: Johns Hopkins University Press, 1987.
[7] F. P. Pramesti, Laboratory and Field Asphalt Fatigue Performance, Matching Theory with Practice: TU Delft, Delft University of Technology, 2015.
[8] A.A.A. Molenaar, "Structural Evaluation and Strengthening of Flexible Pavements Using Deflection Measurements and Visual Condition Surveys, Lecture Note CT 4860 Structural Design of Pavement , Part VI," Delft University of Technology, Delft the Netherlands, 2009.
[9] D. Croney, The Design and Performance of Road Pavements. Transport and Road Research Laboratory. London: Her Majesty’s Stationery Office, 1977.