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Fractal evaluation of the level of alligator cracking in pavements

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Abstract. Pavement management systems require systematic monitoring of pavement surfaces to determine preventive and corrective maintenance. The process involves the accumulation of large amounts of visual data, typically obtained from site visitation. The pavement surface condition is then correlated to a pavement distress index that is based on a scoring system previously established by state or federal agencies. The scoring system determines if the pavement section requires maintenance, overlay or reconstruction. One of the surface distresses forming part of the overall pavement distress index is the Alligator Crack Index (AC Index). The AC Index involves the visual evaluation of the crack severity of a section of a pavement as being low, medium, or high. This evaluation is then integrated into a formula in order to obtain the AC Index. In this study a quantification of the visual evaluation of the severity of alligator cracking is carried out using photographs and the fractal dimension concept from fractal theory. Pavements with low levels of cracking were found to have a fractal dimension equal to 1.051. Pavements with moderate levels of cracking had a fractal dimension equal to 1.1754. Pavements with high degrees of cracking had a fractal dimension that varied between 1.5037 (high) and 1.7111 (very high). Pavements with a level of cracking equal to 1.8976 represented pavements that disintegrated and developed potholes. Thus, the visual evaluation of the state of cracking of a pavement (the AC Index) could be enhanced with the use of the fractal dimension concept from fractal theory.

Keywords: asphalt pavement, cracking, fractal analysis, fractal dimension.

1. Introduction

Pavement management systems require systematic monitoring of pavement surfaces to determine when best to engage in preventive and corrective maintenance. The process involves the accumulation of large amounts of visual data, typically obtained from site visitation and inspection with simple equipment (FHA 2006). The pavement surface condition is evaluated with respect to surface distresses such as cracks (alligator, transverse, and longitudinal), patching/potholes, rutting and roughness. Surface stress indexes are calculated for each of the distresses mentioned above using formulas developed by the Federal Highway Administration (2006). These individual surface distress indexes are then integrated into an overall surface distress index called Pavement Condition Rating (PCR). The value provided by the computation of the PCR index determines if the pavement section

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requires maintenance, overlay or reconstruction (FHA 2006). A PCR index value of 100 would indicate a perfect pavement with no measurable distresses or rough ride. A PCR value of 60 is determined to be *terminable serviceability* and the pavement is considered to have failed. One of the surface distress indexes that forms part of the overall PCR index is the Alligator Crack Index (AC Index).

2. Alligator cracking

Alligator cracks are cracks that form a network of multisided blocks (polygons) resembling the skin of an alligator. The block size can range from a few centimeters to over 0.914 m (Juang and Amirkhanian 1992). Alligator cracks are the result of pavement fatigue resulting from traffic loads, and are ranked as extremely important among the different types of distresses causing the damage of a pavement (Juang and Amirkhanian 1992). The alligator crack severity of a section of a pavement can be classified as low, medium, or high (Table 1) (FHA 2006).

The severity of the alligator cracking of a pavement section is evaluated using Table 1. This information is then integrated into a formula used to obtain the alligator crack index (AC Index). This formula is as follows (FHA 2006)

$$\text{AC Index} = 100 - 40[(\%\text{Low}/70) + (\%\text{Medium}/30) + (\%\text{High}/10)] \quad (1)$$

Table 1 Severity of alligator cracking (FHA 2006)

Severity of Cracking	Description*
Low	An area of cracks with no or very few interconnecting cracks and the cracks are not spalled. Cracks are ≤ 6 mm in mean width. Cracks in pattern are no further apart than 0.328 m
Medium	An area of interconnected cracks form a complete pattern. Cracks may be slightly spalled. Cracks are > 6 mm and ≤ 19 mm in mean width. Cracks in the pattern are no further apart than 150 mm.
High	An area of interconnected cracks form a complete pattern. Cracks are moderately or severely spalled. Cracks are > 19 mm in mean width or any crack with a mean width ≤ 19 mm adjacent to a section with high severity random cracking

*These descriptions are enhanced by the use of visual aids in the form of photographs depicting the different severity levels of cracking in pavements These photographs are similar to those shown in Figs. 3(A), 4(A) and 5(A)

Table 2 Quality of pavements using AC index (FHA 2006)*

Quality of Pavement	AC Index Value
Excellent	95-100
Good	85-94
Fair	61-84
Poor	60

*AC Index is calculated using Eq. (1)

Table 3 Evaluation of alligator cracking using the fractal dimension and the AC index*

Severity of cracking	Fractal Dimension, *D*	AC Index Value	Description
Low	1.051	98	Isolated cracks just formed [Fig. 3(A)]
Moderate	1.1754	83	Alligator pattern formed [Fig. 4(A)]
High	1.5037	77	Number of blocks in alligator pattern increase in number. Spalling of the blocks take place [Fig. 5(A)]
Very High	1.7111	47	Blocks begin to lift [Fig. 6(A)]
Detachment (potholes form)	1.8976	15	Complete disintegration [Fig. 7(A)]

*The AC Index was calculated using Eq. (1)

where the %Low, %Medium, and %High represent the *percent of a total area* of a section of pavement with either low, medium and high severity alligator cracking (Table 1). The quality of a pavement is then evaluated using Eq. (1) and Table 2. The total area used for the evaluation measures 32.19 meters in length and a width which is that of the lane considered.

The evaluation provided by the AC Index is then integrated into the overall Pavement Condition Rating (PCR) Index. The calculation of the overall PCR Index requires extensive data collection (not carried out in this study) about the intensity of longitudinal and transverse cracks (the LC and TC Indexes), the measurement of the unevenness of the pavement surface (Rut Index), how much patching was introduced into the pavement structure (Patch Index), and the degree of roughness of the pavement surface (Roughness Condition Index). The value of the overall PCR index is then used to evaluate the overall quality of a pavement section.

This study is only concerned with alligator cracks (the AC Index) and not with the overall PCR Index. In this study a quantification of the alligator crack severity is carried out using the fractal dimension concept from fractal theory as well as the AC Index [Eq. (1), Tables 1, 2 and 3]. It is expected that the current method used to assess the state of alligator cracking of pavements (the AC Index) can be enhanced with the use of the fractal dimension concept from fractal theory.

3. Fractal analysis of the development of cracks in pavements

Fractal geometry is a relatively new mathematical concept developed by Mandelbrot (1982) to quantitatively describe complex patterns in nature. Recently, engineers and earth scientists have successfully used concepts of fractal theory to analyze phenomenon such as the roughness of rock and soil particles and rock joints (Carr and Warriner 1989, Vallejo 1994, 1995); the distribution of rock fragments resulting from blasting (Perfect 1997); the persistence of fault segments in the earth crust (Hirata 1989); the structure and distribution of pores in clays and sedimentary rocks (Vallejo 1996, Schlueter *et al.* 1997), the degree of roughness of pavement surfaces (Vallejo 2001), the degree of roughness of individual cracks in pavements (LeBlanc *et al.* 1991), and the degree of abrasion and crushing of granular bases forming part of pavement systems (Vallejo and Chik 2009).

In this study, the fractal dimension concept from fractal theory is used to quantify the severity of alligator cracking in pavements. This evaluation will be made using photographs of pavements sections experiencing low, medium and high severity alligator cracking.

3.1 The box method to calculate the fractal dimension of the severity of alligator cracking

For our purposes, the fractal dimension concept from fractal theory will be used to evaluate the severity of alligator cracking in pavements. The fractal dimension measures the spatial distribution and the tendency of crack traces to fill the area in which they are embedded (Hirata 1989). According to Hirata (1989), the fractal dimension, *D*, that measures the spatial distribution and the tendency of the crack traces to fill an area can be obtained using the box method (Figs. 1 and 2). The box method uses a sequence of square grids, each with a different square cell size *r* (Fig. 1). The sequence of grids is first drawn on transparent paper. Each grid is then placed over the area containing the traces of cracks. Next the number (N) of the cells intersected by the crack traces is counted (Fig. 1). The fractal dimension, *D*, can be obtained by plotting the number of cells, *N*, versus the corresponding size of the cells used, *r*, on log-log paper. The points on the log-log paper are then connected with a best fitting straight line. The absolute value of the slope of this line represents the fractal dimension, *D* (Fig. 2). The higher the value of *D*, the higher is the level of cracking of the surface being analyzed.

The box method was used to evaluate the level of cracking of sections of asphalt pavements located in the city of Pittsburgh. Photographs showing pavement sections with low, medium, and high levels of cracking are shown in Figs 3, 4, 5, and 6. Also shown in Fig. 7 is a section of pavement that developed a pothole after a high level of alligator cracking caused the detachment of

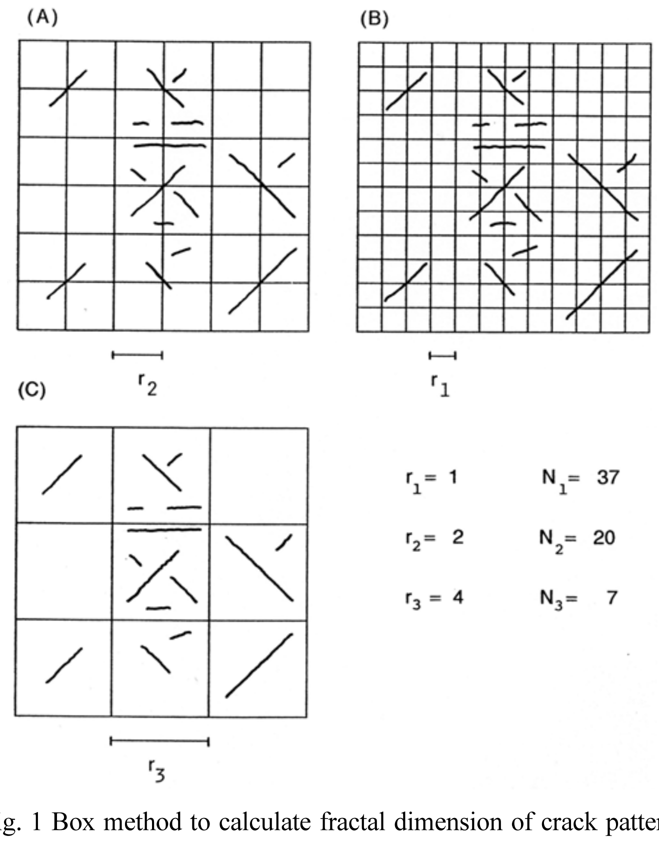

Fig. 1 Box method to calculate fractal dimension of crack pattern.

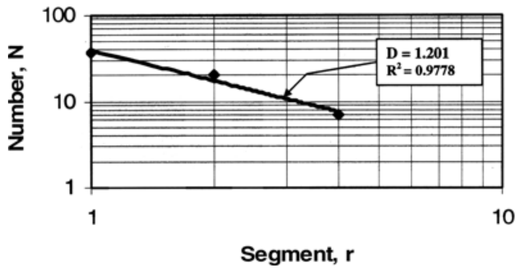

Fig. 2 Fractal dimension, *D*., for crack pattern shown in Fig. 1.

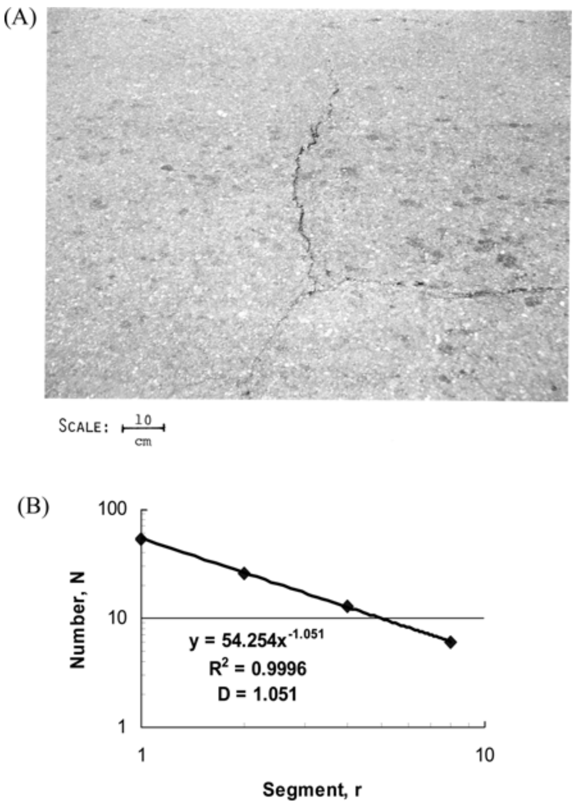

Fig. 3 (A) Pavement with low level alligator cracking. (B) Fractal dimension, *D*, of the low level of alligator cracking shown in (A).

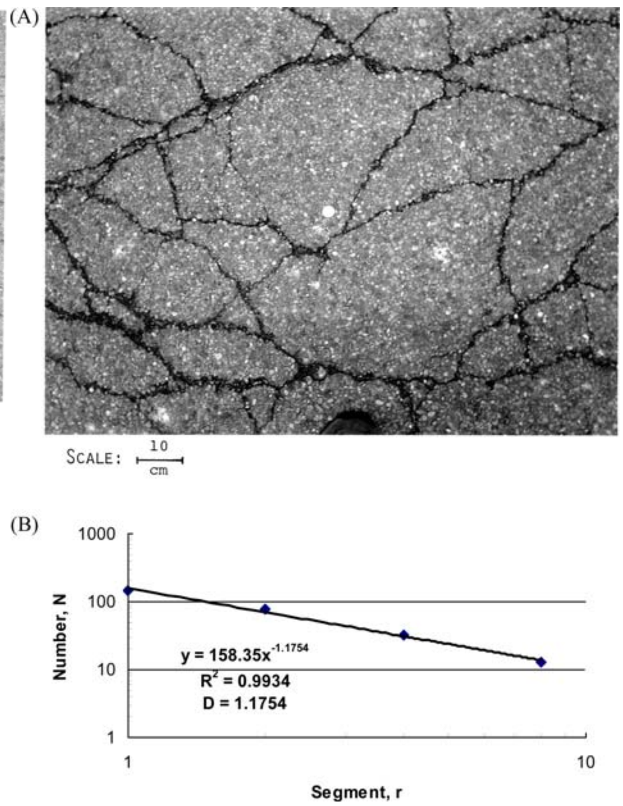

Fig. 4 (A) Pavement with moderate level alligator cracking. (B) Fractal dimension, *D*, of the moderate level of alligator cracking shown in (A).

small blocks of pavement and subsequent removal by traffic induced shear loads.

3.2 The influence of the size of the grid used to calculate the fractal dimension by the box method

Previous studies conducted by Klinkerberg (1994) and Verbovsek (2009) indicate that when the size of the grids or cells used in the box method decreases in size (Fig. 1), the linear relationship in

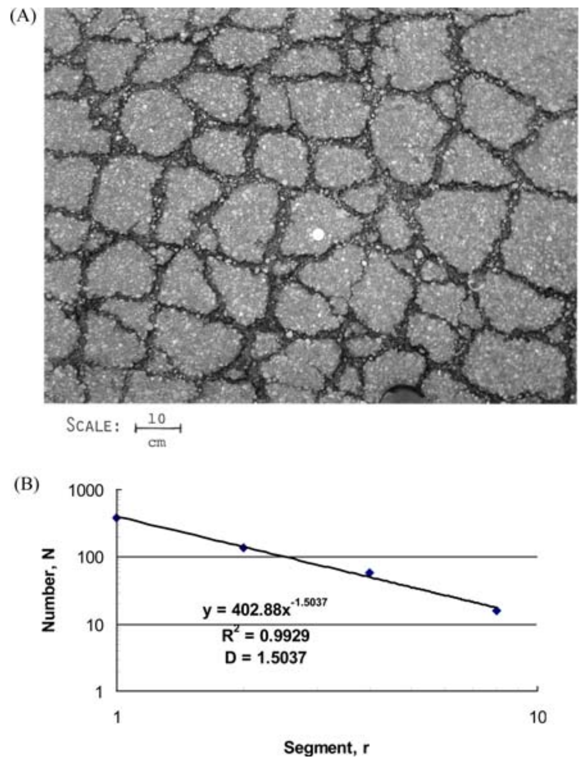

Fig. 5 (A) Pavement with high level alligator cracking. (B) Fractal dimension, D, of the high level of alligator cracking shown in (A).

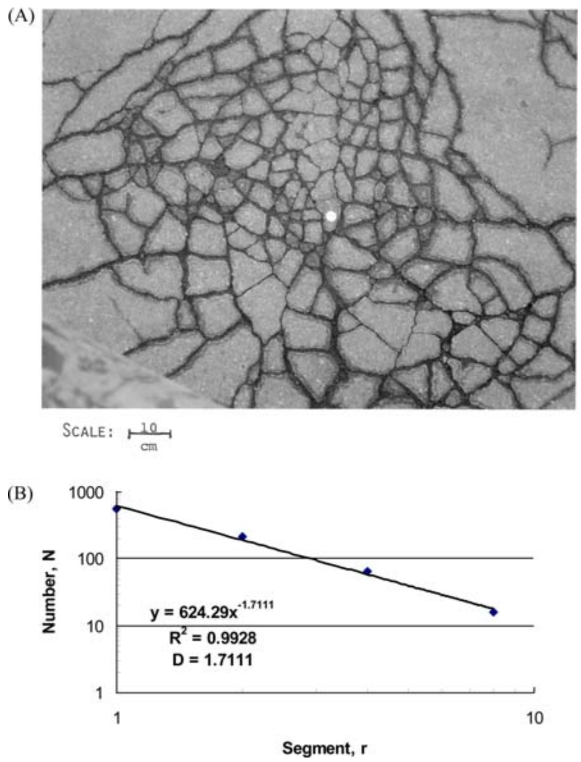

Fig. 6 (A) Pavement with very high level alligator cracking. (B) Fractal dimension, D, of the very high level of alligator cracking shown in (A).

the log-log paper plot between the number (N) of the cells intersected by the crack traces and the size of the cells (r) is lost. For the case of small cell sizes, there is a point at which the relationship between N and r follows a curve instead of straight line. This seems to be not the case for the fractal plots shown in Figs. 3 to 7. Figs. 3 and 7 shows a linear relationship between N and r. Also, the best fitting lines for the points relating N and r have correlation coefficient values R^2 that are greater than 0.99. Thus, the size of the cells r used in this study seems to be appropriate.

4. Analysis of the level of alligator cracking in the pavement sections using fractals

Figs. 3 to 7 show the results of the fractal analysis for the crack severity in the pavement sections. When the number of cracks in the pavement section analyzed was low and their spatial distribution was concentrated in a small area of the pavement section (Fig. 3), the fractal dimension, D, in this section was equal to 1.051 [Carr and Warriner (1989) advise the use of four digits after the decimal point when using the fractal dimension value as a quantity of measurement]. As the number of cracks grew and the spatial distribution covered the section of the pavement being analyzed, the fractal dimension was equal to 1.1754. This fractal dimension applies to a degree of alligator cracking classified as moderate (Fig. 4). When the degree of severity of cracking increased in a pavement

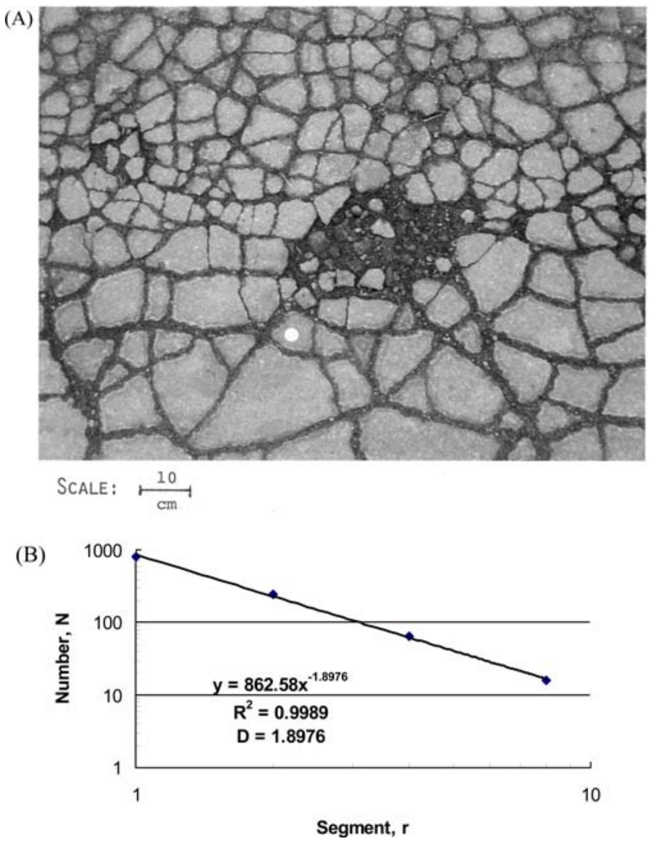

Fig. 7 (A) Pavement with detachment level alligator cracking. (B) Fractal dimension, *D*, of the detachment level of alligator cracking shown in (A).

section to a level classified as high, the fractal dimension, *D*, reached a value equal to 1.5037 (Fig. 5). For the case of a severity of cracking that was very high, the fractal dimension, *D*, increased to a value equal to 1.7111 (Fig. 6). Further increase in the level of cracking produced critical conditions at which small blocks detached from the pavement surface and were removed by traffic induced shear stresses. When detachment occurred, the fractal dimension, *D*, reached a very high value of 1.8976 (Fig. 7). Using the fractal approach, a classification for the level of alligator cracking has been developed and is shown in Table 3. This table also indicates the AC Index evaluation of the level of alligator cracking in the pavements. The level of alligator cracking seems to be well assessed by the fractal dimension values (*D*) and the AC Index values (Tables 2 and 3).

The analysis presented in this study makes use of a typical survey (photographs) taken of sections of pavements experiencing alligator cracking. Recently, automation surveys have been developed for a rapid assessment of a pavement distress. The automation surveys make use of expensive vehicle-carried cameras, laser sensors and other sensor systems to inspect objects from close range (Lee *et al.* 2002). The analysis of the alligator crack data obtained during the automation survey can be analyzed using software that makes use of the box method in order to obtain the fractal dimension value that measures the levels of alligator cracking in pavements. The present study presents a simpler and cheaper method to measure the quality of a pavement experiencing alligator cracking.

5. Conclusions

An experimental and analytical evaluation of the alligator cracking that takes place as a result of traffic loads on asphalt pavements was carried out. Photographs of pavement surfaces with low, moderate, high, very high and critical alligator cracking levels were used for the analysis. The analysis of the intensity of cracking was carried out using the fractal dimension concept from fractal theory and the Alligator Crack Index (AC Index). From the experimental and analytical investigations, the following conclusions were reached:

(1) The severity of alligator cracking in the pavement sections analyzed was reflected in the fractal dimension, D, values. Low levels of cracking were associated with low values of D. High levels of cracking were associated with high values of D. For the pavement sections analyzed, the fractal dimension, D, was equal to 1.051 for low level of cracking, 1.1754 for moderate level of cracking , 1.5037 for high level of cracking , 1.7111 for very high level of cracking, and 1.8976 for critical level of cracking (pothole formation).

(2) The use of the fractal dimension concept from fractal theory proved to be a simple, elegant and powerful mathematical tool to measure the intensity and severity of alligator cracking experienced by asphalt pavements due to traffic loads.

(3) The Alligator Crack Index (AC Index) also gave reasonable values for the level of alligator cracking in the pavements studied. It was determined that the higher the values of the AC Index were, the higher was the quality of the pavements.

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