A Study on the Flood Affected Flexible Pavements in Australia

Masuda Sultana\textsuperscript{1, a}, Gary Chai\textsuperscript{2, b} Tim Martin\textsuperscript{3, c} and Sanaul Chowdhury\textsuperscript{4, d}

\textsuperscript{1}\textsuperscript{2}\textsuperscript{4}Griffith University Gold Coast campus, QLD 4222, Australia
\textsuperscript{3}Melbourne, Victoria, 500 Burwood Hwy Vermont South VIC 3133, Australia
\textsuperscript{a}m.sultana@griffith.edu.au, \textsuperscript{b}g.chai@griffith.edu.au, \textsuperscript{c}tim.martin@arrb.com.au
\textsuperscript{d}s.chowdhury@griffith.edu.au

Abstract. Roads were one of the most valuable assets damaged during the devastating flood of January, 2011 in South-East Queensland. Research by ARRB Group and Griffith University, with Austroads funding, was initiated in early 2013 to evaluate the impacts of extreme weather events such as flooding and frequent heavy rainfall on pavement deterioration. The research examines the structural and functional performance of flood affected flexible pavements using the Falling Weight Deflectometer (FWD) and surface condition data sourced from Brisbane City Council and Roads and Maritime Services of New South Wales, Australia. This paper presents the findings on the structural and functional performance of flood affected flexible pavements in Australia. A comparison is presented of before and after flood data on flooded and non-flooded sections of the pavements. The results indicate that the flood affected pavements suffer losing their structural strength faster than their normal deterioration rate. A reduction in the subgrade CBR value up to 67\% and structural number up to 50\% has been observed. The reductions in the subgrade CBR and structural number would not be so high and rapid if the roads were to deteriorate under normal weather conditions without the flooding event. However, re-testing a number of the pavement sections, several months or years after the flooding, shows a consistent trend of gaining the strength mainly due to the post-flooding rehabilitation works. Preliminary analyses conducted on the surface condition of flood affected pavements indicate a marginal loss of roughness, rutting and cracking. This research will improve the road network condition prediction for flooding events and is expected to identify the adaptation options to reduce the flooding impacts in terms of cost at road network level.

Keywords: Structural Strength, Functional condition, Flood Affected, Local Roads, Flexible, Pavements, Australia

Introduction

August to December of 2010 was a very wet weather period in Australia with the heavy rains of earlier months extending south to include most of Victoria and Tasmania. The rainfall for this period was the highest on record across vast areas of eastern Australia, particularly Queensland, as well as the top end of the Northern Territory, and the Gascoyne region of Western Australia. Flooding was a regular occurrence and there was substantial recharge in many depleted water storage system [1]. During the final week of December 2010 to January 2011, Queensland experienced widespread flooding, with three quarters of the state declared a disaster zone [2]. Floods are the most expensive type of natural disaster in Australia with direct costs estimated over the period 1967-2005 averaging at $377 million per year (calculated in 2008 Australian dollars). Until recently, the most costly year for floods in Australia was 1974, when floods affecting New South Wales, Victoria and Queensland resulted in a total cost of $2.9 billion. The Queensland Government estimates costs for the 2011 floods would exceed this figure for Queensland alone; with the damage to local government infrastructure estimated at $2 billion, and the total damage to public infrastructure across the state at between $5 and $6 billion [2].

Roads were among the assets destroyed when Queensland experienced the worst flooding in more than a century in January, 2011. Rainfalls of between 600-1000mm were recorded in most of the Brisbane river catchment during December 2010 and January 2011. Most of this rainfall fell
between 9 January 2011 and 13 January 2011 with rainfall exceeding the 1% Annual exceedance probability (100 year Average Recurrence Interval) intensities for parts of the catchment [3]. Within Brisbane, approximately 22,000 homes and 7600 businesses across 94 suburbs were flooded [4].

Modelling pavement performance subject to extreme weather events such as flooding and heavy rainfall is not a simple task. Unlike the conventional approach of modelling the deterioration of pavements under normal climatic conditions, flooded pavements and extreme heavy rainfall events introduce a new dimension into the already complex mathematical model when pavements are either partially or fully saturated [5]. These dynamic conditions add new challenges to road engineers in managing the road asset. Moreover, condition data prior to and after the flooding events needs to be gathered to assess existing pavements as it will provide valuable information for building resilience into future pavements and will help to predict the cost consequences when resilience cannot be built-in.

Aim of the Research

The research aims to advance the knowledge on the effect of extreme weather events such as flooding or frequent heavy rainfall events, on pavement deterioration. The aim of this paper is to address the long term impact of flooding on the sealed local roads. An extensive and long-term monitoring of flood affected roads is very significant to assess the rapid deterioration phase of pavement after flooding. Hence, it is necessary to implement a systematic program to investigate the deterioration of flood affected roads.

This study commenced in early 2013; it was funded by Austroads and the ARRB Group in a collaborative research arrangement between the ARRB and Griffith University. The study examines the structural and functional performance of flood affected flexible pavements using the Falling Weight Deflectometer (FWD) and surface condition data sourced from the Brisbane City Council (BCC) and the Roads and Maritime Services of New South Wales (RMS, NSW). CIRCLY5.0 program [6] was used to analyze FWD deflection data. SPSS, Excel spreadsheet and OriginPro8 were used to process data. ‘Linear Rate of Progression (LRP) Software Tools’ from ARRB will be used to analyze surface condition data.

Literature Review

The design of roads is based on the moisture and temperature patterns reflecting the historical climate of the location. The changes in the rainfall, temperature, and evaporation patterns can alter the moisture balances in the pavement foundation which can lead to the reduction of the structural strength of the pavement. As the frequency of the extreme rainfall events increased over the past few years, it may influence the structural strength and surface condition of the pavements. It can significantly impact the planning and management of both maintenance and rehabilitation of the roads.

The prediction of pavement performance is a critical element of the pavement management systems currently being developed in Australia [7]. The objective of the structural evaluation of pavement is to determine the present structural condition of a pavement and its capacity to withstand traffic and environmental forces over the design period. It is also the foundation for the design of any (structural) rehabilitation treatments that may be required [8]. As structural capacity cannot be determined directly, a number of indirect indicators are used. These include:

- Surface defects observable during a visual survey (e.g. rutting, cracking and shoving);
- Structural response to load (i.e. deflection data);
- Properties of pavement and subgrade materials (e.g. as determined from field sampling and laboratory testing); and
- Moisture related defects [8].

The assessment of current structural capacity, and therefore the remaining structural capacity, has to be made relative to a definition of when the terminal structural condition has been, or will be, reached. The actual terminal structural condition and its associated distresses will depend on the levels of service, or functionality, required of the pavement. These levels of service and their
limiting distress values are based on avoiding rapid or catastrophic failure and its consequences. This means that stricter distress limits are maintained for heavily trafficked pavements relative to lightly trafficked pavements. Table 1 outlines some possible distress limits for defining the terminal structural condition of pavements for their service life [9].

<table>
<thead>
<tr>
<th>Road Function</th>
<th>Surface Deflection D0 (mm)</th>
<th>Roughness Limit (IRI)</th>
<th>% Road Length with Rut Depth &gt; 20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeways, etc.</td>
<td>0.8</td>
<td>4.2</td>
<td>10</td>
</tr>
<tr>
<td>Highways and main roads (100 km/h)</td>
<td>0.85</td>
<td>4.2</td>
<td>10</td>
</tr>
<tr>
<td>Highways and main roads (80 km/h)</td>
<td>0.9</td>
<td>5.4</td>
<td>20</td>
</tr>
<tr>
<td>Other sealed local roads</td>
<td>1.6</td>
<td>No defined limit</td>
<td>No defined limit</td>
</tr>
</tbody>
</table>

The network level structural deterioration models developed for asphalt and unbound granular pavements, with the $SNC_{\text{ratio}}$ as the dependent variable, are as follows [10]:

$$SNC_{\text{ratio}} = 0.991 \times (2 - \exp\left(0.00132 \times \text{TMI}_i + 0.256 \times \frac{\text{AGE}_i}{\text{DL}}\right))$$  \hspace{1cm} (1)

$$SNC_{\text{ratio}} = 0.9035 \times (2 - \exp\left(0.0023 \times \text{TMI}_i + 0.1849 \times \frac{\text{AGE}_i}{\text{DL}}\right))$$  \hspace{1cm} (2)

Equation (1) is for asphalt pavement and equation (2) is for sealed unbound granular pavements, where,

- $SNC_{\text{ratio}} = \text{current strength of pavement/subgrade relative to its initial strength (}=SNC_i/SNC_0)$
- $SNC_i = \text{modified structural number at the time ‘i’ of measurement}$
- $SNC_0 = \text{modified structural number at the time of the pavement construction (AGE = 0)}$
- $\text{TMI}_i = \text{Thornthwaite Moisture Index at the time ‘i’ of assessment}$
- $\text{AGE}_i = \text{age of pavement (number of years since construction or last rehabilitation)}$
- $\text{DL} = \text{Pavement design life (years)}$.

The above interim structural deterioration models predict that the impact of the TMI variable is greater on the deterioration of unbound granular pavements than it is for asphalt pavements [10].

The diversity of extreme weather events impacting transportation is immense and each event poses unique challenges. It can create havoc with transportation asset management plans, which are often based on predictable deterioration curves [11]. When the two devastating Hurricanes, Katrina and Rita hit New Orleans and south-eastern and south-western portion of the state Louisiana in 2005, approximately 3,220 km of roadway in the Greater New Orleans area were submerged in floodwaters for up to 5 weeks. Immediately after the hurricanes, there was great concern in the state about the integrity of the pavement structures in the flooded area due to the sustained flooding. Such impact, if it existed, was certain to have a profound influence on the recovery and future social and economic development of the area [12]. The roadway level analysis followed by Hurricanes Katrina and Rita showed that on the roadways that were partially flooded, the flooded sections had higher deflection values (worse structural condition) than the sections that were not flooded, indicating possible damage due to flooding [13]. Hurricanes Katrina, Irene and Sandy in USA probably did more damage in a few days than the deterioration caused by normal weather condition on the nation’s road network over decades [11].

An extensive review of literature on the deterioration of the pavements confirms that no deterioration model has considered the direct impact of gradual rise of flood water yet. Therefore, it would be hard to predict the deterioration of flood affected pavements accurately using these
models. Long term monitoring and regular testing of the flood affected roads is imperative to assess these pavements. A comparison of pre- and post-flood deflection data and flooded versus non-flooded section of the pavement is vital to assess the direct impact of inundation on the roads. This paper has presented such comparisons in the data analysis section.

Methodology and Data Collection

It is essential to assess the impact of flood on the deterioration of pavement as there has been an increase in the extreme weather events in recent years. One of the most important factors to analyze the deterioration of flood-affected pavement is the existence of historical data [5]. Data collected prior to and after flood is necessary in that kind of research to compare the before and after scenario. Obtaining strength data measured by FWD is necessary for roads submerged by flood water or eroded by flood water. These data are required to develop a model for the roads subject to flooding. If flooding has any effect on the pavement, the affected sections should have a higher deflection, a lower structural number or modified structural number (SN or SNC), and lower subgrade resilient modulus than prior to flooding. To achieve the research objective, a methodology was followed which is shown in Figure 1.

![Figure 1: Research Methodology](image)

CIRCLY5.0 was used to calculate layer moduli and subgrade CBR from the surface layer thickness of the pavement and deflection data. The software was actually used as a tool to forward calculation of the deflection values from the surface layer thickness, layer moduli and subgrade CBR. At first, surface layer thickness and FWD deflection values for each testing location were recorded from the pavement history file. Layer moduli, CBR values and surface layer thickness were used as the input parameters in CIRCLY5.0. Trial and error method was used to estimate layer moduli and CBR values until the deflection values from CIRCLY 5.0 matches the field deflection values. Deflection values were finally obtained as an output from CIRCLY5.0 which were similar to the field deflection values.

Modified structural number was calculated using Equation (3) from Paterson [14].
\[ SNC_i = 3.2 \times D_0^{-0.63} \]  

where, 
- \( SNC_i \) = modified structural number at age ‘i’ \[14\]
- \( D_0 \) = maximum deflection (mm) at load centre at age ‘i’.

This study has used the road network of the BCC and RMS, NSW as some of their roads were flooded by the January, 2011 flood. Table 2 shows the total network area inundated during that flood in Brisbane.

<table>
<thead>
<tr>
<th>Traffic Density Category</th>
<th>Total Network Area (m^2)</th>
<th>Approx. Flooded Area (m^2)</th>
<th>% Flooded Roads in Traffic Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Cul-de-Sac/dead end</td>
<td>4,691,896</td>
<td>110,478</td>
<td>2.4%</td>
</tr>
<tr>
<td>B Residential Collector</td>
<td>29,103,363</td>
<td>934,209</td>
<td>3.2%</td>
</tr>
<tr>
<td>C Distributor</td>
<td>6,191,256</td>
<td>258,009</td>
<td>4.2%</td>
</tr>
<tr>
<td>D Sub-arterial</td>
<td>6,243,718</td>
<td>286,780</td>
<td>4.6%</td>
</tr>
<tr>
<td>E Industrial</td>
<td>3,538,454</td>
<td>459,640</td>
<td>13.0%</td>
</tr>
<tr>
<td>F Arterial</td>
<td>1,480,970</td>
<td>105,236</td>
<td>7.1%</td>
</tr>
<tr>
<td>G Major Arterial</td>
<td>2,695,503</td>
<td>464,939</td>
<td>17.2%</td>
</tr>
<tr>
<td>N No Traffic</td>
<td>65,489</td>
<td>3,124</td>
<td>4.8%</td>
</tr>
<tr>
<td>Total</td>
<td>54,010,649</td>
<td>2,622,415</td>
<td>4.9%</td>
</tr>
</tbody>
</table>

BCC provided FWD deflection data for the flood affected roads. They have a record of historical data in their pavement management system (PMS) which included deflection data from FWD testing for different chainages and lanes, traffic category, and surfacing layer thickness data. They have provided data for 16 flood affected road sections.

RMS NSW provided information such as pre-and post-flood FWD deflection data, pavement type, pavement category, surface width, construction year, carriageway type and year of last rehabilitation or resurfacing. RMS, NSW has also provided surface condition data which includes measurements of roughness, rutting and cracking before and after flood.

Mean, standard deviation and coefficient of variation were calculated for maximum deflection of inner wheelpath (iwp) and outer wheelpath (owp) of roads using equations (4) and (5). Coefficient of variation was calculated dividing standard deviation by mean. The mean is the average number in a total data set and measures the central tendency and can be calculated using equation (4). The standard deviation is the average distance a value is to the mean and can be calculated using equation (5).

\[
\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{4}
\]

\[
S = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{5}
\]

where,
- \( \bar{x} \) = Mean
- \( x_i \) = Sum of sample
- \( n \) = Number of samples
- \( S \) = Standard Deviation
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Data Analysis

BCC conducted investigation on several inundated pavements after January 2011 flood to determine the impact of inundation on the condition and life of the pavement. FWD testing was carried out on Luxford Street in Chelmer, Haig Road in Milton, and Aldersgate Street in Oxley, Brisbane. An assessment on the structural strength of these pavements is presented in this section. Separate analysis was carried out on the surface condition data of RMS, NSW and its outcomes are also presented in this section. Table 3 shows the total number of testing points of each road and the years when FWD testing was done.

Table 3: The number of testing points and the years of FWD testing

<table>
<thead>
<tr>
<th>Road Name</th>
<th>Length tested (m)</th>
<th>No of testing points</th>
<th>Years of FWD testing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Non-flooded</td>
<td>Flooded</td>
</tr>
<tr>
<td>Luxford Street, Chelmer</td>
<td>133</td>
<td>-</td>
<td>59</td>
</tr>
<tr>
<td>Haig Road, Milton</td>
<td>270</td>
<td>-</td>
<td>52</td>
</tr>
<tr>
<td>Aldersgate Street, Oxley</td>
<td>380</td>
<td>10</td>
<td>21</td>
</tr>
</tbody>
</table>

Analysis of Structural Strength

Luxford Street (Chelmer) and Haig Road (Milton) in Brisbane were totally flooded during the January 2011 flooding. Luxford Street was last resurfaced with asphalt in 1975. It is a 39-year old pavement and a traffic category “B” street (relatively lightly trafficked residential street). Local Asset Services has previously carried out maintenance in the form of AC patching. Figure 2 shows the FWD maximum deflection data versus chainages and structural number versus chainages graph of Luxford Street (Chelmer) in Brisbane. Here 1/L represents to outer wheel path and 1/R represents to inner wheel path of lane 1. Figures 2(a) and 2(b) clearly indicate that deflection values are higher and there is a decrease in the pavement’s modified structural number (SNC) after the flood. Therefore, structural strength of this pavement section reduced significantly after the flood. The reduction of modified structural numbers in different pavement sections ranges from 1.5% to 50%. It indicates the need for further investigation of the data to quantify the strength reductions.

Figure 2(a): Comparison of Maximum Deflection and Modified Structural number in inner wheelpath of Luxford Street, Chelmer in Brisbane
Luxford Street was rehabilitated on 26th May 2011. Another testing was conducted on that street almost four years post-flood in December, 2014. It indicates (refer to Figure 2(a) and 2(b)) that the pavement is regaining the structural strength in many chainages from 10% to 100% mainly due to the post-flooding rehabilitation works and subsequent dry weather period.

Haig Road (Milton) is a traffic category “E” (Industrial Access) road. The existing surface is believed to be 26-year old asphalt (since 1989) in non-reconstructed areas. FWD testing was undertaken in 1/L (outer wheelpath) and 1/R (inner wheelpath) of lane 1 at four different times; 19 December, 2010, 3 April, 2011, 26 March, 2013 and 9 December, 2014. Figure 3 and 4 shows that there is an increase in deflection and a decrease in structural number after flooding in many chainages. The rate of loss of structural strength of this street is not as high as Luxford Street in Chelmer because it has cement treated base (CTB). Second FWD testing of Haig Road was conducted three months after the flooding and the pavement has experienced some dry weather period. This also indicates the fact that pavements regain some strength during the dry weather period. FWD testing conducted two years after the flood confirms that some chainages have gained more than a 50% increase in the structural strength.
The Pavement History File shows that Haig Road, Milton was resurfaced after 24 February 2011. It is clearly visible from the deflection data of March, 2013 that resurfacing of the pavement also helped to regain the structural strength post-flood.

Aldersgate Street in Oxley is also a traffic category “B” (residential collector) Street. This Street was tested after the flooding on 13 April, 2011, two years after the flooding on 1 April, 2013 and almost four years post-flooding on 8 December, 2014. Chainages 0 to Ch. 105 was not flooded and Chainages 105 to Ch. 380 was flooded. Here 2/R represents the outer wheel path and 2/L represents the inner wheel path of lane 2. Figures 6(a) and 6(b) show that deflection has decreased significantly in both non-flooded and flooded section two years after the flooding. Some areas in the flood affected section of the street were resurfaced on 25th May 2011. It was selective reconstruction (patches) with 25mm overlay where most of the repairs were in areas where there was flooding. Figure 6(a) and 6(b) depicts that flooded section of the pavement continues to regain strength four years after the flooding as a result of dry period and at some parts of the flooded sections due to both rehabilitation and dry period. Maximum deflection is lower in non-flooded section compared to the flooded section. Structural number is higher in non-flooded section compared to the flooded section.
Figure 6(a): Comparison of Maximum Deflection and Structural number in inner wheelpath of Aldersgate Street, Oxley

Figure 6(b): Comparison of Maximum Deflection and Structural number in outer wheelpath of Aldersgate Street, Oxley

Figure 7(a): Increase or decrease in strength (%) post-flood in non-flooded and flooded section of the pavement at Aldersgate Street, Oxley (inner wheelpath)
Figure 7(b): Increase or decrease in strength (%) post-flood in non-flooded and flooded section of the pavement at Aldersgate Street, Oxley (Outer wheelpath)

Figures 7(a) and 7(b) compare the increase or decrease in strength (%) post-flood in non-flooded and flooded section of the pavement of Aldersgate Street, Oxley. Flood-affected section gained strength from 6% to 63%. On the other side, non-flooded section gained strength from 1% to 38% without any repair.

It can be concluded from the analysis and discussion that both resurfacing/rehabilitation and subsequent dry weather period following flood and heavy rainfall events contributed to the strength gain of the pavements.

Loss of Subgrade Strength

Subgrade CBR values were estimated using the method described in the ‘Methodology and data collection’ section. Subgrade strength was significantly decreased during the flooding. Figure 8 shows the deterioration curve for loss of subgrade strength in Luxford St in Chelmer. There is a loss of subgrade strength from 7% to 67% at different chainages due to the inundation.

Figure 8: Deterioration curve for subgrade CBR vs chainage in inner and outer wheelpath of Luxford St in Chelmer

Statistical Analysis

There is a significant difference between values of the FWD data for the same pavement before (November, 2010) and after (2011 and onwards) flood. The distinction between flooded points and non-flooded points for each pavement type was based on the flooding conditions prevalent on January 13, 2011 when flooding was at its greatest extent.

Figure 9 to 11 compares mean, standard deviation and coefficient of variation (CVAR) of Luxford Street in Chelmer, Haig Road in Milton and Aldersgate Street in Oxley, Brisbane.
Mean maximum deflection is higher immediately after the flood for Luxford Street in Chelmer and Haig Road in Milton, while the four years post-flood mean deflection value is lower for Luxford Street in Chelmer. The two years post-flooding mean deflection value has improved for Haig Road because of the post-flooding rehabilitation work. The data that was collected in 2014 indicates a higher mean deflection value than 2013 data. Average maximum deflection is lower in non-flood affected areas compared to the flood affected section of Aldersgate Street in Oxley.
Analysis of Surface Condition: Roughness, Rutting and Cracking

RMS, NSW has provided surface condition data of flood affected roads. They have provided data of roughness (NAASRA Roughness Meter - NRM roughness values in counts/km), rutting and cracking from year 2009 to 2012. The road segment analyzed here is a highway constructed in 2008. The road was submerged for 10 days.

A marginal increase in roughness (NRM), rutting (mm) and cracking (mm) was observed after flooding in some parts of the pavements which can be found in Figure 12, 13 and 14.

Figure 12: Comparison of pre- and post-flood roughness data of Sturt Highway, RMS NSW

Figure 13: Comparison of pre- and post-flood rutting data of Sturt Highway, RMS NSW

Figure 14: Comparison of pre- and post-flood cracking data of Sturt Highway, RMS NSW
Outcome of the Research

The January 2011 flooding in South-East Queensland especially in Brisbane was a river flood; the water rose gradually and relatively slowly. The river water deposited its mud on the road and slowly washed the area. It was unlikely that the damage was caused by prolific scouring often associated with the rapid rise of river water or flash flooding. The damage was more likely to be caused by loading or immediate trafficking of the saturated pavement and moisture entering the pavement. Results obtained from several road sections indicate a consistent trend with increased FWD deflection and reduced structural strength immediately after the flooding. Flooded section of the pavement has lower structural strength than the non-flooded part of the same road in the case of partially flooded roads.

Strength gain was observed in several pavement sections two years after the flood due to the post-flooding rehabilitation works and subsequent dry weather period. However, four years post-flooding FWD testing data of some pavement sections revealed a further reduction of the structural strength compared to the two years post-flooding data despite of rehabilitation. This may indicate underlying problems with the subgrade and ongoing loss of the subgrade strength. It warrants the need for further investigation to determine what is causing this possible damage to the subgrade strength. The main outcome of this work is to present the long term impact of flood and heavy rainfall events on the flexible pavements in Australia. Long term observation of flood affected roads indicates that flood will continue to increase the need for more frequent rehabilitation as a result of strength reduction. It will also increase the road network repair costs in future. Regular and frequent testing is vital to monitor the impact of flooding on the surface condition such as roughness, rutting and cracking.

Conclusion

Pavements subject to flooding and inundated for a certain period of time deteriorates rapidly rather than gradually as predicted by most of the available road deterioration models. Even the models discussed in the literature review section of this paper, were also developed considering that the pavement would undergo normal climatic condition such as average rainfall and design traffic. It is imperative to gather historical data and continue to monitor the pavement sections subject to extreme weather events such as flooding and frequent extreme heavy rainfall to compare the structural performance of partially or fully saturated pavements. It is a significant step in assessment of the flood affected roads. Until recently not many road authorities across Australia have started collecting data on such occurrences. Prediction and assessment of the deterioration of pavements after flooding would assist the road engineers to quantify the damage caused by extreme weather events. It would improve the decision making process by optimizing the use of fund to rehabilitate or repair the pavement.

This paper analyzed and addressed the impact of flooding on the structural and functional condition of the pavement. It establishes the fact that the impact of extreme weather events might not always be visible immediately without testing as it may only effect the structure of the pavement. However, the surface condition of the pavement may start to deteriorate quicker than expected as a result of ongoing weakening of the subgrade. This research is expected to identify the adaptation options to reduce the flooding impacts in terms of cost at road network level. Although this paper only presented the impact of flooding on the pavements, this research will also address the road network condition prediction for flooding and frequent extreme heavy rainfall events in future.

References


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