DEVELOPMENT OF A PERFORMANCE PREDICTION MODEL TO MANAGE FLUSHING OF SPRAYED SEAL PAVEMENTS

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ABSTRACT

Flushing is a defect which has a damaging effect on the functional performance of sprayed seal (chipseal) pavements. Accurate understanding of flushing can have a significant impact when predicting the future performance and maintenance needs of pavements. The reported study was conducted to develop a prediction model to effectively identify, asses and manage flushed pavements. The study also aimed to develop a decision-making tool for treating flushed pavements. This study utilised pavement data from New Zealand's Long-Term Pavement Performance programme and data analysis was conducted to develop a model to predict the flushing potential of chipseal pavements. Additionally, the study conducted laboratory testing on pavement samples from flushed chipseal pavements. The conducted tests included wheel tracking and rutting measurements, air void volume measurements, as well as computed tomography scanning and image analysis. The laboratory test results were used to supplement the outputs of the performance prediction model in detecting the mechanisms that were causing flushing. The outcomes of this study included a model that was able to predict a) the probability of flushing initiation, and b) the quantity of flushing on a pavement. This model was statistically robust where the flushing initiation model had an accuracy of 76%. The flushing prediction model and the laboratory results were incorporated into an overall pavement assessment guideline for flushed pavements. This assessment guideline will aid pavement practitioners with accurate identification of flushing on a pavement network as well as with selecting the best method of maintenance treatment for flushed chipseal pavements.

Key words: flushing; chipseal; sprayed seal; performance prediction

INTRODUCTION

A sprayed seal (chipseal) is a type of pavement surfacing that consists of layers of aggregate and bituminous binder and is used to provide a suitable surface for the safe movement of vehicles. Chipseal surfacings are generally economical to construct, which makes them an ideal surfacing type for low volume roads. A defect that can significantly reduce the structural integrity and safety performance of chipseal surfaces is flushing, which is commonly characterised by a smooth area on the pavement surface having low skid resistance. Flushing occurs as a result of full or partial covering of surface aggregates due to either the upward migration of bituminous binder or the embedment of surfacing aggregate into the pavement layers underneath (*1*). Flushing is a predominant surfacing problem in countries such as New Zealand, and it is becoming increasingly more common on chipseal pavements in the United States of America and Canada (*2; 3*). However, it is often not modelled in pavement management systems as currently there is no model incorporated in World Bank's HDM-4 and NZdTIMS system to forecast flushing.

The assessment of flushing of chipseal pavements is generally performed using visual ratings or is evaluated by measuring the surface texture depth (*4-7*). These assessment methods are useful when investigating local texture irregularities, although when considering large parts of a pavement network, visual ratings and texture depth measurements can be inaccurate and inefficient. Consequently, there is a need for a systematic procedure to effectively identify flushing patterns on chipseal pavements, and the use of pavement deterioration models to predict defects such as flushing is an efficient and accurate method of pavement management (*8*), that can simultaneously overcome the limitations of visual and indirect management methods.

OBJECTIVES

The main objective of the presented study was to develop an assessment technique to effectively predict the occurrence of flushing on chipseal pavement surfaces. As part of this objective, it was aimed to firstly, develop a data-driven prediction model that identified the presence and the quantity of flushing, and secondly, to establish performance characteristics of chipseal surfacings that indicated their flushing potential.

METHODOLOGY

The main component of the test methodology of this study consisted of data analysis that was performed on pavement data that was collected from the New Zealand Long-Term Pavement Performance (LTPP) programme's databases. The LTPP dataset contains highly accurate pavement condition data from selected pavement sections in New Zealand (Henning et al., 2004, Brown, 2005). The LTPP dataset comprised of pavement performance data which had been collected annually since the year 2001 from 58 state highway calibration sections and 83 local authority calibration sections. Data items included in the LTPP database consist of pavement characteristics, namely pavement and surface age, surface thickness and materials, traffic volumes, structural condition of pavements as identified from visual recordings of distresses, and maintenance carried out on the sections. Flushing measurements in the LTPP database were obtained by performing visual inspections and are recorded as the percentage of area of the pavement surface displaying flushing. The Average Annual Daily Traffic (AADT) volumes on the LTPP sites ranged from 42 vehicles per day (vpd) and 24,360 vpd. Further information about the LTPP dataset and the variables that are recorded in the LTPP database has been previously reported (*9*). The data that was used in the development of the flushing model consisted of pavement performance data gathered from year 2001 to year 2011 (10 survey years). The dataset was then separated into two subsets: one subset was used for model development and the other subset was used for model validation. The LTPP dataset covered a wide range of pavement thicknesses, surface ages and traffic volumes, which made it ideal for developing the flushing prediction model.

Laboratory testing chipseal samples were also conducted as part of the reported study to supplement the data analysis task. The testing that was performed consisted of mechanical testing of pavement samples such as wheel tracking, measurements of flushing quantity, rutting and air void volumes, bitumen content measurements, Computer Tomography (CT) scanning and image analysis of chipseal samples. Pavement samples (cores) that were obtained from in-service chipseal pavements from the Auckland, Waikato, Christchurch and Dunedin regions of New Zealand were used for testing. Detailed information about the sampling methodology and laboratory testing that were conducted as part of this study are presented elsewhere (*10; 11*).

DATA ANALYSIS RESULTS

Data analysis was conducted to develop a model to predict flushing of chipseal pavements. The flushing model consisted of two sub-models, where one model was used to predict the initiation of flushing and the other model was used to predict the progression of flushing.

When undertaking pavement distress modelling it is important to determine when a distress reaches an extent such that intervention is needed to minimise the progression of that distress. This distinction is important for flushing because a pavement can have a small amount of flushing and still be structurally sound and safe for use by traffic. Once flushing becomes more widespread on the pavement surface, such that the safety performance and the structural integrity of the seal layers are compromised, the pavement must be monitored for maintenance. Thus, when modelling flushing the point at which intervention is needed for flushing can be considered as the point at which flushing initiates.

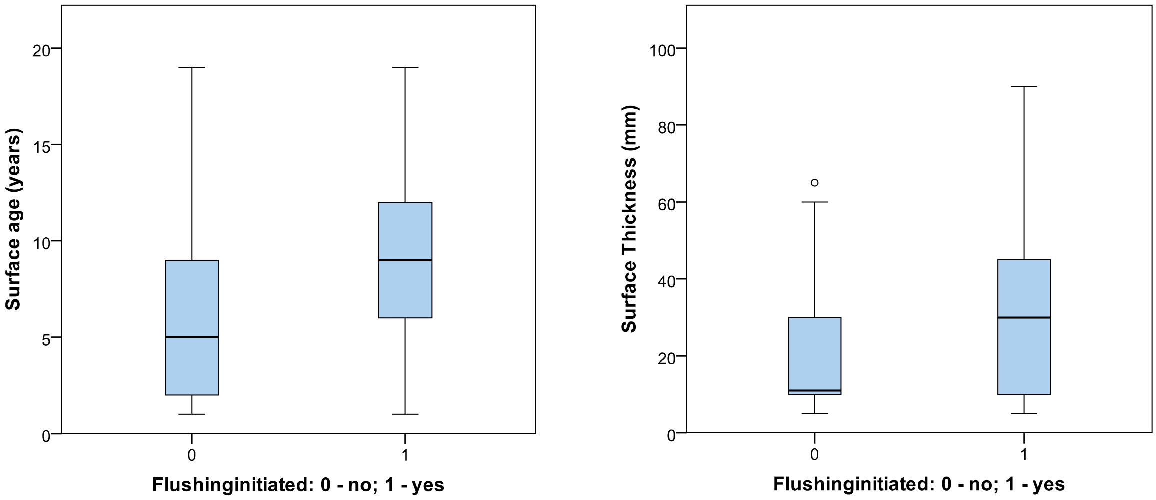
The point of initiation of flushing was modelled using logistic regression (*12*), which is a method that is commonly used to model the likelihood of a certain event occurring, in this case being the initiation of flushing (*13*). The advantage that a logistic model format has over a simple linear regression model format is that the former provides the probability of failure occurring, which allows for flexibility when applying the model to a wide range of datasets. In the logistic model, the dependant variable takes a binary form, typically 1 to denote the occurrence of an event and 0 to denote the non-occurrence of the event, and the output of a logistic model is a probability plot of the event occurring with respect to an independent variable. The percentage of flushing recorded on each pavement site in the LTPP database was converted to a binary variable, *FlushingInitiated*, where 1 was used to indicate that flushing had initiated on a pavement and 0 was used to indicate that flushing had not initiated. The selection of the flushing initiation threshold was based on analysis that was conducted as part of a separate study which analysed the relationship between flushing and surface texture depth as given by Mean Profile Depth (MPD) (*14*). The analysis revealed that the greatest change in surface texture occurred when flushing was between 0% and 20%. When flushing reached higher than 20% the change in surface texture was slower. The point of deterioration of surface texture is an important maintenance trigger which also indicates the presence of noticeable levels of flushing. Hence, a flushing threshold value of 20% was chosen as the point at which flushing initiates on a given pavement site.

The variables that were included in the logistic regression were determined by investigating the effect that each potential independent variable had on flushing initiation. Figure 1 shows the effect of surface age (measured in years) and surface thickness (measured in millimetres) on flushing initiation. It is clear that surface age and surface thickness have an effect on flushing initiation, where for both variables the difference in the mean between pavements that had flushing initiating and pavements that did not have flushing initiating was statistically significant (*p* value = 0.000). Additionally, the effects of rutting and number of Heavy Commercial Vehicles (HCV) on flushing initiation were also tested, however, it was found that these two variables were not significant to be included in the flushing initiation model development.

Logistic regression was performed using a forward stepwise method, and based on the regression results the logistic model to predict the probability of flushing initiation is as shown in Equation (1):

$$\mathrm{p(FlushingInitiated)} = 1 / 1 + e^{-(0.293\mathrm{surfage} + 0.046\mathrm{Surfthickness} - 2.913)} \tag{1}$$

Where, *p(FlushingInitiated)* is the probability that flushing has initiated; *surfage* is the age of the pavement surface in years; and *Surfthickness* is the thickness of the pavement surfacing layer in millimetres.



a) Surface age on flushing initiation **b) Surface thickness on flushing initiation**

Figure 1 Effect of surface age and surface thickness on flushing initiation

The graphical representation of the logistic model format to indicate the initiation of flushing is shown in Figure 2, which presents the probability of flushing initiating on a given pavement surface with respect to surface age and for different surface thicknesses. From the information in Figure 2 it can be seen that the time of flushing initiation varies significantly for different surface thicknesses. When considering a surface with a 10 mm thickness, at 8 years there is a 0.5 probability that flushing had initiated on that surface, while a surface that is 30 mm thick has a 0.5 probability of flushing initiation at 5 years. When the surface thickness of a pavement is approximately 60 mm, the likelihood of flushing initiation is high, where immediately from the beginning of pavement life there is a 0.5 probability of flushing initiation. The model results in Figure 2 indicate that surface thickness has a significant role in flushing initiation. The prediction accuracy of the logistic model was tested using the second subset of LTPP data, and the model was found to correctly predict flushing initiation at an accuracy of 76%.

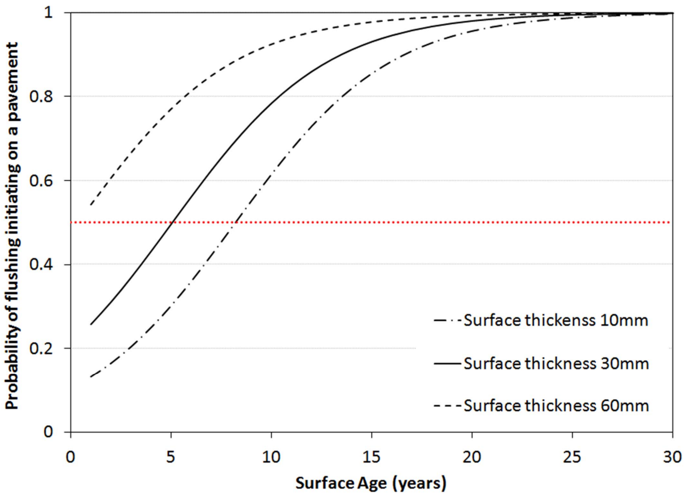


Figure 2 Model outcome to predict the probability of flushing initiation

Progression of Flushing

The progression of flushing on the LTPP sites was modelled using a non-linear model format where a forward stepwise reverse-linear regression method was used to develop the model (*15-17*). The independent variables that were used in the regression included pavement surface thickness, surface age, percentage of HCVs, rutting and grade of aggregates in the seal. A square-root transformation was applied to the original flushing data to obtain a normally distributed independent dataset which was required for linear regression. The independent variables that were found to be significant contributors to the regression model (p value <0.000) were surface age (surfage), surface thickness (Surfthickness), rutting (RutLANE) and grade of aggregates (Chipsize). The R^2 value of the non-linear model was 0.643, which was statistically robust, and the resulting model for flushing progression prediction is shown in Equation (2):

$$\text{Flushing} = [0.416\text{surfage} + 0.040\text{Surfthickness} + 0.110\text{RutLANE} + 0.170\text{Chipsize}]^2 \qquad (2)$$

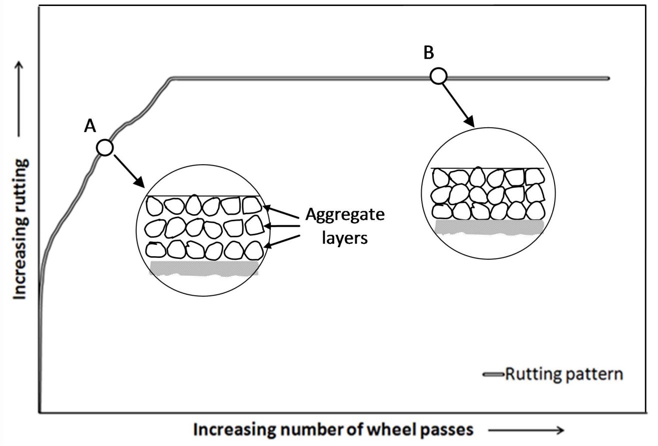
Where, *Flushing* is the amount of flushing on the pavement (percentage of surface area); *surfage* is the age of the pavement surface; *Surfthickness* is the thickness of the pavement surfacing layer (in mm); *RutLANE* is the average rutting on the pavement (in mm); and *Chipsize* is the grade of aggregates on the pavement surface.

The flushing progression model was tested using the second subset of LTPP pavement data. The model had statistically significant strength in its predictions of flushing with the R^2 value of the relationship of observed flushing and model predicted flushing being 0.561.

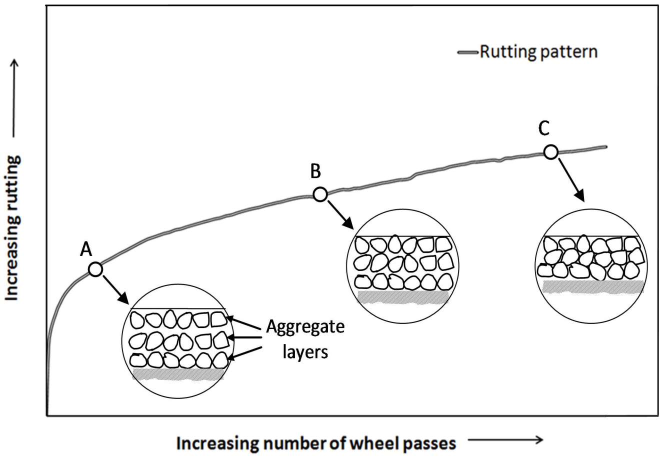
The results from this study provide a valuable understanding of the nature of flushing, as currently there is no known model which considers the combination of different variables and their effect on flushing. The developed model considered a number of site characteristics when determining the likely amount of flushing at a site, and therefore this method can give a more accurate indication of flushing than when using a single measure to identify flushing. As this method of flushing detection considers the whole site when determining the flushed condition, it is an efficient method to use for flushing identification and management on large pavement networks. The presented models can also be used by pavement management authorities to predict the likelihood of future flushing occurrence on chipseal pavements in a pavement network.

Laboratory Testing and Summary of Results

In order to supplement the findings of the above described flushing model development, laboratory testing was conducted on chipseal pavement samples (cores) that were obtained from in-service pavements. Wheel tracking tests were conducted on the cores to investigate the relationship between flushing and rutting pattern. From all the cores that were wheel tracked some distinct rutting patterns were identified, and these patterns were used to understand the behaviour of the aggregate layers within the cores and the effect of that behaviour on the flushing quantities that were present on the core surfaces. One rutting pattern that was identified from the wheel tracked cores was a pattern where rutting developed up to a point in the wheel tracking test and then reached a stable state where no further rutting developed up until the termination of the tracking test (Figure 3a). The enlarged portions of the rutting pattern in Figure 3a shows the likely state of the chipseal layers within the core, where at the beginning portion of the tracking test when rutting is still developing (at point A), there is spacing between the aggregate layers. As the core continues to be tracked the spacing between the aggregate layers decreases and the core reaches a stone-on-stone state where the aggregate layers are lying directly on top of each other (at point B). The other rutting pattern that was identified was a pattern where rutting continued to develop until the termination of the tracking test (Figure 3b). In this situation the aggregate layers slip past each other and the chipseal structure continues to deform with increasing loading, as shown at point B and C.



a) Stable rutting pattern



b) Continuous rutting pattern

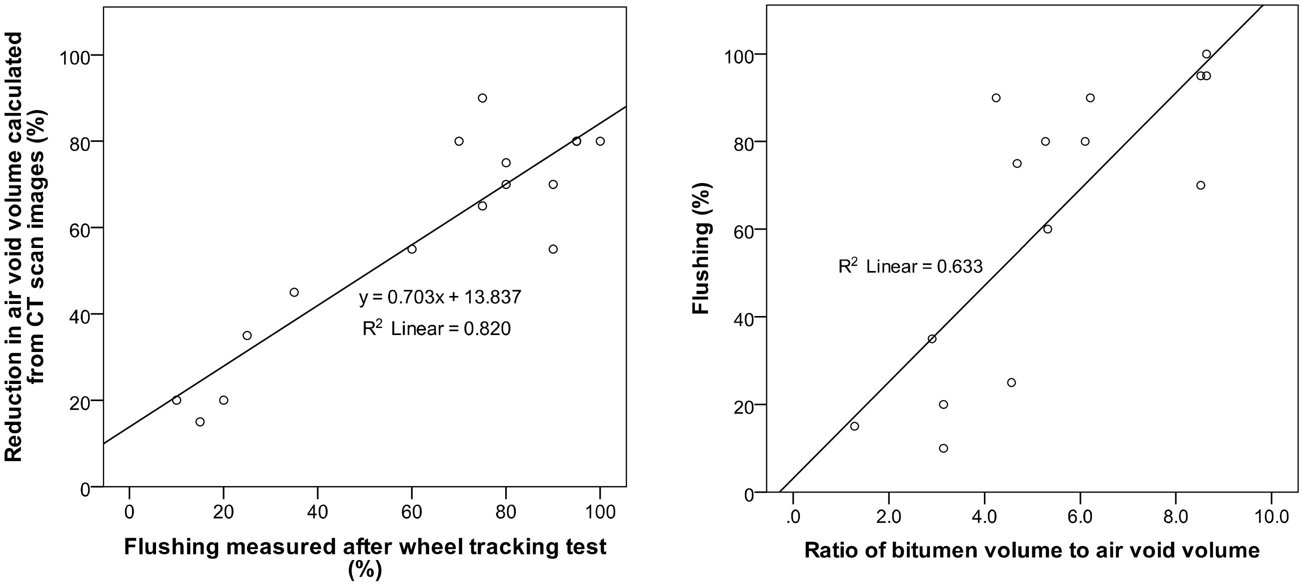
Figure 3 Schematic showing the development of rutting patterns and the corresponding state of aggregate layers

Due to limitations in available space, only a portion of the wheel tracking results and analysis are presented here. The complete results of wheel tracking are presented elsewhere (*11*).

Relationship between Air Voids Reduction and Flushing Trends

The wheel tracked chipseal cores were further analysed using Computed Tomography (CT) scanning and image analysis techniques to examine the internal characteristics of the chipseal cores. As part of this task, the air void distributions within the chipseal cores were analysed, and these air void volume results were used to establish the correlation between air void volumes and the quantity of flushing that was measured on the chipseal cores at the end of the wheel tracking tests. For each core, the reduction in air void volume that had occurred in the core during wheel tracking was determined and this air void volume reduction was compared to the quantity of flushing that was measured on that core. The results are shown in Figure 4a. An understanding of chipseal behaviour and knowledge from previous studies (*18-20*) indicate that the volume of air voids in a chipseal plays a significant role in its volumetric balance, and is particularly important for the occurrence of flushing. A lack of air void volume in a chipseal structure affects the movement of bitumen when subjected to loading, which in turn leads to flushing. Figure 4a, shows a strong correlation ($R^2 = 0.820$) between the quantity of flushing and the reduction in air void volume. This correlation aligned with the supposition that flushing was caused by a reduction in the volume of air voids. In order to extend the investigation into the contribution of air void volume reduction to flushing, analysis was conducted to investigate the inter-relationship between flushing, air void volume and binder volume. For each core, the ratio between the binder volume and the air void volume after being wheel tracked (bitumen-to-air void volume ratio) was calculated, and this value was plotted against the amount of flushing. The results are shown in Figure 4b, and as can be seen, there is a strong correlation between flushing and the bitumen-to-air void volume ratio ($R^2 = 0.633$). This result confirmed that the air void volume reduction that causes flushing occurred due to the chipseal surface having an excessive quantity of bitumen in comparison to its available volume of air voids. The result shown in Figure 4b aligned with findings from past research that had investigated the behaviour of asphalt concrete pavements where it was found that the primary reason for the appearance of bitumen on a pavement surface was the lack of availability of air void volume for bitumen movement (*20-22*). Therefore, it can be concluded that flushing occurs as a direct result of a chipseal surface having a high bitumen-to-air void volume ratio.

When determining maintenance treatments for a flushed site, multiple investigative methods must be used for selecting the most effective maintenance treatment for the site. Combining the outcomes from the flushing prediction model with laboratory-based testing is a robust and efficient method of selecting the best maintenance treatment for a potential flushed site. Figure 5 presents a condition assessment guideline that is recommended for use in assessing and selecting appropriate maintenance treatments for flushed pavements.



a) Correlation between flushing and the air void volume reduction

b) Correlation between flushing and the ratio of bitumen volume to air voids volume

Figure 4 Effect of air void volume on flushing

The developed flushing prediction model is the first method of assessment that can be applied to a pavement network where the model can be used to identify specific pavement sections that are failing or likely to fail due to flushing. Once a problem site has been identified, then laboratory-based assessment methods can be used to conduct an in-depth inspection of the identified site and to confirm the model findings. The network-wide application of the assessment guideline presented in Figure 5 will aid with establishing a balance of different types of maintenance treatments for the whole pavement network. Presently, the lack of availability of a flushing prediction model in pavement management systems means most chipseal surfaces are resealed on a regular basis to prevent future flushing. While this process delays flushing development in the short term, maintenance by resealing is ineffective in the long term. The use of the presented flushing assessment guideline therefore will aid with early identification of potential flushing within a pavement network, allowing selection of the most effective methods of maintenance for specific areas of a pavement network. Furthermore, identification of the specific maintenance needs of a pavement network allows efficient allocation of funds within asset management programmes.

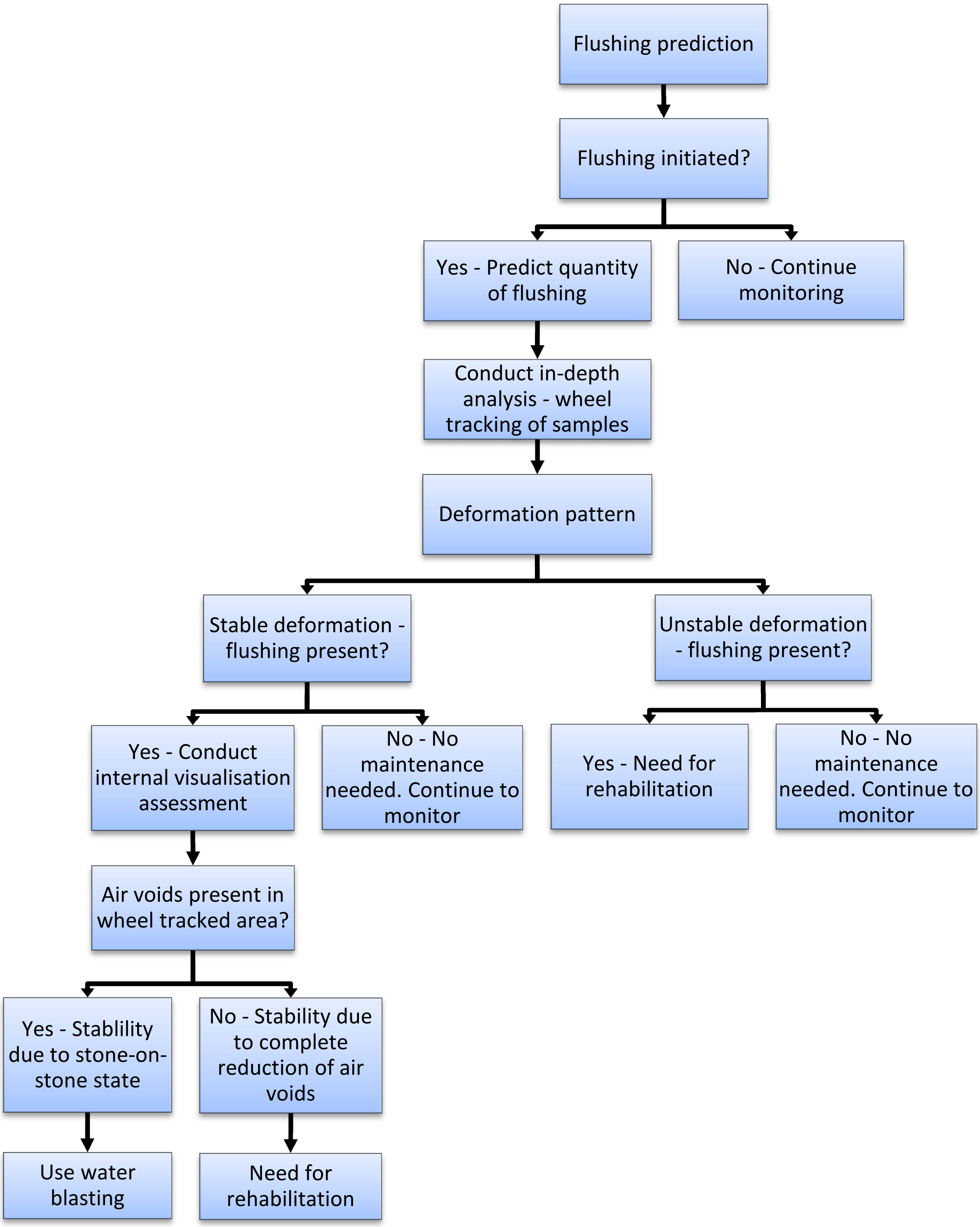


Figure 5 Assessment of flushing of chip seal pavements

CONCLUSIONS

The reported study was undertaken to develop techniques to effectively identify and assess flushed pavements. The objectives of the study were to develop a data-driven model to predict the initiation and the progression of flushing as well as to establish how performance characteristics of chipseal surfacings that indicated their flushing potential, particularly investigating the correlation between flushing and rutting, and the role of air void volume on the development of flushing of chipseal surfaces.

The development of the flushing prediction model was undertaken using pavement condition data collected through New Zealand's LTPP database, and from the data analysis it was found that the combination of variables that provided the best indication of flushing were surface thickness, surface age, grade of aggregates of the surface and the rut depth on the pavement surface. Flushing was modelled in two stages, one stage being the initiation of flushing and the other stage being the progression of flushing. The point of flushing initiation was modelled with a logistic model format to obtain the probability that flushing has initiated on a given pavement based on the age and thickness of the surfacing layer. The model was found to have an accuracy of 76% when used to predict the initiation of flushing on a separate set of data, which showed robustness in the model. The trend in the progression of flushing was modelled using a non-linear model format and the model was tested using a separate set of LTPP data. The model predictions revealed that the developed model was robust at predicting the progression of flushing. Thus, the flushing progression model is recommended for use as part of the management process for pavement networks containing chipseal pavements.

The laboratory testing demonstrated how a chip seal structure behaves when subjected to loading, where two distinct rutting patterns were observed from the wheel tracking results. One pattern was a continuous deformation pattern and the other pattern was a stable deformation pattern. The pattern of deformation of a chipseal indicated the state of stability of that chipseal structure, whether the structure would reach a stable state when loaded or whether the structure would continuously deform and become unstable with continued loading. The laboratory investigations also revealed strong correlations between flushing and the reduction in air void volume, and flushing and the bitumen-to-air void volume ratio of chipseal cores. This correlation confirmed the supposition that flushing was caused by a reduction in air voids.

The results of the flushing model were combined with the findings from laboratory testing to develop a pavement assessment guideline to select the best method of maintenance treatments to use for flushed chipseal pavements. By identifying the specific maintenance needs of a pavement network it is possible to achieve efficient allocation of funds within asset management programmes. Thus, overall through the presented research, more efficient and effective methods for identifying, assessing and managing flushing on chipseal pavement networks have been identified.

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