Evaluating the Flooding Effects on Pavement Materials and the Benefits of Light Stabilisation from Accelerated Model Pavement Testing

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The impact of flooding on regular pavement structures is well documented in research and pavement design, however, the typical methods for obtaining data are in situ tests of pavement behaviour after flooding has occurred. It is of greater importance in the short term that a pavement’s structural behaviour under cyclic loading will be sustained during flooding. This project has evaluated the flooding effects on the structural behaviour of a lightly stabilised road base under cyclic loading by the application of 750, 1000 and 1250 kPa loadings in an accelerated model pavement test to analyse the usage of lightly stabilised granular materials in a pavement. The resilient modulus of the lightly stabilised base was found to be reduced by 64.3%, 37.2% and 32.3% for the three load cases when flooded for a period of 10 days. Additionally, permanent deformation when flooded was found to be approximately three times higher than when undergoing otherwise the same load cycles when unflooded. The pavement model, upon undergoing $7.2 \times 10^5$ load cycles did not meet the Austroads guidelines for rutting and as such can be considered suitable for usage in terms of permanent deformation for lightly trafficked pavements.

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1 LT Zachariah Bryant, School of Engineering & Information Technology. ZEIT4500/4501 Engineering Project A/B.
I. Introduction

Flood events are noted as some of the most damaging events on the serviceability of pavements worldwide. With the onset of climate change, severe precipitation events and storms are more likely to occur more often. The incorporation of these events into pavement design, including material choice and their associated behaviours will become increasingly important as the earth prepares for more frequent flood events causing damage to pavements and therefore higher rehabilitation and maintenance cost. Whilst the impact of extreme precipitation has no immediate effect on the performance of a pavement, the associated flooding occurring is considered to be one of the largest threats to pavement serviceability in its lifetime. The effects of flooding on the pavement structure are most notably manifested in the change in stiffness of the granular base and subgrade (ARA, 2004; Mayrberger, 2010). Evaluation of Southeast Queensland pavements after the 2010 and 2011 flood events found that pavements can undergo a strength reduction of up to 50% (Sultana et al., 2014). The resilient modulus of a soil is also greatly affected by moisture content, and at high levels of saturation is dependent on moisture content (Vuong, 1992). The development of pavement modelling and design to better incorporate flood effects and withstand these events will lead to more efficient transport bodies. Introducing a lightly stabilised granular soil as a road base has been shown to be a cost-effective method of producing a good standard road for light usage, however, requires evaluation of its structural behaviour under flooded conditions.

Whilst there has been extensive research into the effects of flooding on existing pavements, these are typically in-situ non-destructive strength tests and surface roughness inspection. This investigation will utilise Accelerated Model Pavement Test (AMPT) methods to determine the behaviour of a pavement section under flooded conditions and compare this data to that of the same test under otherwise the same conditions of the sample when dry. Additionally, this investigation will examine the usage of lightly stabilised granular materials and their application into pavement design under flooded conditions. This will allow a comparison to be made between unbound granular materials – whose behaviour in the presence of saturation is well documented – with cementitious granular materials which has not previously been deeply researched.

Lightly bound cemented materials are those which typically have a small amount (<3%) of binder added to them to increase their structural strength (Austroads, 2019a). Austroads (2019a) categorises them as having an unconfined compressive strength between 1 and 2 MPa, providing greater modulus after curing and rut-resistance than otherwise unbound materials as well as a reduced sensitivity to moisture content, despite being susceptible to fatigue cracking.

The project aims to determine whether flooding significantly effects the model pavement structure and in particular, the structural properties of a lightly stabilised granular base pavement section over a repeated number of loadings. The key relationship to be determined is the variation of the stabilised material’s resilient modulus with applied pressure and under unflooded and flooded conditions. The permanent deformation of the pavement will also be examined under varying conditions. This project will focus primarily on the structural strength of a model pavement and the effects flooding has on it. Repeated loading will be applied onto a model pavement consisting of lightly stabilised granular base over a Queensland black clay subgrade. The tests to be completed will be several AMPT under differing loads of 750, 1000 and 1250 kPa. The method in which this work will be undertaken is the usage of a small-scale pavement sample under a load actuator to simulate traffic loading. The tank will be filled with a 600-millimetre subgrade consisting of a Queensland black clay, and a 150-millimetre layer of granular road base stabilised with 1.5% binder (75% cement and 25% fly ash), consistent with the recommendations made by Harch (2011), Paul (2011) and Cunningham (2013).

II. Methodology

A. Material Preparation

The material properties of the above-mentioned soils have been determined previously from testing and are displayed in Table 1. Basic Geotechnical Properties of the Materials (Gnanendran, 2011).

<table>
<thead>
<tr>
<th>Subgrade</th>
<th>Granular Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDD (kg/m³)</td>
<td>1342</td>
</tr>
<tr>
<td>OMC (%)</td>
<td>32</td>
</tr>
<tr>
<td>Laboratory soaked CBR</td>
<td>1.5</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>93.4</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>37.0</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>56.4</td>
</tr>
<tr>
<td>Linear shrinkage (%)</td>
<td>24.4</td>
</tr>
</tbody>
</table>
To have the materials reach the OMC, as it is impractical to oven dry the large amount of material, an average moisture content was taken from the soils, and water added to reach a MC near to the OMC value. Three samples of the soils were taken after the soils were mixed to disperse particle sizes and differing sections of the soil containers, and oven dried to obtain an existing moisture content. The mass of each layer was taken and mixed in a concrete mixer and the amount of water added to reach the OMC before being sealed in an airtight container until required to construct the specimen.

Following the construction of the sample, the materials will be left for 28 days to cure to reach its final strength (Paul, 2011).

B. Instrumentation

Inside the sample, there were four sets of sensors to collect data relating to the behaviour of the sample under loading. Care had to be ensured at each installation to ensure that data is being collected from the sensor whilst it is being emplaced within the test tank, during compaction of the material surrounding the sensor, and also once the sample has been fully constructed.

These sensors provided data to the connected computer-controlled data acquisition setup, where the data was gathered with the use of LABView data acquisition software. The first three tests during the unflooded condition had data written as excel files, though this proved to greatly affect the quality of data obtained. The following tests conducted whilst flooded were written as LVM text files to more ably be processed by MATLAB.

1. Strain Gauge

Horizontal strain at the interface between the road base and subgrade layers is one of the most important indicators of the performance of the stabilised base (Paul, 2011; Gnanendran et al., 2011). For this test, KM-50F Strain Transducers have been used, manufactured by Tokyo Measuring Instruments Lab. The instruments are waterproof and are designed to measure strain in materials such as concrete and resins which suits the stabilised granular base due to its requirement to cure.

These gauges are not required to be calibrated prior to use and as such have only been tested to ensure they record values.

2. Linear Variable Differential Transformer (LVDT)

Vertical deformation is another significant measurement to be taken in this test. The plotting of vertical deformation with time and cyclic loading is key to determining the pavement material’s resilient modulus from the recoverable strain as well as permanent deformation.

There was total of eight LVDTs – two 50-millimetre and six 20-millimetre sizes. The LVDTs function by movement of an inner steel rod generating a change in voltage recorded by the data acquisition software. As a result, the LVDTs required calibrating by causing a known change in displacement and recording the voltage change in 2-millimetre increments between 0.0-20.0 or 0.0-50.0 millimetres depending on the LVDT size.

3. Earth Pressure Cell (EPC)

The distribution of pressure throughout the sample will change drastically between the point of applied pressure and the remainder of the sample, as the load applied at the pavement surface spreads at an angle of approximately 45 degrees (Harch, 2011), in typical pavement materials, though may spread at a greater angle in the case of bound materials. It is important to note how the lightly stabilised base will distribute this pressure when it is both dry and saturated and a comparison made.

To calibrate the earth pressure cells, the relationship between the pressure required to induce a change in voltage must be recorded. The earth pressure cells were placed in a cylindrical split device and surrounded by a sandy soil, which would optimise the detected pressure. A triaxial membrane was placed between the two metal interfaces to ensure the water would not flow through the sand and out of the hole located at the bottom of the device, with a circle of rubber below this to ensure the sand would not disrupt the effectiveness of the membrane. Pressure was applied with a Standard Pressure Volume Controller, manufactured by GDS Instruments, and voltage measurements corresponded to the controlled pressure in the Data Acquisition Software.

Upon curing of the sample and the application of small loads by the actuator, it was found that three of four pressure cells were not registering values. Over the course of the unflooded tests, only the pressure cell situated in the centre of the stabilised base was registering values, of which were far below the theoretical load prediction.

4. Moisture Probe

As the material properties and behaviours vary significantly with moisture content, it was important to monitor the change in moisture content between setting the test up and curing, during dry testing and also during flooding.

The moisture probes to be utilised will be MP306 Moisture Sensors, manufactured by ICT International, which measures Volumetric Soil Water Content (VSW%). The moisture probes were placed in prepared samples of the soil materials and the reading they produced was recorded. These samples were then transferred to be oven dried and a Gravimetric Moisture Content (GMC) obtained and graphed against the VSW% to obtain a relationship. The equation of the best fit line was used to calibrate the MP306 to obtain a GMC value when measurements are taken.
C. Construction of Model Pavement

1. Subgrade

   As per Appendix A, the subgrade will be divided into 24 layers to be placed into the test tank and compacted. Each layer of 36.4 kilograms was added to the concrete mixer and stirred for 10 minutes. Following this 7.3 kilograms of water will slowly be added, followed by further mixing for 10 minutes. The soil will then be placed into the sealed boxes until construction of the specimen. The inner walls of the test tank were marked at 25-millimetre intervals to ensure maximum dry density was reached and compacted using a jack hammer to approach its maximum compaction, indicated by compacting to the marked lines. This was repeated for all 24 layers until a depth of 600-millimetres was reached.

2. Road Base

   The road base will be divided into six layers to be placed into the test tank and compacted. Each layer of 61.5 kilograms will be added to the concrete mixer and stirred for 10 minutes. Following this 5.3 kilograms of water was slowly added, followed by the addition of 0.69 kilograms of cement and 0.23 kilograms of fly-ash with further mixing for 10 minutes. The soil was then placed into the test tank, which was marked at 25-millimetre intervals and compacted using a jack hammer to approach its maximum compaction, indicated by compacting to the marked lines. This was repeated for all six layers until a depth of 150-millimetres reached.

3. Sensor Installation

   Fig. 1 – 4 below display the placement of relevant sensors within the sample.

   a. Strain Gauge

   ![Figure 1. Placement of strain gauges within road base layer.](image)

   b. LVDT

   ![Figure 2. Plan view of LVDT placement.](image)

   ![Figure 3. Cross sectional view of LVDT placement.](image)

   c. EPC

   ![Figure 4. Placement of EPCs in road base layer.](image)
D. Testing

Once the tank had been setup under the load actuator, a pressure of 750, 1000 and 1250 kPa was applied for 80000 load cycles for each pressure. This loading, along with the other parameters described earlier, was graphed against time to determine the relationship of these variables. Austroads (2017) takes tyre-pavement contact stress as 750 and 800 kPa for analysis purposes, however, contact pressures can vary from 500 to 1200 kPa (Chowdury and Rallings, 1994). It is for these reasons that the applied pressure was selected as 750, 1000 and 1250, ensuring that the test is consistent with the loading requirements of a typical pavement.

The load was applied at a frequency of 1 Hz for the duration of its 80 000 cycles. To prevent a rocking effect of the actuator on the pavement, there was a seating load of 50 kPa to ensure the actuator remained in contact with the loading plate for the duration of the tests. For each load cycle, the designated load was applied, followed by a 0.5 second ‘rest’ to simulate the pause between loadings on a typical pavement. This resulted in the load being applied for 0.5 seconds, in a ‘pulse’ rhythm, observable in Fig 5.

Following one week of testing, the sample was flooded by placing a hose into the outer tank. This then flowed through to the inner tank which was lined with a geosynthetic filter-drainage geocomposite via the holes in the connecting tank wall. This flooding process was conducted for ten days, with the moisture content of each layer reaching a plateau after several hours. Following the flooding of the pavement, testing will be conducted under otherwise the same conditions as previously. This flooding cycle was intended to continue for a number of iterations to validate the data obtained for the flooded cycles, however, due to time constraints only two flooded tests were completed, with only the data obtained from the unflooded and first flooded test being usable.

E. Analysis

During the 80,000 cycles for each test, data was obtained from each of the sensors at a frequency of 100Hz, with the exception of the moisture probes, of which were less susceptible to changes over time. This resulted in a significant amount of data being obtained for the six tests which were able to be analysed. To process these 48,000,000 data points, the individual cycle data was extracted using a MATLAB code designed to take data corresponding to the lowest load applied followed by the highest load applied and repeating for all the obtained data. This data per cycle was then input into a spreadsheet for each unflooded and flooded conditions and each pressure and change in values over the course of a cycle were obtained to then be input into the calculation of a resilient modulus. In addition, a measurement of surface deformation was taken from the specimen after the application of 72 000 000 load cycles to evaluate rutting of the specimen.

III. Results

As the predominant factor under investigation, it was necessary to monitor changes in pressure at varying intervals throughout the stabilised base both vertically and horizontally, in order to determine the deviatory stress within the pavement. In addition, the vertical deformations – converted into vertical pavement strain – is a key value for the input into resilient modulus, in line with Equation 1 below.

\[ M_R = \frac{\sigma_d}{\varepsilon_r} \]  

(1)

where

- \( M_R \) = the pavement resilient modulus
- \( \sigma_d \) = deviatory stress (stress change between the surface and bottom of a pavement layer)
- \( \varepsilon_r \) = recoverable strain. That is, the deformation which is ‘rebounded’ by the pavement once loading is removed

As a result of three of four pressure cells not registering values, the only experimental value for deviatory stress obtained is for the top stabilised layer in the vertical direction. In lieu of reliable data throughout the rest of the specimen, a theoretical value of stress was calculated at each significant layer, being between the upper and lower layer of the stabilised base, at the interface between subgrade and at the bottom of the test tank. The value taken for each layer is based upon a simple distribution of load at an angle of 45 degrees. A distribution angle of 26.6 degrees was also trialled, however this presented a greater variation from the experimental data than the 45-degree distribution angle.

Overall, as expected, the performance of the lightly stabilised base and the subgrade decreased markedly in the presence of flooding. This was observed both in the results obtained, as well as the appearance of severe cracking under the load of 1000kPa when flooded as seen below in Fig. 6. This cracking was further amplified after the application of 1250 kPa, seen in Fig. 6, along with the severe rutting occurring over the testing life seen in Fig. 7.
The resilient modulus plotted against moisture content of the top half of the lightly stabilised base can be seen as above. The trendline has been plotted as an exponential curve as seen in Wang, et.al’s (2015) investigation into resilient modulus under varying moisture contents.

Regarding the change in resilient modulus under varying loads, the following series of figures display the change in resilient modulus with number of cycles for the unflooded condition and number of log cycles for the flooded condition. It is important to note, that although the unflooded data displays values up to 3000 load cycles, the dataset has been obtained throughout the 80 000 applied loads, and that the reduction in data is a result of the files written by the data acquisition software.

Figure 6. Visible cracking under 1000 kPa when flooded and amplification of cracking under 1250 kPa.

Figure 7. Rutting of the pavement occurring after 720 000 load cycles at various pressures.

Figure 8. Variation of Resilient Modulus with Moisture Content for the lightly stabilised base.
Figure 9. Resilient modulus for a) whole base, b) upper base layer, c) lower base layer and d) subgrade under 750kPa for both unflooded and flooded.

Figure 10. Resilient modulus for a) whole base, b) upper base layer, c) lower base layer and d) subgrade under 1000kPa for both unflooded and flooded.
Figure 11. Resilient modulus for a) whole base, b) upper base layer, c) lower base layer and d) subgrade under 1250kPa for both unflooded and flooded.

Due to the significance of some of the outliers obtained in the data for 1250 kPa tests in the unflooded condition, resulting from poor data collection by the data acquisition software, values varying greatly from the trend have been removed for the figures above.

Figure 12. Resilient modulus of the upper stabilised base for all three load cases when a) unflooded (cumulative) and b) flooded

Figure 13. Permanent deformation occurring at each applied pressure over 80 000 cycles for a) stabilised base and b) subgrade.
In Figure 1313 above, it is clearly seen that the permanent vertical deformation caused by loading in the flooded condition is much greater than that when otherwise unflooded. The exception here is the initial 750 kPa unflooded test, although a significant amount of settling and compaction should occur in the first few thousand load cycles.

Table 2 below displays the average resilient modulus for the duration of 80 000 cycles for each pavement material under each load case and flooded condition.

<table>
<thead>
<tr>
<th>Load (kPa)</th>
<th>Unflooded</th>
<th>Flooded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical Deviatory Stress</td>
<td>Measured Deviatory Stress</td>
</tr>
<tr>
<td>Stabilised Base (Upper Layer)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>662.4</td>
<td>833.0</td>
</tr>
<tr>
<td>1000</td>
<td>443.7</td>
<td>532.6</td>
</tr>
<tr>
<td>1250</td>
<td>334</td>
<td>345.1</td>
</tr>
<tr>
<td>Stabilised Base (Lower Layer)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>613.2</td>
<td>253.1</td>
</tr>
<tr>
<td>1000</td>
<td>389.6</td>
<td>316.4</td>
</tr>
<tr>
<td>1250</td>
<td>332.2</td>
<td>308.4</td>
</tr>
<tr>
<td>Subgrade</td>
<td>417.9</td>
<td>116.9</td>
</tr>
<tr>
<td>1000</td>
<td>504.1</td>
<td>260.5</td>
</tr>
<tr>
<td>1250</td>
<td>460.9</td>
<td></td>
</tr>
</tbody>
</table>

IV. Discussion

A. Resilient Modulus

1. Explanation of decreasing modulus with pressure

Firstly, the trend for resilient modulus to decrease with increasing pressure is contrary to the hypothesised outcome, in addition to previous laboratory testing conducted by various researchers. For both the unflooded and flooded conditions, resilient modulus tended towards lower values under higher loads, with the exception of Mₑ at 750 kPa under flooding. This could be explained by considering the pavement to have failed, and thus was unable to respond appropriately to the application of higher loads. For the flooded 1250 kPa case, this is a likely occurrence, as it is seen in Figure 1313 above that the permanent deformation of the stabilised base was significantly higher compared to previous load applications, implying a severe failure of the pavement structure which was verified by the amplification of the cracking occurring under 1250 kPa and the large rutting effect left after the flooded 1250 kPa test seen in Figure 77. Additionally, these values are significantly lower than those determined from previous similar testing by Harch (2011) and Piratheepan & Gnanendran (2013), although comparable to those completed by Nguyen (2014).

2. Permanent deformation and plateau of modulus

The data obtained throughout these tests shows a trend of the resilient modulus to be initially higher and tending towards a lower limit value upon the application of 60 – 80 thousand cycles. This leads to the conclusion that throughout each test, there is a period of plastic strain, which is to be expected, although the time taken for the pavement to undergo completely elastic deformation when flooded is significantly higher than that of the unflooded tests. This phenomenon could be as a result of the pavement’s subgrade swelling when flooded. It was noticed that during the flooded tests, as the actuator applied load to the surface of the pavement, water was expelled through the cracks in the pavement surface – along with some fines. This expulsion of water is deduced to be due to the compaction of the pavement materials under a high load, with the water being pushed out of the pavement material’s voids. Additionally, the permanent deformation caused by 750 kPa for both the unflooded and flooded tests implies that the pavement must initially undergo compaction before ‘settling’ into the repeated load cycles. It can be inferred, that this has occurred within the 750 kPa cycles, with the 1000 kPa mostly tolerable by the pavement despite the 1250 kPa being unbearable, leading to larger permanent deflections for the 750 kPa and 1250 kPa cycles.

3. Decreases in modulus under flooded conditions

Overall, throughout Figs. 9 – 12, there is a clear impact of flooding on the resilient modulus of the model pavement, with reductions of modulus of 64.7%, 37.2% and 32.3% for 750, 1000 and 1250 kPa load cases within the stabilised base, and reductions of 72.0%, 64.8% and 65.0% in the subgrade. Comparatively, however, this demonstrates the stabilised base’s ability to retain strength whilst undergoing flooding, noting that the black clay is not expected to perform well in the presence of high levels of moisture. The decrease in modulus of the lightly stabilised base is also principally below the upper limits of Sultana et al.’s (2014) investigation into the reduction of pavement strength of Queensland pavements after the 2010 and 2011 flood events of 50%.

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Interestingly, although the modulus decreased significantly in the presence of flooding, it reached a somewhat residual value for all three load cases. This is an important finding, as the modulus could be considered constant for flooded design in calculations and modelling.

4. Measured earth pressure versus theoretical pressure distribution

As mentioned previously, three of four earth pressure cells designed to measure the pressure being distributed throughout various depths of the pavement did not register values. As such, the only known pressure besides that of applied pressure at the surface was at the centre of the stabilised base. Following from this, the resilient modulus was calculated using an assumed pressure distribution at an angle of 45 degrees. Interestingly, the resilient modulus from measured values was notably higher than that based on theoretical distribution, seen in Figs. 9 – 12. Increases in modulus were 25.8%, 20.0% and 3.3% for the load cases of 750, 1000, 1250 kPa respectively. It can be inferred that due to the stabilised nature of the material, a distribution angle of greater than 45 degrees is obtained. The binders used greatly increase the shear strength of the material which is also a factor in the load spreading ability of the pavement. Using an approximate 20% increase in load distribution over the 75mm depth of the upper layer of stabilised material, an angle of 50 degrees is obtained as the angle of load distribution, neglecting the transfer of load to horizontal pressures in the pavement materials.

B. Permanent Deformation

Fig. 13 highlights the differences in permanent deformation between unflooded and flooded conditions under varying applied pressures. Despite the unflooded 750 kPa having the second-highest permanent deformation over its 80 000 cycles, considering the tendency of a pavement to undergo most plastic strain under initial loading, we can take the permanent deformation of the pavement to be higher for all cases of flooded loading. In the cases of 1000 and 1250 kPa tests, the permanent deformation was approximately three times greater for the flooded condition than for the unflooded condition in the stabilised base material. Inspection of the subgrade, however, reveals that the effects of flooding on plastic strain were even more significant, in the order of five – ten times that of the unflooded permanent deformation. The accumulation of plastic strain of both materials within the pavement result in the large rutting effect seen in 7. The measured deformation on the surface of the pavement was approximately 15mm – correlating to a 2% decrease in total depth. Using the Austroads (2019b) guide to pavement evaluation, Table 6.1 sets out guidelines for indicative investigation levels of rutting, which is based on a percentage of road length with rutting over 20mm. The rutting experienced by this pavement model is less than the recommended level requiring investigation and treatment and therefore could not be considered to have failed due to rutting, however, due to the shape of the cracking around the loaded area it is likely that shear failure or shoving has occurred. These failures are typically attributed to an inadequate depth of road materials, moisture in pavement and/or subgrade and densification of pavement layers under traffic early in the life of the pavement (Austroads, 2019b).

C. Issues and Errors

The focus area of this test was the pavement’s resilient modulus and how it varies between flooded and unflooded loading. The resilient modulus of the stabilised base was found to not follow a typical pavement material’s trend of gaining modulus under higher loads, leading to the conclusion that the pavement was not sufficiently structurally sound for the loads it was undergoing. The most probable cause of this is the construction of the sample. As the compaction of the pavement materials was strictly controlled, it is likely that the loss of strength and stability occurred as a result of poor curing of the binders. The pavement specimen was left in the open-air laboratory with wet cloths and plastic sheeting to prevent loss of moisture, however this was not as effective as some other methods i.e. the use of a liquid latex coating. The poor curing process would result in the stabilised base not reaching its intended strength after 28 days. In addition, during the unflooded tests, the pavement was open to the air due to the many sensors and equipment located on the surface, causing further drying of the pavement which would also decrease its effectiveness.

The data acquisition software paired very poorly with Microsoft Excel to write files in the .CSV format. The data for the unflooded tests was found to be very inconsistent, with certain data points not being logged, as well as some lengths of data not being chronological. Whilst some useful data was able to be extracted, more exact calculations and graphing were not possible for every cycle of the 80 000 applied loads.

Whilst interference with the pavement model was limited whilst it remained in the laboratory, especially whilst loading occurred, during flooding periods the tank was used as a bench for other tests. This caused movement of the LVDT frame between tests, eventuating in the calculation of swell of the sample being unattainable. A more robust LVDT and sensor frame which is anchored to either the test tank or the outer regions of the pavement would alleviate this issue to an extent, allowing further deduction of the pavement to be made during period of flooding.
D. Recommendations

It is clear that the effect of flooding on the stabilised base used in this and prior tests is significant. To gather a more exact comparison of the behaviour of the stabilised base when flooded and unflooded there are a number of options. Firstly, although time and material consuming, having a specimen for the unflooded condition, and a specimen for the flooded condition would allow a more direct comparison between conditions to be made. This would allow both pavement models to be tested and characteristics measured under the exact same number of load cycles, rather than the unflooded portion of this test being conducted after 240 000 cycles. With two specimens, either the test could be conducted immediately after curing, or post the application of a pre-loading of 80 000 – 100 000 cycles to consolidate the pavement and reach a residual accumulation of plastic strain prior to the application of test loads in either condition. Another possibility is the unflooded/flooded tests being conducted in cycles. Once the flooded test has been conducted, the pavement could be dried to the point where the moisture content of the materials is equal to the moisture contents when beginning the initial unflooded test. Undergoing these wet-dry cycles would more than likely require a more robust pavement arising from an increased base depth, though would allow the base’s susceptibility to intermittent flooding and lifetime analysis to be conducted.

To make additional deductions of the lightly stabilised base’s performance characteristics, the instrumentation is required to be completely effective. The inclusion of extra sensors such as suction probes are useful although Austroads (2017) have methods of converting gravimetric moisture content to a negative water pressure in pavement materials. The earth pressure cells which gathered absent values for the testing are of high importance, as they allow experimental calculation of the modified material’s properties, which were found to be noticeably higher than those based upon theoretical load distribution. With properly function pressure cells, horizontal modulus and stresses are able to be found, which is a key performance indicator for stabilised materials, along with strain at the subgrade/base interface (Paul, 2011; Gnanendran, 2011).

V. Conclusions

The modulus calculated for the upper layer of the lightly stabilised base used in this test was found to be 833, 533 and 345 MPa for the 750, 1000 and 1250 kPa loadings in the unflooded condition respectively. This does not reflect our understanding of the behaviour of pavement materials, as these values should increase with increasing pressure. These values are also significantly lower than those obtained in previous testing and numerical modelling. It is hypothesised that the pavement failed early in its life, with higher loads then transmitting to more permanent deformation rather than elastic strain. Upon 10 days of flooding the resilient modulus in the same layer was found to be 237, 279 and 226 MPa for the 750, 1000 and 1250 kPa load cases, reflecting a reduction of 71.5%, 37.2% and 32.3%. Along with an approximate residual modulus being reached for all three flooded tests, this reduction in modulus was significantly lower than the change in modulus of the subgrade of 72.0%, 64.8% and 65.0% for the three load cases between unflooded and flooded conditions.

Additionally, despite the loss of modulus under higher stress levels, due to the pavement undergoing $7.2 \times 10^4$ cycles at higher than typical pressures, we can consider the pavement to be successful in the application of a lightly trafficked road in moist conditions when reviewing its permanent deformation over its design life.

This test has evaluated the effects of flooding on a lightly stabilised road base over a Queensland black clay and quantified these changes in terms of permanent deformation and resilient modulus between unflooded performance and flooded performance in an accelerated model pavement test to attempt to replicate the real-world loading of pavement materials. More rigorous test equipment and a more direct test comparison is required to be made in order to properly quantify the material’s behaviour under flooded conditions, as well as a comparison made to the un-stabilised base material in both unflooded and flooded conditions for use in road design in flooded areas, or for the evaluation of a pavement’s capacity when undergoing flood events.

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