

The Influence of Trench Reinstatements on Flexible Pavement Failure

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Signed MBrown date 27/05/2020

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Technical Abstract

Utility cuts are made in existing pavement sections to install, upgrade and maintain a variety of underground conduits and drainage pipes. Poor workmanship during the excavation and reinstatement of such road openings, as well as non-compliance with national specifications has been shown to substantially reduce the service lives of pavements. To date, the majority of research carried out on trench reinstatements has focused on analysing changes at the pavement surface. This allows the development of pavement failure to be monitored but does not identify the subsurface failure mechanisms which are largely responsible. This research investigates soil movement below the surface of poorly constructed trench reinstatements and examines the soil deformation mechanisms which occur as a result of pavement failure in and around the trench.

An Accelerated Pavement Tester (APT) was used to physically model real-life traffic conditions within a compressed period of time. Pavement sections were constructed in a pit below the APT, which housed a Perspex window on one side to allow the tracking of subsurface soil movement in the direction of travel. The window was situated adjacent to the APT's wheel path so that the deformation viewed was of soil directly below the wheel. Cameras were placed opposite the window to capture images of the soil over the course of testing. Images were then analysed using particle image velocimetry (PIV) to obtain information about soil displacement. Surface images were also captured during each test. These images were then inserted into Agisoft Metashape to create 3D models of the surface for different points of a test. By comparing models from the start and end of testing, the overall vertical displacement of a pavement surface could be calculated.

As part of the research seven pavement sections were tested using the APT. Four of these sections were single-layered, whilst the remaining three were two-layered. The single-layered sections were constructed using only Kazakhstan medium sand-silt subgrade. The two-layered pavement sections used the same subgrade but with the addition of a limestone aggregate base course layer (two sections) or a layer of cold lay macadam (one section). After the construction of the subgrade layer for each test section, a trench was cut into the subgrade. The trench was then backfilled with the same in-situ material, but to a lower level of compaction than the original layer.

Results for the single-layered pavements show that a poorly compacted reinstatement leads to increased surface rutting over the trench. The addition of a base course layer helps spread the wheel load over a greater area in the subgrade, therefore reducing the increase in rutting over

the trench. Once the base course thickness is large enough that failure of the subgrade in the trench is avoided, rutting becomes much more uniform. Deformation of the subgrade beyond the downward edge of a trench resembles the mechanism for a vertically loaded footing on sloping ground. This simple failure mechanism can be used to predict whether the increased rutting inside the trench propagates into the surrounding subgrade. Due to spreading of the wheel load through the base course layer, the resistance to deformation beyond the downward edge of a trench in a two-layered pavement is greater than for a single-layered pavement.

Trench reinstatements observed in the field show aspects of the same damage pattern, with settlement in the trench causing traffic to have to climb up onto the existing road surface, leading to concentrated damage at the trench's downward edge.

This work has provided a useful insight into the mechanics of damage around trench reinstatements which could lead to improved designs of remedial works.

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1. Introduction

1.1 Background

Across England, the number of potholes and road defects is growing year on year. In the 2018-19 financial year alone almost 700,000 potholes and road defects were reported, marking a 13% jump on the year before (Federation of Small Businesses, 2019). The presence of potholes and road defects presents a significant challenge to the country's motorists, with many vehicles succumbing to damage as a result of pothole encounters. To try to control the issue, hundreds of millions of pounds is invested each year to fix damaged roads and holes. Figures for the 2018-19 financial year show that the bill faced by councils for repairs to the road network was just under £950 million (Federation of Small Businesses, 2019). With axle loads and volume of traffic likely to continue to increase, the scale of the problem on Britain's roads is unlikely to reduce in the near future. As a result, the UK government is set to pledge £2.5 billion in funding over the next five years to fix potholes across England (BBC News, 2020).

1.2 Pavement Design

There are two main types of pavement structures used for road design; flexible pavements and rigid pavements. Flexible pavements are most common due to having a lower installation cost. The design of flexible pavements is based on the principle that for any load applied, the force is distributed over an increasingly larger area as it is transferred downwards from the surface. Therefore, there can be a grading in the quality of materials used, with higher strength materials used closer to the surface. Typically, a flexible pavement structure will consist of four layers: wearing course, base course, subbase and in-situ subgrade.

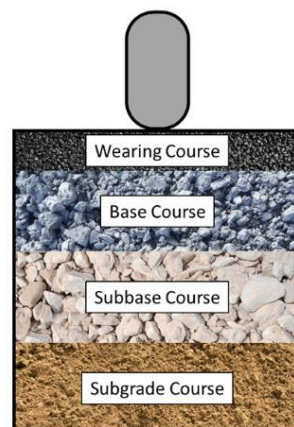


Figure 1 - Typical layers of flexible pavement structure

The standard method to design layer material types and thicknesses is an empirical approach, which utilizes design charts and empirical equations developed from experimental works and field tests. However, this method has severe limitations due to the large variety and uncertainty around design factors, such as environment, construction materials and traffic load, which fluctuate greatly due to climate, technology, economic growth and population changes.

More advanced design approaches can be undertaken but even these are limited in predicting phenomena such as rutting.

1.3 Pavement Failure

The majority of pavement failures occur due to distress in the form of either fatigue cracking or rutting (a surface depression in the wheel path). Both of these failure methods are a result of repeated heavy loading of the pavement surface. Thus, traffic loading data is used in design to minimise the probability of each of these failure methods over the pavement's lifetime.

There are other factors besides traffic loading, which can increase the probability of both fatigue cracking and rutting. Two of the main factors which contribute to pavement failures are water infiltration, and trench excavation and reinstatement. Layers of pavement affected by either of these factors will experience a reduction in structural performance. Therefore, the pavement's traffic load capacity will be lower than originally designed for.

The lack of maintenance work carried out on Britain's roads is a common reason for infiltration of water into the underlying layers of pavements. Road owners are generally unwilling to spend the level of cash required to maintain a road system at the same condition it was originally built. A result of this is that vegetation and other objects can accumulate in a roads drainage system. This in turn affects the water flow through the system, potentially resulting in water entering the pavement structure. This causes a weakening of the pavement layers due to decreased effective stress, therefore reducing the traffic load capacity of the structure.

Many utilities are located beneath roads up and down Britain. To perform maintenance and upgrade works on pipes and cable situated beneath roads, utility companies commonly use open cut trenches at the point of interest. There are trenchless methods available, such as pipe bursting, pipe eating and sliplining, which allow for cable/pipe rehabilitations to be performed without affecting the pavement structure. However, restrictions on the application of trenchless technologies, as well as contractor's familiarity with open trenching, mean that it is still commonly used. Past experimental evidence has shown that poor workmanship during excavation and reinstatement of trenches, and non-compliance of specifications can

significantly reduce the service life of pavements. Though, it also appears that an increased rate of surface deterioration can be caused even if reinstatements are carried out in full accordance with the required specifications (Zohrabi & Burtwell, 2003).

So far research carried out on utility trenching is limited, with significant gaps still present in the understanding of the long-term performance of trench reinstatements. To be able to develop improved design procedures which will allow for reduced rehabilitation and maintenance of pavements, further understanding of progression of trench reinstatement failure is required.

1.4 Aims and Objectives

The project's main aim will be to provide more understanding into the influence that trench reinstatement can have on the behavior of a flexible pavement structures. The specific objectives set for the study were to:

- Investigate how backfilling of a trench using the same in-situ subgrade material affects the structural performance of a pavement structure;
- To study how the addition of more structural layers (base/wearing course) alters the performance of a trench backfilled using the same in-situ materials;
- To identify deformation mechanisms which occur during failure of a backfilled trench;
- To identify any correlations between pavement failure mechanisms identified and real-life road defects and potholes

2. Literature Review

2.1 Flexible Pavement Design

The design of flexible pavements has traditionally relied on empirical practice. This is because a pavement structure is difficult to model theoretically and is constructed from materials with complex mechanical properties (Brown, 2012). The application of the commonly used empirical approaches to flexible pavement design, regularly results either in premature failure of the pavement or building up of uneconomical pavement sections. Relationships between design inputs and pavement failure have been deduced from experience, experimentation or a combination of both. As a result, these relationships are limited to a certain set of environmental and material conditions. It is for this reason why no internationally acceptable method of pavement design has emerged (Brown, 2012).

In recent decades, major research to develop standard empirical methods has been carried out in the USA. The result was the development of ‘mechanistic-empirical’ (M-E) design approaches (Brown, 2012). These approaches use mechanical analysis to determine the tensile and compressive strains developed within pavement layers. However, due to gaps that exist in the knowledge base, empirical models are still required as part of the process to examine several pavement distress modes. The American Association of State Highway and Transportation Officials (AASHTO) developed the Mechanistic-Empirical Pavement Design Guide (MEPDG) which provides a rational design framework to characterize the impacts of traffic, climate and materials’ properties on pavement performance. The empirical damage model in the MEPDG has been calibrated based on a nationwide pavement performance data-set.

To evaluate the MEPDG design software, many states have carried out research to compare results of local pavement structures with existing pavement data. Research carried out for the state of Louisiana (Wu et al., 2012) showed that the comparison between predicted and measured performance had a strong dependency on the pavement structure type. The differences in predicted and measured values for some structures shows the difficulty of producing a universal model applicable to the vast range of pavement structures and material used. The initial MEPDG model over-predicted rutting for three out of the four structure types present in the research. By performing local calibrations of the rutting model, the accuracy of the predictions was significantly improved (Figure 2). Therefore, to obtain accurate pavement predictions, the calibration of the M-E model to incorporate local factors and site-specific factors is a critical step. Validating these local calibration factors with accurate material inputs, traffic data and previous performance data is important to achieve the required high levels of accuracy.

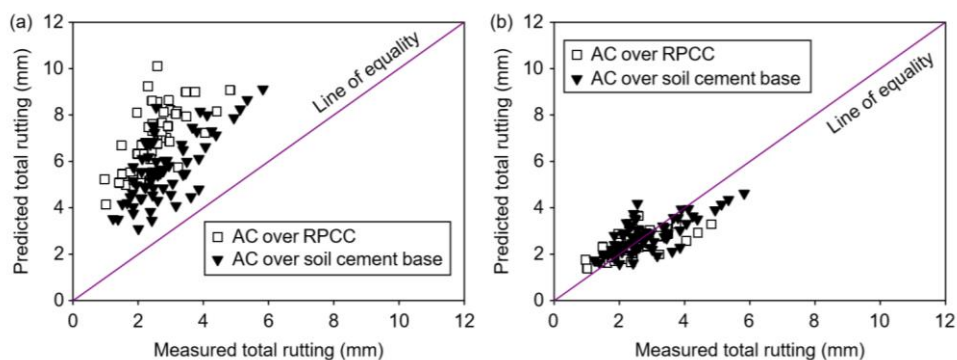


Figure 2 - Predicted versus measured total rutting (a) before and (b) after local calibration (Wu et al., 2012)

The MEPDG design methods have been shown to significantly improve the accuracy of prediction of pavement performance over empirical methods (Retherford & McDonald, 2013).

However, they do not completely eliminate uncertainty within the models. One common uncertainty is model form error which occurs because of a lack of fit between predicted and actual behaviour of pavements. The source of this error is primarily attributable to inadequacy of the model in incorporating all the mechanistic properties of the pavement behaviour. This proved to be an issue when Erlingsson (2012) developed an M-E approach to calculate degradation behaviour of an arterial road in Southern Sweden. Predicted rutting results were shown to follow the actual measurements well for the first 8-9 years but thereafter the model indicated a much milder rutting development (Figure 3). The variation was due to the fact no ageing, seasonal variation or changes in structural integrity of the pavement structure were incorporated in the numerical analysis. In reality, cracking was seen to commence in the structure after 8 years. Incorporating changes to material properties gradually as cracking increases could have improved the accuracy of predictions.

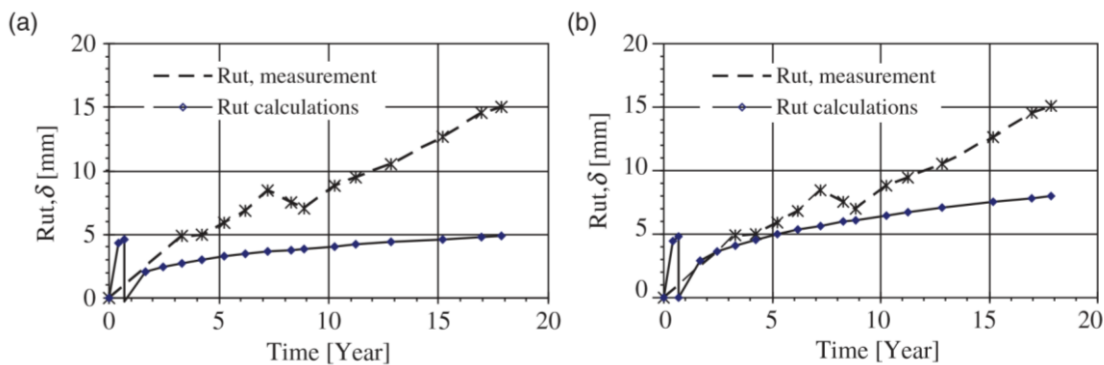


Figure 3 - Comparison of calculated with measured development rutting as a function of time. Two models have been used for predicting the permanent deformation in the unbound base course and subbase layers, a model according to (a) Gidel et al. (2001) and (b) Korkiala-Tanttu (2005).
(Erlingsson, 2012)

Developing a better understanding of the underlying physics relating to pavement failure is important in obtaining more accurate predictions (Retherford & McDonald, 2013). Understanding the failure mechanisms present in different types of structures, materials and environments will allow for more accurate local calibration factors to be derived, whilst it will also result in improved mechanistic modelling. This will reduce the uncertainty in M-E approaches, therefore increasing their effectiveness. In addition, increased knowledge of pavement failure will be crucial when developing new design methods which transfer away from the reliance on empirical models.

2.2 Subsurface Deformation Mechanisms

When rutting occurs, soil undergoes a loading-unloading sequence resulting from wheel contact that ultimately induces extremely large and inherently three-dimensional deformation (Hambleton & Drescher, 2009). Research has been performed to identify deformation mechanisms present both in the longitudinal and transverse directions.

Bowman & Haigh (2019) used the Cambridge accelerated pavement tester (APT) and digital image correlation (DIC) to observe subsurface soil displacement in the transverse direction for two pavement structures with varying thicknesses. Observing soil displacement during repeated wheel loading cycles allowed for progressive failure to be monitored and the changes in soil displacements and strains with different layer thickness to be quantified. Results confirmed that surface deformations were the result of an accumulation of subsurface plastic shear and volumetric strains. The deformation behaviour witnessed in the transverse direction was shown to alter depending on layer thickness. For thin surface layers, deformation was witnessed to closely resemble an Osman & Bolton (2005) mechanism for loading of a circular surface foundation (Figure 4 (a)). Due to the small thickness of the base, the mechanism was assumed to occur over a single layer with properties the same as the subgrade. On the other hand, for thicker surface layers the mechanism became distorted with a sliding block mechanism occurring in the strong surface layers, underlain by a Houlsby & Burd (1999) type mechanism (Figure 4 (b)) in the subgrade soil.

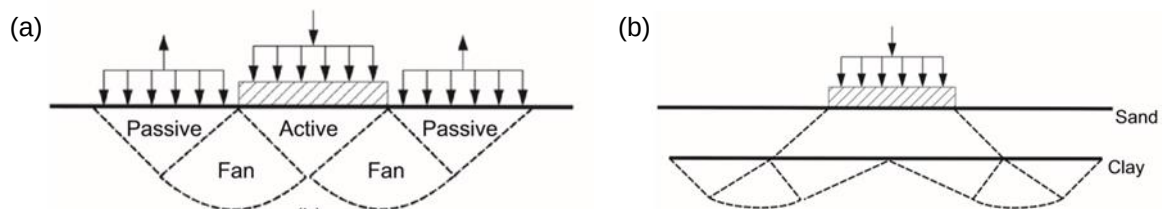


Figure 4 - Failure mechanisms: (a) Osman & Bolton mechanism (displacement boundary the same as for Prandtl mechanism); (b) Houlsby-Burd mechanism

Research on the deformation mechanism in the longitudinal direction has also been performed through the use of the Cambridge APT and DIC (Tse, 2019). Subsurface soil displacement was monitored for an incremental wheel step over both single- and two-layered pavement structures. The test on the single-layered subgrade pavement resulted in the deformation mechanism shown in Figure 5 (a) below the wheel contact area. The deformation witnessed is expected to be a combination of a Wong (1967) mechanism and a Prandtl mechanism for a shallow foundation subjected to an inclined load. Testing of the two-layered pavement structure, consisting of a base course and subgrade layer, produced the displacement vector field displayed in Figure 5 (b). Deformation of the subgrade was seen to be similar to a Prandtl

mechanism for an inclined load acting on a shallow foundation. When compared to the results of the single-layered pavement, the base course was shown to be very effective in reducing deformation due to it distributing the wheel load and mobilising soil movement over a greater area in the subgrade.

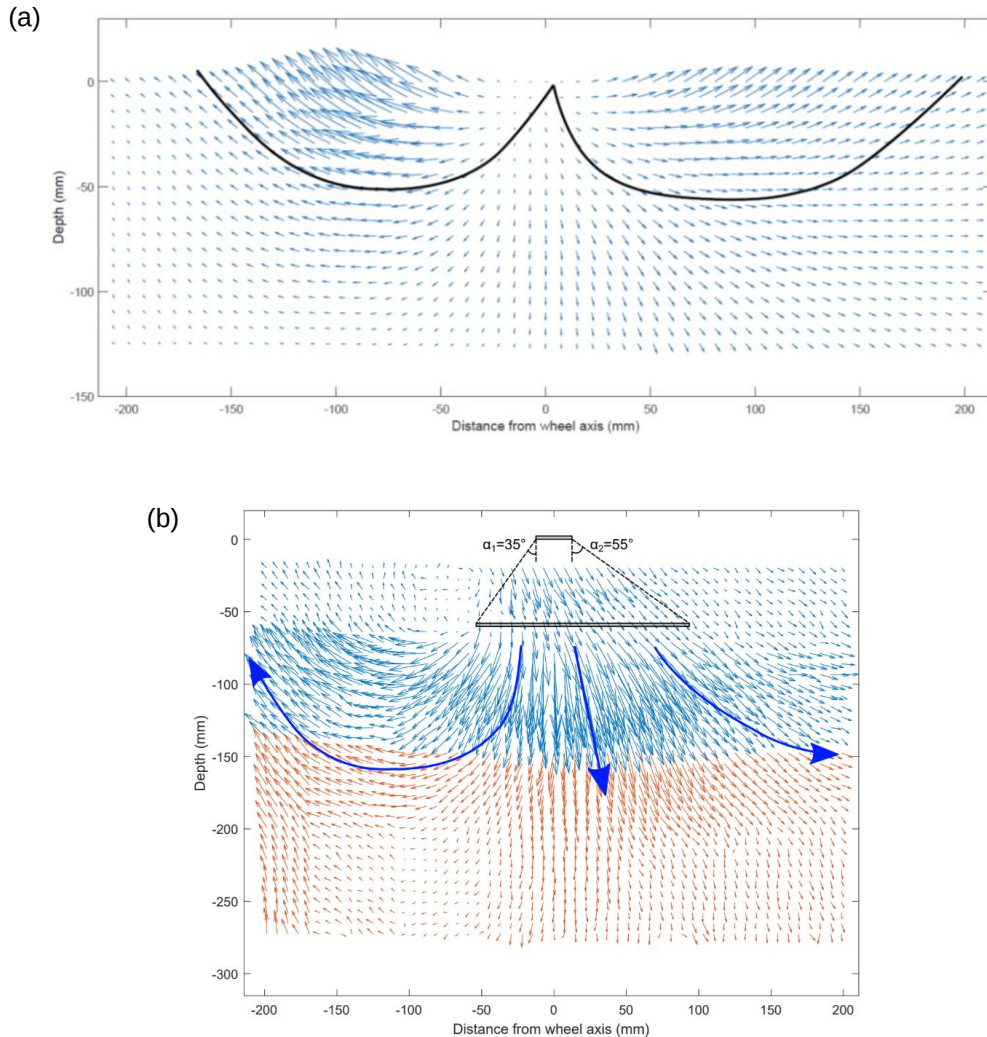


Figure 5 - Subsurface soil displacement for an incremental wheel step over (a) single-layered subgrade pavement and (b) two-layered pavement (70mm base course layer underlain by subgrade) (Tse, 2019)

Hambleton & Drescher (2009) simulated numerically the rolling process of a towed wheel in three-dimensions using the finite element code ABAQUAS. To achieve computational stability, cohesion needed to be included in the simulation regardless of the soil type. To assess the capability of the numerical simulation, a preliminary small-scale experiment on granular material was performed to compare simulated and measured deformation for an incremental wheel step. Figure 6 displays the measured soil displacement obtained through particle image velocimetry (PIV) and also the predicted soil displacement from the simulation. Due to the cohesion required in the simulation, discrepancy arose in the zone directly below and to the

rear of the wheel. This is expected as it is this region where tensile isotropic stresses develop in the numerical simulation.

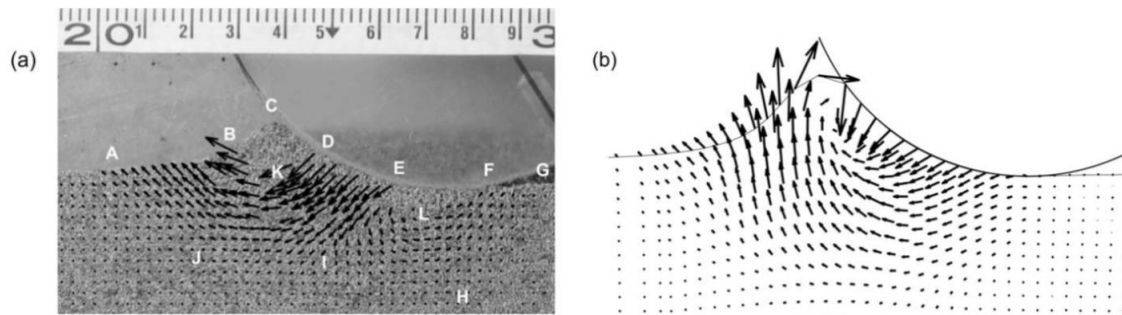


Figure 6 - Soil displacement from incremental wheel step for (a) experiment and (b) numerical model (Hambleton & Drescher, 2009)

Numerical solutions revealed that the advanced three-dimensional process of rutting can be regarded as steady. Using steady state conditions an approximate analytical model for predicting shrinkage was also developed by Hambleton & Drescher (2009). It was assumed that the soil-wheel contact interface was equivalent to a flat rectangular surface with area and inclination determined by sinkage. In addition, the average stress over the surface was taken as the average ultimate stress for an equivalent shallow foundation. Using these assumptions two methods which handle the effects of inclined loading differently were considered.

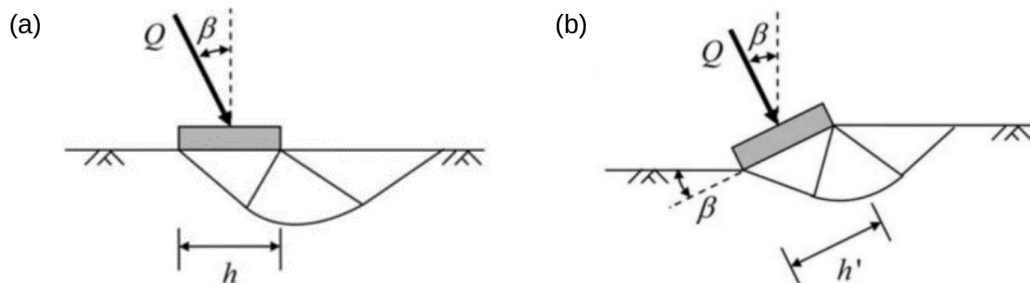


Figure 7 - Proposed analytical models: (a) inclined load; (b) inclined footing (Hambleton & Drescher, 2009)

Predictions using the two analytical models were compared with force-sinkage data from tests with rigid wheels on clay and sand. The inclined footing method provided more realistic predictions, with the solutions agreeing reasonably well with the measurements.

So far research into deformation mechanisms below the surface of a pavement have only been performed for structures with uniform layers. When a trench is excavated and reinstated in a pavement, the structural layers no longer have uniform properties. The following research looks into the effects that trench reinstatements have on a pavement's structural properties and surface deformation. In addition, deformation in the longitudinal direction has only been

explored for an incremental wheel step. In the project, progressive failure over repeated loading cycles will be explored.

2.3 Trench Reinstatements

Research has been performed in many regions across the world to determine the effect that trench reinstatements have on pavement performance. A common method used to achieve this is to analyse changes in pavement performance measures, such as Pavement Condition Index (PCI), Utility Cut Condition Index (UCCI) or Pavement Quality Index (PQI), for both reinstated and non-reinstated pavements. These performance measures are typically based on measurements of pavement surface features, such as distress, deflection and roughness. Relating pavement performance values with pavement ages allows relationships to be determined between the two. By setting a threshold for the performance measures, the relationships can be used to estimate the average life time of a pavement both with and without a trench reinstatement. Table 1 shows the results of this method for a range of regions in America and Canada (Zohrabi & Burtwell, 2003). For each area, failure is shown to be significantly accelerated as a result of trenching.

		Vermont, America	Cincinnati, America	Los Angeles, America	Ottawa, Canada
Average Lifetime (years)	Reinstated Section	8.5 – 12.1	7 – 9	16.5	8.6
	Non-reinstated Section	19.8 – 25.9	15 – 20	25	12.7

Table 1 - Estimated average life times of reinstated and non-reinstated pavements in different regions across North America (Zohrabi & Burtwell, 2003)

Zhang et al. (2005) used in-situ probing techniques to diagnose the causes of surface dips in the pavement over trenches. Results of penetration tests performed on the surface of trench reinstatements suggested that the relative stiffness between the materials within and outside the trench, were an important factor in dip formation. Dynaflect tests indicated that dips would occur at the surface if the resilient modulus of the backfill was significantly lower than the resilient modulus outside the trench. Using the penetration test results, penetration resistance ratios (PRR) (ratio of average penetration resistance within and outside trench area) were calculated for about 30 trenches. The results plotted in Figure 8 indicate that a $PPR < 0.7$ will predetermine the occurrence of a dip. Overall, the results show that using a backfill with a stiffness larger than that of the subgrade will prevent dip formation.

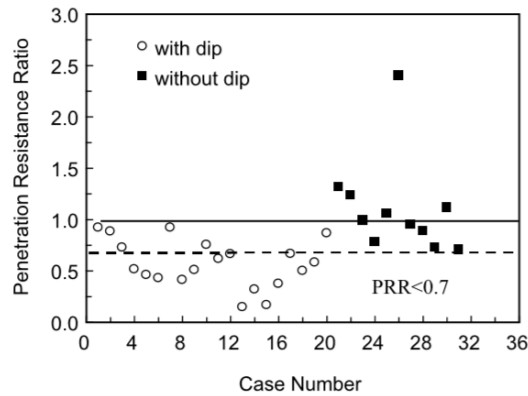


Figure 8 - Ratio of penetration resistances within and outside of trenches (Zhang et al., 2005)

Stiffness of the backfill is dependent on the compaction achieved during reinstatement. A full-scale laboratory study was carried out in New York to compare the performance of poorly- and well-compacted backfill (Todres & Baker, 1996). The trial subjected 12 trench reinstatements (6 well-compacted and 6 poorly-compacted) to 2.5 million repeated loadings each. The results showed no failures within the well-compacted trenches. However, all the poorly-compacted trenches showed deflections greater than 6mm, with four exceeding 10mm. This study emphasizes the critical role of compaction in producing stability and good performance of pavement surface layers.

A higher degree of compaction will result in backfill having a greater density. Between 1985-88 analysis was carried out for twenty-two trenches in and around Southampton, comparing comparative density (field value compared to the laboratory derived optimum) to the settlement measured during the active life of the trench (Fleming & Cooper, 1995). Results displayed in Figure 9 show that, as expected, a correlation is apparent between comparative density and settlement.

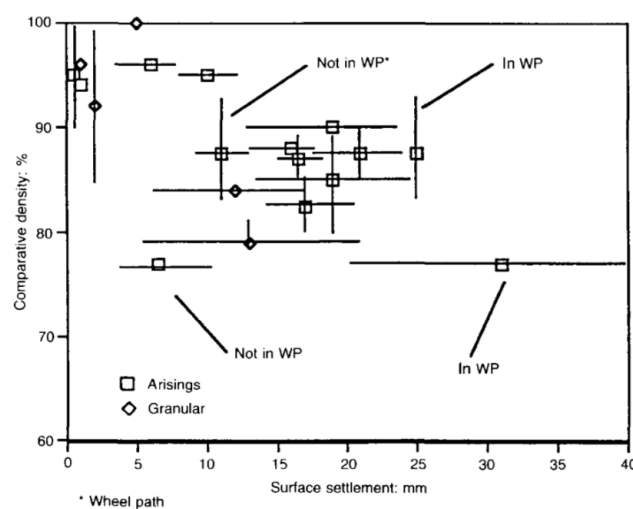


Figure 9 - Relationship between comparative density and settlement (Fleming & Cooper, 1995)

In-situ tests performed on trench reinstatements in Iowa showed that in most cases stiffness was greater at the centre of the trench compared to the edges (Schaefer et al., 2005). Similar findings were shown in Kansas City, Missouri when falling weight deflectometer (FWD) tests were carried out to evaluate 24 sites of composite pavement containing less than two-year old patched reinstatements. Measurements taken showed that the edges of the reinstatements had 50-60% of the structural capacity of the centre (Zohrabi & Burtwell, 2003). The reduction in performance at the edge of the trench is a result of poor compaction achieved due to difficulty in using compaction equipment in the more confined area (Zohrabi & Burtwell, 2003).

Trenching does not only affect the areas within the trench reinstatement. When a utility cut is made the native material surrounding the perimeter of the trench is subjected to loss of lateral support. This leads to loss of material under the pavement and bulging of soil on the trench sidewalls into the excavation. Subsequent refilling of the excavation does not necessarily restore the original strength of the soils within this weakened zone, known as the “zone of influence” (Schaefer et al., 2005). As a result of the weakening of the soil, pavement within this zone can fail more rapidly than other parts of the pavement. In Ottawa, Canada pavement deflection and profile roughness measurements were taken to determine the average distance beyond the trench effected by utility trenching (Lee & Lauter, 1999). Results from the testing of hundreds of sections were found to give an average zone of influence of 0.275m, which is equivalent to about 30% of the average urban road network trench of 1.9m.

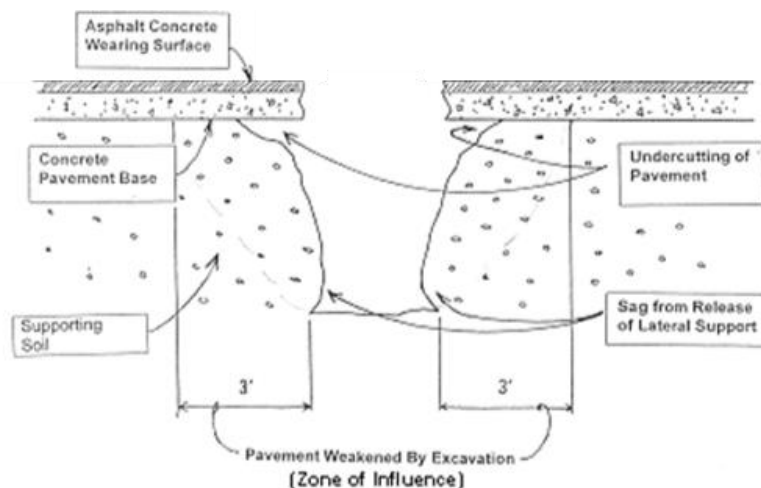


Figure 10 - Overstressing of the pavement and natural materials adjacent to the trench (Schaefer et al., 2005)

The introduction of utility cuts is much like the introduction of cracks on the pavement. If improperly sealed water intrusion can occur resulting in loss of fine materials from the underlying base and subgrade. Consequently, this can result in a loss of strength in the surrounding pavement structure (NVA, 2000).

During research carried out on trench reinstatements in Iowa, moisture contents were measured for a variety of backfill materials collected from the field (Schaefer et al., 2005). At several locations, backfill material was measured to have a moisture content within or just below the bulking moisture content. Bulking is a capillary phenomenon occurring in granular materials in which capillary menisci between soil particles hold them together in a honeycombed structure. A structure at this moisture content is prone to collapse upon the small addition of water, as the capillary tension between the soil particles is destroyed. Therefore, the settlement potential is increased for backfill materials with moisture contents within or just below the bulking moisture content. To reduce the chance of settlement, the soil should be compacted at moisture content just above the bulking moisture content.

Research has consistently shown that the rate of pavement failure is increased due to trenching, yet minimal research has been performed to identify the mechanisms behind such failure. This research project will focus on investigating the deformation mechanisms which occur below the pavement surface as a result of trench failure. Increasing the understanding of trench failure will help develop new and improved design and construction methods to increase the life time of trench reinstatements.

3. Methodology and Experimental Setup

To accomplish the research objectives detailed in section 1.4, the Cambridge Airfield Pavement Tester (APT) has been used to carry out accelerated tests on seven pavement sections with trench reinstatements. Four of the pavement sections tested were single-layered whilst the other three were two-layered. Whilst constructing each pavement section, a trench was excavated into the subgrade layer and then poorly backfilled using the same in-situ material. During testing, images of both the surface and subsurface soil were captured to allow for deformation to be monitored.

3.1 Cambridge Airfield Pavement Tester (APT)

The APT's main purpose is to physically model the traffic conditions that pavement structures would be exposed to in the field within a compressed time period. Through the controlled application of wheel loading to a pavement surface, the amount of damage that might take months to occur in the field can be achieved in a matter of days or even hours in the laboratory.

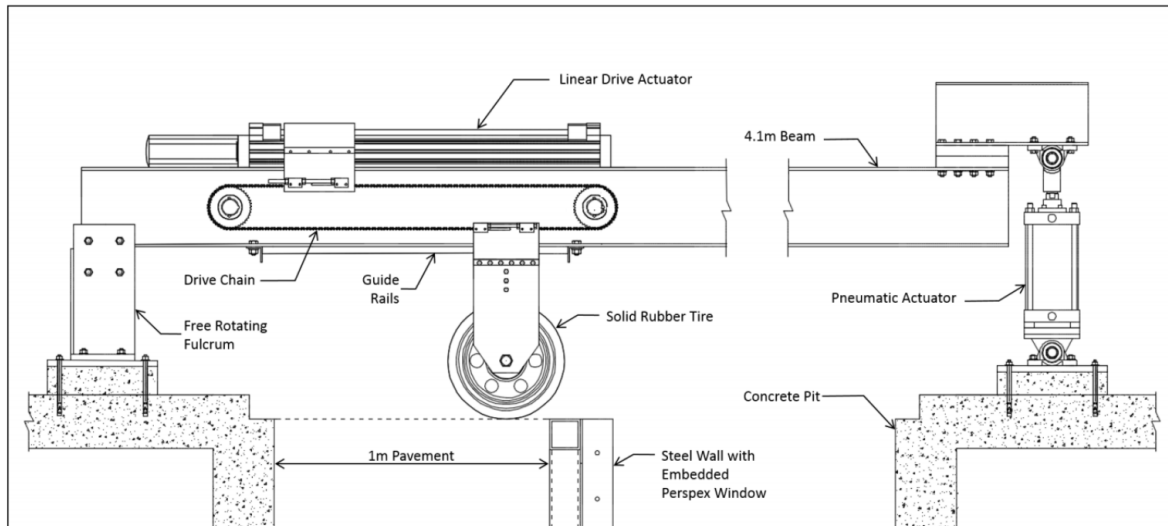


Figure 11 - Side view of Cambridge Airfield Pavement Tester (Bowman & Haigh, 2016)

Figure 11 shows the primary structural elements of the APT used for this research project. The pavement structure to be tested was constructed in a pit below the APT. A controlled, constant load was applied to the pavement by a pneumatic actuator, which pulls down on the 4.1m beam, applying a force to a single solid tyre. For the project the load applied to the pavement was set at 4.5kN (around quarter the weight of the average car). As deformation occurs during the test, the pneumatic actuator must still apply a constant load to the surface. Strain gauges attached to the wheel-supporting plates measure the tyre load and provide feedback to a control system which makes the necessary adjustments to the pressure in the pneumatic actuator. Once the specified load is reached, the tyre is driven along the pavement surface by an electric stepper motor. The load is continually monitored during the tyres movement along the surface, with the feedback loop continuing to make any adjustments. In the tests, the pavement structures are subjected to unidirectional loading. Therefore, when the tyre reaches the end of the test section, the pressure applied by the pneumatic actuator is released causing the tyre to be lifted away from the surface. The tyre is driven back to the starting position before the process is repeated (Bowman & Haigh, 2016).

3.2 Material Properties

Three different materials were selected to use as subgrade, base course, and wearing course in the pavement structures tested:

- Subgrade: Kazakhstan medium sand-silt (KW15)
- Base course: Limestone aggregate
- Wearing course: Cold lay macadam

Bowman (2018) previously performed laboratory tests to determine intrinsic properties for different Kazakhstan sand-silts as well as the limestone aggregate. Table 2 displays the properties determined for the two soils used.

Soil Name	Mean Particle Size (D_{50}) (mm)	Specific Gravity G_s	Optimum Moisture Content (%)	Maximum Dry Unit Weight (kNm^{-3})
Kazakhstan Medium Silt-Sand (KW15)	0.3	2.68	9.8	19.00
Limestone Base Course	5.6	2.60	12.8	16.08

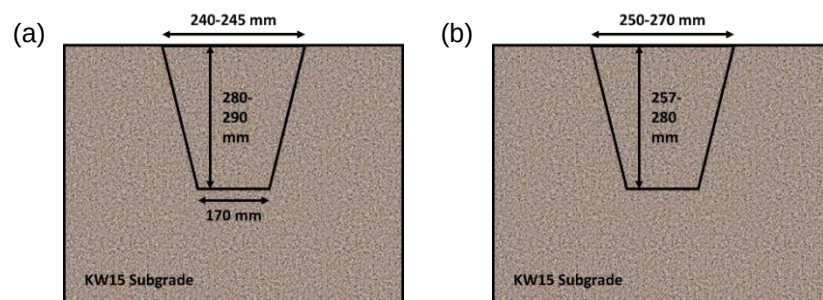
Table 2 - Properties of KW15 and limestone aggregate

3.3 Pavement Structures

Three pavement structure designs were tested as part of the research. The primary design tested consisted of just compacted KW15 subgrade. The two other pavement structure designs were constructed using KW15 subgrade with a layer of either limestone base course or cold lay macadam on top. After the construction of the subgrade layer for each structure, a trench was dug into subgrade and backfilled with the same in-situ KW15 soil. When backfilling the trenches, the KW15 soil was deliberately compacted less than the surrounding subgrade to simulate a poorly carried out trench reinstatement.

For this research project seven accelerated pavement tests were performed. The following sections display the layout of the pavement structures tested as well as the moisture content of the subgrade. Measurements for the top and bottom widths as well as the depth of each trench were taken at three different locations (front, middle and back). Each figure lists the range of measurements recorded for these three dimensions.

3.3.1 Single-Layered Pavements



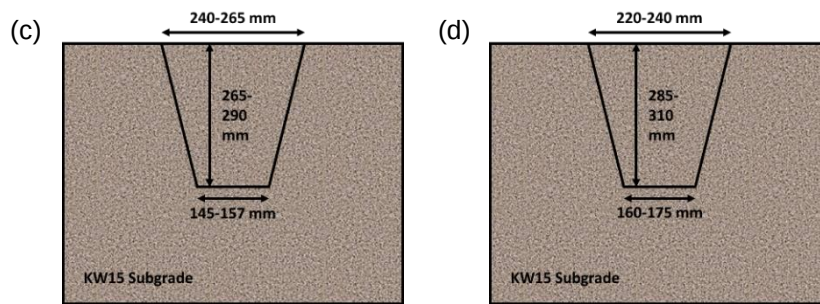


Figure 12 - Single-layered pavement structures constructed for (a) test 1, (b) test 2, (c) test 3 and (d) test 6

The KW15 subgrade used for test 1 had been placed and compacted at least 5 months prior to testing with no information present on the moisture content of the soil.

Test	1	2	3	6
Moisture Content (%)	N/A	6.1	6.9	5.8

Table 3 - Moisture content of subgrade at construction in single-layered pavements

3.3.2 Two-Layered Pavements with Base Course

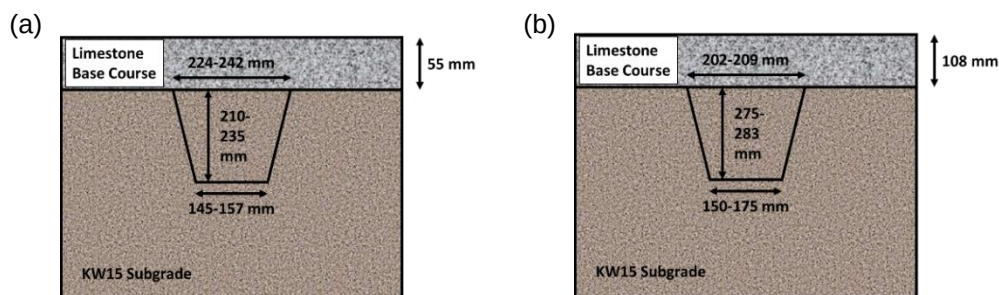


Figure 13 - Two-layered pavement structures constructed with base course for (a) test 4 and (b) test 5

Test	4	5
Moisture Content (%)	6.9	4.4

Table 4 - Moisture content of subgrade at construction in two-layered pavements constructed with base course

3.3.3 Two-Layered Pavement with Cold Lay Macadam

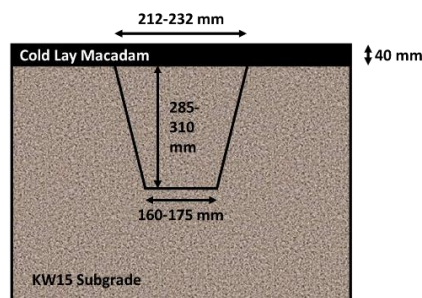


Figure 14 - Two-layered pavement structure constructed with cold lay macadam

For test 7 the moisture content of the subgrade was not measured.

3.4 Image Capture

3.4.1 Soil Displacement

A Perspex window was used to enclose the pavement structure on one side of the pit to allow for soil deformation to be monitored. The window was located so that the edge of tyre was adjacent to the window. This meant that the deformation viewed through the window was of soil directly below the wheel path.

Six Raspberry Pi cameras were located on a plate opposite the Perspex window to capture images of the pavement layers during testing. The layout of these cameras relative to the window can be seen in Figure 15. To make sure the whole area of interest was captured, each camera was positioned so that its images overlap with those of the surrounding cameras. For the majority of tests carried out the cameras were set to capture images at intervals of 20 seconds. However, for tests 6 and 7 the interval was reduced to 7 seconds.



Figure 15 - Camera setup located opposite Perspex window to monitor soil displacement

To ensure that the images captured were of a high enough quality for future analysis, an LED light was placed on top of the window. A mat was also placed over the top of the gap between the window and the camera plate to prevent any glare.

3.4.2 Surface Deformation

Six Raspberry Pi cameras were used to capture images of a pavement surface over the course of testing so that 3D reconstructions of the surface could be created. The algorithms used by the 3D modelling software are not very tolerant to significantly different distances and angles to the surface. Therefore, two cameras were placed underneath the 4.1m beam of the APT, whilst a further three cameras were placed at roughly the same height, but to the side of the pavement surface. To improve the accuracy of vertical displacement measurements, a sixth

camera was added at the far end of the pit, looking along the wheel path of the APT. Figure 16 shows the final camera setup, with the locations of the cameras highlighted by red circles.

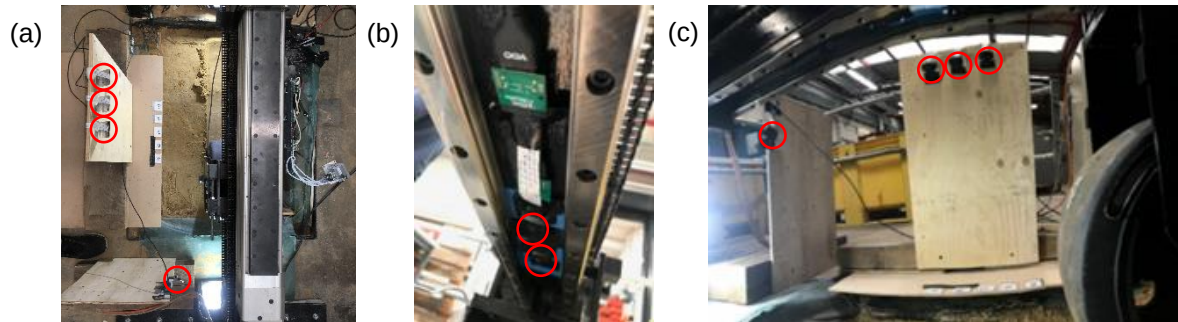


Figure 16 - Final camera setup to monitor surface deformation

To enhance the texture captured in the images, and therefore improve surface reconstructions, a light was placed at either end of the pit. The cameras were programmed to capture images twice during each wheel cycle. Images were taken when the wheel was at the start of the loading cycle and then again after the wheel had travelled across the surface to the other end of the test section.

3.5 Pavement Structure Construction

The pavement structures were constructed in a concrete pit with dimensions of 860mm x 800mm x 1000mm. To reduce boundary effects caused by friction between the concrete walls and the soil, the concrete pit was lined with a combination of plastic sheeting, silicon grease, geomembrane and geosynthetic. Bowman (2018) performed interface direct shear tests using the concrete wall interfaces and soils described in section 3.1. Substantial reductions in shear stress of 96% and 95% were observed in the subgrade and base course, respectively. The layout of a pavement structure in the pit is shown in Figure 17.

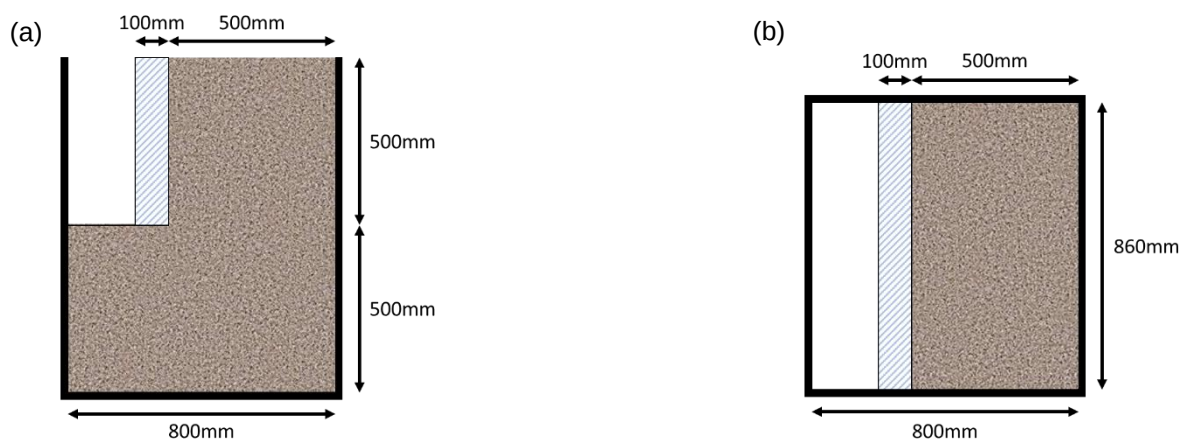


Figure 17 - Layout of pavement structure inside concrete pit from (a) front view and (b) plan view

The bottom 500mm of the concrete pit was completely filled with KW15 soil before the start of the research project. This layer remained untouched throughout the experimental work, with only the top 500mm of soil altered in between tests. The procedure for constructing a pavement structure in the top 500mm of the pit was as follows:

- The water content of the subgrade to be used in construction was calculated from a sample which had been placed in an oven for 24 hours. If the water content was below optimum, water was added to the subgrade which was then well mixed.
- Before placing the subgrade into the pit, the Perspex window was cleaned with plastic cleaner to remove any soil or debris left from the previous test.
- The subgrade was placed into the pit in layers of roughly 100mm until the required height for the chosen pavement design was met.
- Each 100mm layer was compacted using a plate compactor to optimum modified Proctor values.
- After completion of the subgrade layer, a trench perpendicular to the wheel path was dug across the centre of the layer.
- The trench was refilled with the same in-situ subgrade in layers of around 50mm.
- Each 50mm layer was compacted by 100 strikes of a wooden stake, making sure that compaction was below optimum modified Proctor values.
- If required by the pavement design, layers of base course or cold lay macadam were placed on top of the subgrade and compacted using the same method as described for the original subgrade layers.

3.6 Analysis Techniques

3.6.1 Particle Image Velocimetry (PIV)

PIV is a velocity-measuring procedure originally developed in the field of experimental fluid mechanics. GeoPIV is a MatLab software which implements PIV to allow for soil movement and associated strains to be observed and measured in-situ. It operates by tracking the texture within an initial image of soil through a series of subsequent images. The initial image is divided up into a mesh of test patches. The displaced location of a patch in a subsequent image is found by analysing the correlation of the initial patch with larger patches across the subsequent image. The location where the correlation is highest indicates the displaced location of the initial patch. This operation is repeated for the entire mesh of patches within the image and then repeated for each image within the series to produce complete trajectories of each test patch (White & Take, 2002). This method works for multiple soil types and for any type of

movement, therefore making GeoPIV a useful tool for analysing the deformation of the pavement structures tested.

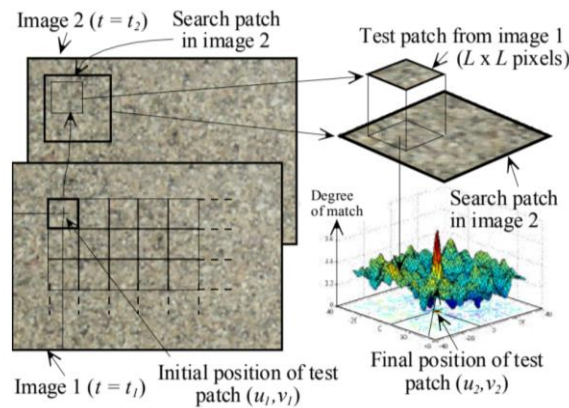


Figure 18 - Principles of PIV analysis (White & Take, 2002)

The precision of GeoPIV was found to be a strong function of patch size. Although larger patch size leads to improved precision, the number of measurement points that can be contained within a single image is reduced. This results in the displacement field in areas of high strain being ‘smeared’. For the analysis carried out a patch size of 75 x 75 pixels was used, which corresponds to an upper bound on precision of 0.008 pixels.

To allow for the scaling of soil displacements, control points, in the form of circular stickers, were placed on the inside of the window at a distance of 50mm from each other.

3.6.2 Agisoft Metashape

To capture the evolution of the pavement surface during testing, 3D models were produced using the software Agisoft Metashape. The software constructs 3D models by combining the computer vision approaches of ‘structure-from-motion’ (SfM) and ‘multi-view stereo’ (MVS). To start SfM reconstruction, images are processed by an automatic feature-detection-and-description algorithm called SIFT (Scale Invariant Feature Transform). It works by taking the most prominent image ‘features’ and matching them in different images within the image set. Using the resulting network of matched features, the camera model parameters and camera orientations are determined. Simultaneously, 3D coordinates for feature points are computed, thus producing a sparse point-cloud of the most prominent features within a 3D space. To produce a more detailed 3D model, the subsequent dense MVS matching process is next performed by PMVS2. PMVS2 generates large numbers of points by working over a grid of pixels in an image, effectively searching for the best matches for each grid cell (James & Robson, 2012).

10 control points of known distances from each other were used to scale the 3D models. Figure 19 shows the locations of the control points, with five located on the top of the Perspex and another five on the opposite side of the test section.



Figure 19 - Layout of control points used in pavement surface reconstruction

Different numbers of images are used to create different parts of a model and therefore the Metashape software calculates error for each of these parts within a reconstruction. Each reconstruction also has different error due to the quality of the images, the clarity and the number of tie points identified by the software. In each reconstruction produced there are two types of error to consider; error of the placement of the reference markers and error of the position of the model points relative to each other. For the reconstructions in this project, the error of placement of the reference markers in the x-y plane is around 0.7cm, while in the z direction the error is in the region of 1.7cm. The surface deformations shown in the reconstructions are well defined and so it is reasonable to assume that the accuracy of the model points relative to each other is much better than the accuracy of the placement of the reference markers. From analysing laboratory measurements from other tests performed using the same technologies and techniques it is likely that the error of the position of the model points relative to each other is between 100µm and 1mm. Therefore, the influence of this error type is minimal.

3.7 Compaction Issues

Achieving high levels of compaction for all pavement layers proved challenging, but it was especially difficult when constructing the base course and wearing course. In the field, large petrol-powered compactors, such as rollers, are used for pavement compaction. However, as the APT is located within an enclosed space, such methods are not acceptable due to the emissions they produce. Even though the most powerful electric compactor available was selected for the project, it was significantly smaller than the petrol alternatives. Consequently,

the electric plate vibrator used was not be able to provide a large enough compressive force to obtain the high levels of density required for the base course and cold lay macadam. As a result, the wheel was able to easily embed into each of these layers and shove the material along in the direction of travel.

To achieve the highest density possible for the subgrade layer, the moisture content needed to be at the optimum level during compaction. Determining the moisture content of subgrade during testing involved placing samples into an oven for at least 24 hours. Over this period moisture in the remaining subgrade would evaporate meaning that the sample measurements would be different to the actual subgrade used for construction. As a result, it was difficult to achieve optimum moisture content of the subgrade.

3.8 Issues with Tracking Soil Movement using PIV

Whilst digging the trench, the Perspex window became heavily scratched resulting in PIV not being able to track the subgrade movement in test 1. PIV determines soil movement by tracking the texture within a patch of an image over a series of subsequent images. As scratches remain stationary during the course of a test, PIV assumes that the soil at these locations also remains stationary. With the window containing a large amount of scratches, significant amounts of soil movement were not captured. This was not noticed until after the test was performed and so PIV could not be used. The scratches were removed from the window for subsequent tests using an orbital buffer.

To be able to gain the best understanding of soil movement due to wheel loading, the soil profile directly below the centre of the wheel should be monitored. For test 2, a second piece of Perspex, with a height of 475 mm and a thickness of 10 mm, was installed next to the existing window to monitor soil closer to the centre of the wheel. However, the resulting images captured by the cameras were dark and showed very little soil texture. As a result, PIV was not able to determine subgrade displacement for the test. Unlike the initial Perspex window, the second one installed was not illuminated by an LED light, whilst the top was also covered with a 25mm layer of subgrade. It is thought that the dark images were a result of a lack of light entering the second Perspex window. After test 2 the second piece of Perspex was removed and the original test setup was used for the following tests.

Movement of the base course was not able to be tracked accurately by PIV for tests 4 and 5. During compaction and throughout testing the base course was found to scratch the Perspex window, therefore introducing the same tracking issues as described above. In addition, the

silty fines in the base course were seen to form a paste which stuck to the window preventing the tracking of the base course behind.

The control points stuck on the Perspex window were found to either move from their original position or be completely removed from the window during pavement construction and testing. Due to each point moving randomly, the new distances between them were unknown. Therefore, it was not possible to accurately scale PIV results for subsurface soil displacement. As a result, all PIV data presented in the following sections has the dimension of pixels.

4. Result and Analysis

4.1 Pavement Structures without Base Course or Cold Lay Macadam

Four tests (tests 1, 2, 3 and 6) were performed on single-layered pavements, constructed using KW15 subgrade. However, the first three tests all encountered issues which affected the quality of data obtained. For tests 1 and 2 soil movement was not captured due to issues with the quality of images taken (see section 3.8). The number of images captured for the surface and soil profile of test 3 were reduced due to faults with two of the cameras. In addition, the pavement surface of test 3 was constructed at a lower level than the first two tests. This resulted in only 34-wheel passes being achieved before the APT ran out of stroke. At this point the pavement had only experienced small levels of rutting at the surface. Due to the premature end of test 3 and the camera problems experienced, it has not been analysed further.

4.1.1 Surface Rutting

Figure 20 shows the surface rutting at the end of tests 1, 2 and 6. Red lines have been used to show the location of the trench within each structure, whilst arrows are used to show the direction of travel. All tests performed on the single-layered pavements led to the formation of a large rut along the wheel path. The depth of the ruts were seen to increase over the trench before leveling off to a constant depth just after the trench's downward edge. At the end of the test section rut depth was shown to decrease due to restrictions of soil movement. The side wall of the pit prevents longitudinal movement of the subgrade, therefore leading to a buildup of subgrade at this wall. It is expected that if wall was not in place then the rut would propagate further.

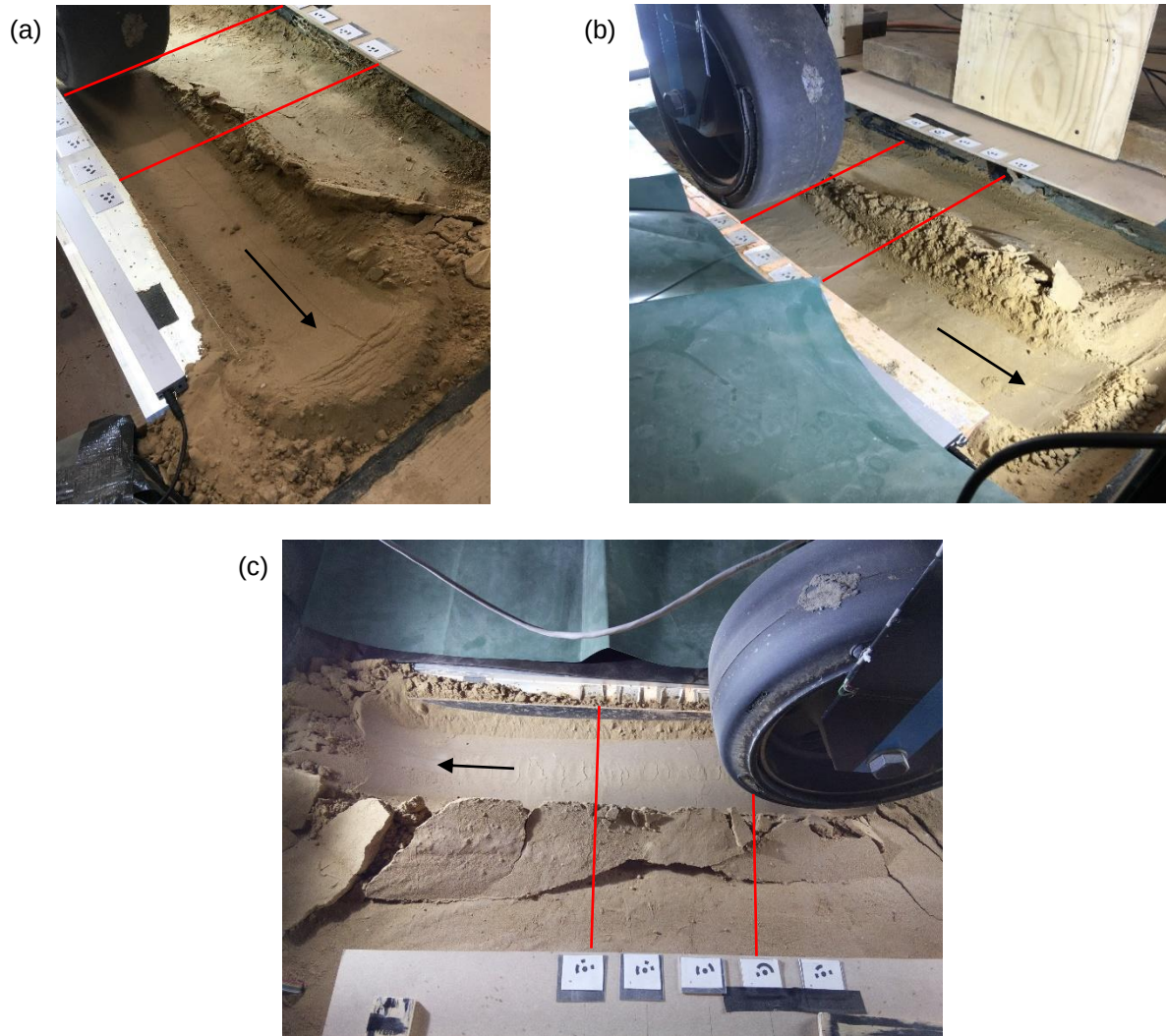


Figure 20 - Surface rutting present at the end of (a) test 1, (b) test 2 and (c) test 6

Figure 21 shows the final rut for test 1 when looking from the start of the wheel path. A significant increase in the rate of displacement along the wheel path is seen just before the upward edge of the trench. Before this point downward deformation is relatively small and constant along the path. An increase in rut slope at the upward edge of the trench was also present for the other two tests.

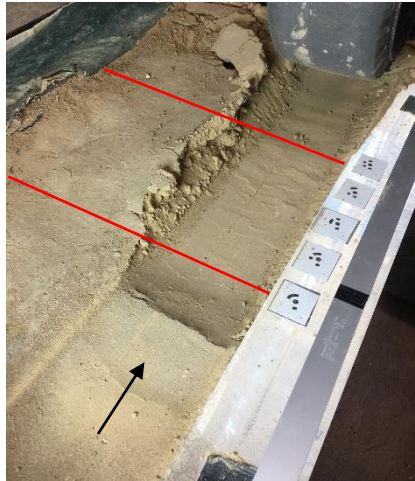


Figure 21 - Surface rutting present at the end of test 1 as seen from the start of the wheel path

The development of the rut witnessed in test 1 was slightly different to that of tests 2 and 6. In test 1, the first significant vertical displacement was witnessed near to the centre of the trench, where a slight dip formed at the surface. The formation of the dip indicates wheel loading caused failure of the weaker subgrade in the trench but not of the surrounding original subgrade. As the number of wheel passes increased, there was an increase in depth of the dip, as well as in the slope angle of the dip's sides. Eventually, the wheel broke through the downward side of the dip forming the shape of the rut shown in Figure 20 (a). It is anticipated that the stronger subgrade after the downward edge of the trench failed due to loading of the sloped side of the dip.

For tests 2 and 6, an initial dip did not form within the trench. Instead, after a low number of passes, downward displacement of the surface was witnessed from the upward edge of the trench through to the far end of the test section. In test 1, downward displacement was seen to decrease from the centre of the trench to the downward edge, therefore forming a dip. However, for test 2, downward displacement was seen to continue to increase after the downward edge. This implies both the subgrades within the trench and after the downward edge fail during the same wheel cycle, despite the subgrade outside the trench being stiffer and stronger.

4.1.2 Subsurface Deformation

In the early stages of each test performed, upheaval of the subgrade in the front of the wheel was witnessed during each wheel cycle. During a cycle, upheaval first became noticeable after the wheel had passed the upward edge of the trench. Upheaval was then continually witnessed over the location of the trench with it most prominent around the trench's downward edge. It is presumed that the upheaval witnessed in front of the wheel is a result of the upward subgrade movement in the front flow zone of Tse (2019) deformation mechanism (Figure 5(a)). Therefore, implying that the subgrade within the trench is failing due to shear.



Figure 22 - Upheaval of subgrade in front of wheel in test 2

PIV was used to determine soil movement below the pavement surface for test 6. The results of the analysis are presented in Figure 23, with the area of the trench represented by a grey shaded block.

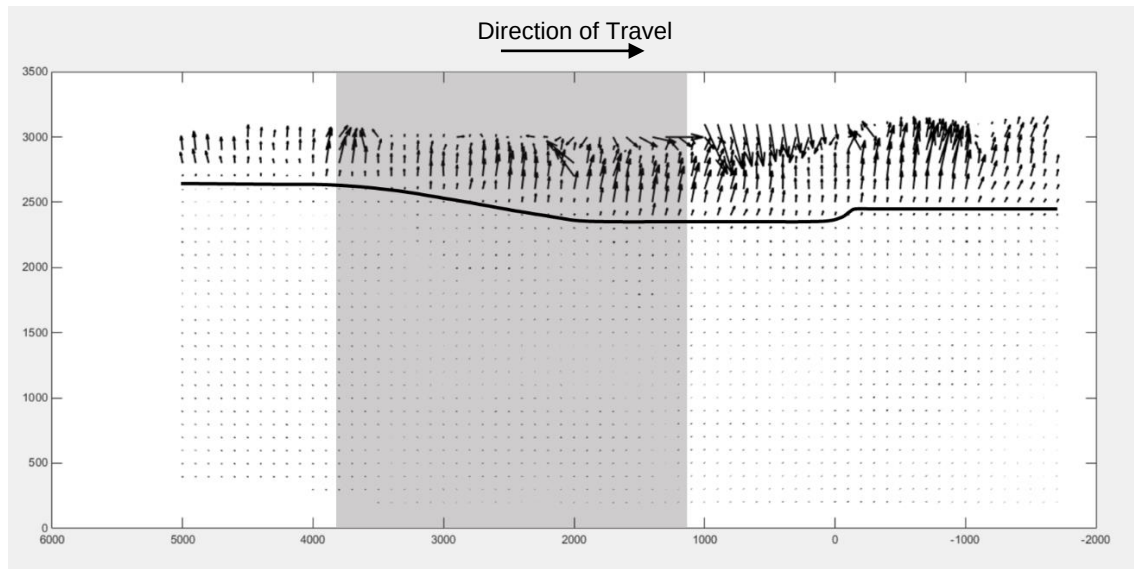


Figure 23 - Movement of subgrade below the pavement surface in test 6

Large upward movements of the subgrade were shown to occur in the upper layers of the structure with very little horizontal movement present. As shear failure of the subgrade was witnessed during testing it was expected that significant horizontal movement would be measured by PIV. Surface images taken at the end of the test (Figure 20 (c)) show that the surface by the window is located at a substantially higher level than the rest of the wheel path. This suggests the wheel does not come into contact with the subgrade by the window, therefore resulting in it not being influenced by the deformation mechanism in the longitudinal direction. Rutting however is three dimensional. Upheaval of the subgrade to the side of the wheel path opposite the window suggests that shear failure has occurred in the transverse direction. As the window is placed adjacent to the wheel path any deformation mechanism in the transverse

direction will be interrupted. This could be the cause for the upwards movement of the soil by the window.

Even though PIV analysis does not determine an exact failure mechanism for the subgrade, the results can be used to provide an insight into the subgrade's failure. The large soil movements seen in the upper layer of the subgrade show that the soil at these locations must have been damaged in some form. Figure 23 shows that the depth at which the subgrade is damaged increases across the trench before remaining relatively constant after the downward edge. Damaged soil is likely a result of shear failure and therefore it is assumed that the depth to which the subgrade is damaged can be linked to surface deformation. Using this assumption, a profile for surface rutting has been drawn on Figure 23. The profile is shown to match to a good level of accuracy the actual surface deformation shown in Figure 20(c).

4.1.3 Failure Mechanism

For each of the single-layered pavements, significant rutting was first seen when the wheel passed over the trench. Tse (2019) has previously determined failure mechanisms beneath single-layered pavements for incremental wheel steps in the longitudinal direction. Deformation of the subgrade in the longitudinal direction across the trench is considered to be the superposition of many finer mechanisms, originating from incremental wheel steps (Figure 24). The proximity of the wheel to the upward edge of the trench is likely to affect the deformation mechanism. It is expected that when the wheel is located closer to the stronger subgrade adjacent to the trench's edge, the amount of deformation from an incremental wheel step is reduced. Therefore, from the upward edge to the centre of the trench there is an increase in downward vertical displacement.

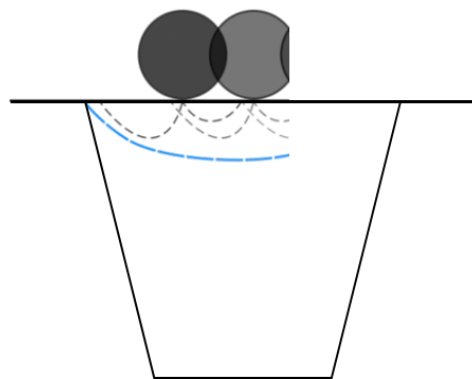


Figure 24 - Superposition of deformation mechanism for incremental wheel steps over front side of trench

As the wheel moves away from the centre of the trench and towards the downward edge, it comes in closer proximity to the stronger subgrade past the trench. Due to the sinking of the wheel over the first part of the trench, it is at a lower level than the subgrade surface in front.

As a result, the wheel load is applied to the subgrade via an inclined slope. Figure 25 presents a relevant failure mechanism derived from lower bound analysis. Due to the subgrade's high silt content (low permeability) as well as the short load application time on the pavement surface, the subgrade is assumed to behave in an undrained manner and is hence characterised as a Tresca material. The partially saturated nature of the soil also causes it not to behave in a conventional drained manner, as might be expected of a sandy soil. The wheel has been assumed to move at a constant speed parallel to the surface, which results in the resultant load acting perpendicular to the surface. In reality the wheel moves at a constant speed horizontally but as the slope angle remains small during testing this makes minimal difference. The shear surface of the mechanism will span across both the subgrade inside and outside the trench. The amount of each subgrade that is present in the mechanism will depend on the proximity of the wheel to the downward edge. For the analysis within this section, the failure mechanism is only considered for wheel loading right at the downward edge and so the stronger undrained shear strength of the original subgrade is used. However, it may be sensible to apply a safety factor to any strength measurements to account for loss of strength in the zone of influence surrounding the trench.

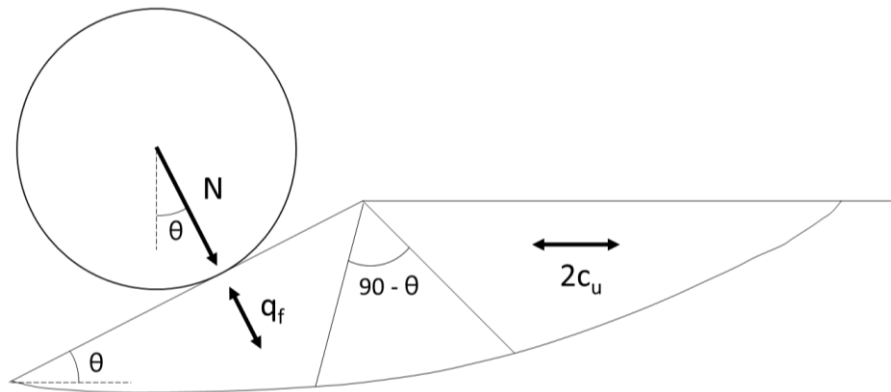


Figure 25 - Failure mechanism at the downward edge of trench for single-layered pavement derived from lower-bound analysis

From the failure mechanism, a lower bound for the bearing capacity of the subgrade, q_f , is determined using:

$$q_f = \frac{N}{A} = c_u(2 + \pi - 2\theta) \quad (1)$$

Where N is the resultant force, A is the contact area between the wheel and the surface and c_u is the undrained shear strength of the subgrade. For the tests carried out, the vertical force applied by to the tyre was held constant at 4.5kN. Therefore, N is calculated from:

$$N = \frac{4.5}{\cos \theta} \text{ kN} \quad (2)$$

Inserting equation (2) into equation (1) and then rearranging for c_u produces the following:

$$c_u = \frac{4.5}{(2 + \pi - 2\theta)A \cos \theta} \text{ kPa} \quad (3)$$

The value of A is dependent on the normal force acting at the wheel-subgrade interface. The resultant force increases with θ and therefore so does the contact area. Bowman (2018) has previously determined a relationship between the normal force and contact area for the APT (Figure 26). Using this relationship along with equation (3) allows for the minimum c_u needed to avoid shear failure to be predicted for any slope angle. Figure 27 presents the minimum c_u needed for slope angles between 0° and 85° .

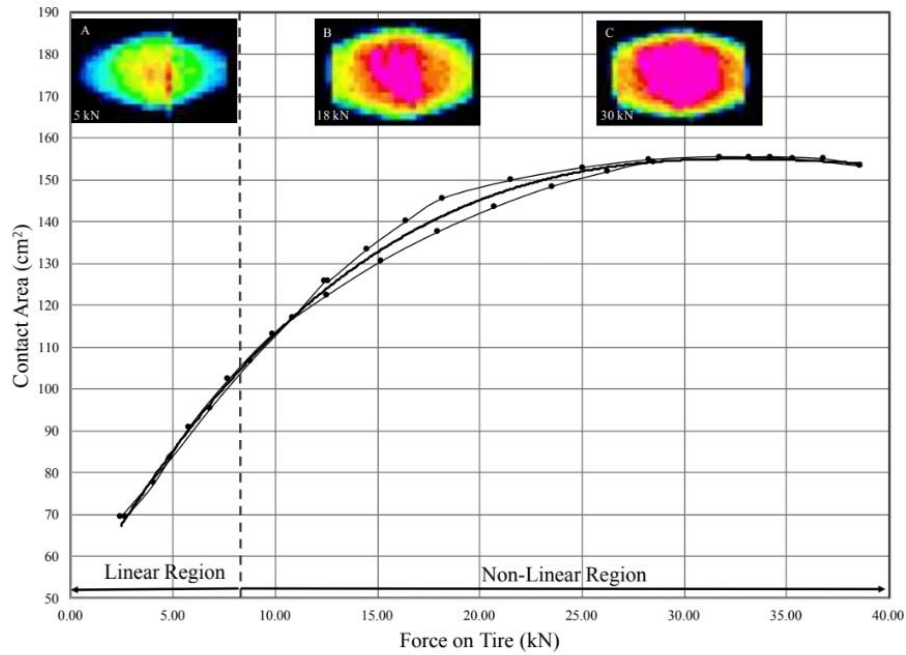


Figure 26 - Contact area of APT tyre due to load including pressure distribution at various loads (Bowman, 2018)

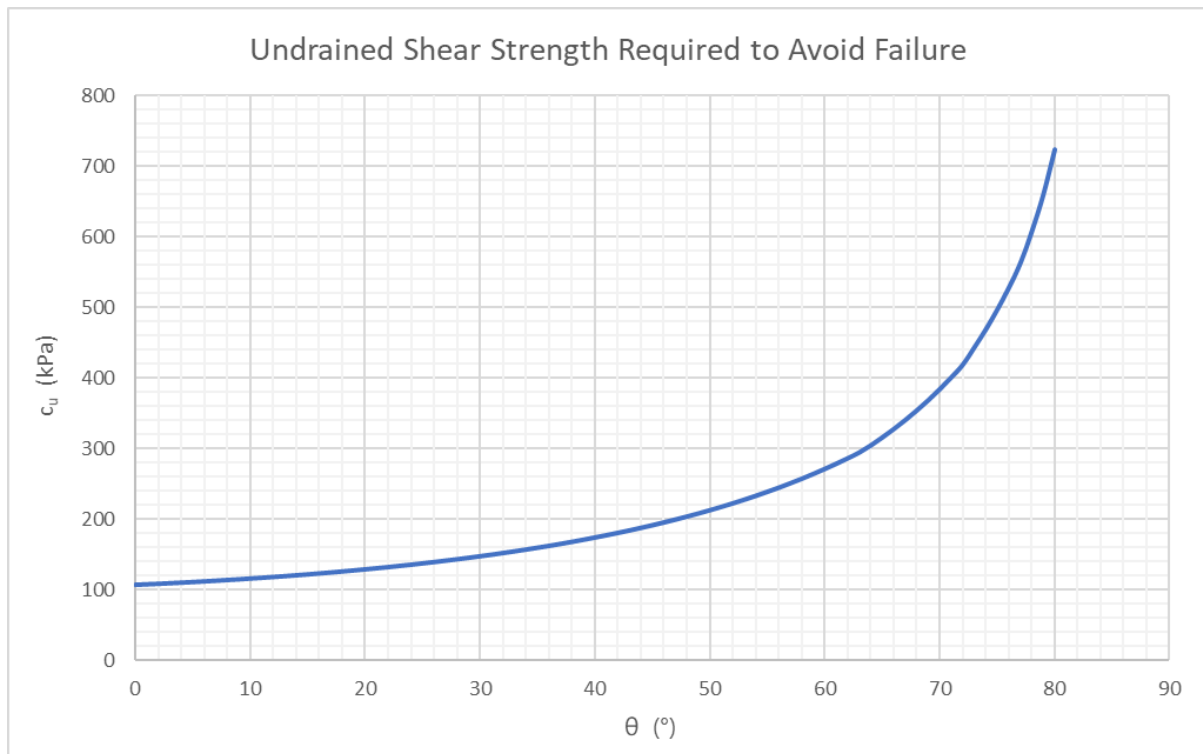


Figure 27 - Minimum undrained shear strength required to avoid failure for a given slope angle

If for the initial slope angle the subgrade's shear strength is above the curve in Figure 27, then failure of the subgrade beyond the downward edge will not occur. This leads to the creation of a dip over the trench, as seen in test 1. Subsequent wheel passes will cause further failure of the subgrade in the trench leading to the depth of the dip increasing, along with the angle of the sloped sides (Figure 28). The increase in slope angle, means that a higher shear strength is needed to avoid failure. Eventually the angle of the dip becomes great enough that the shear strength is below the curve therefore causing failure beyond the downward edge of the trench.

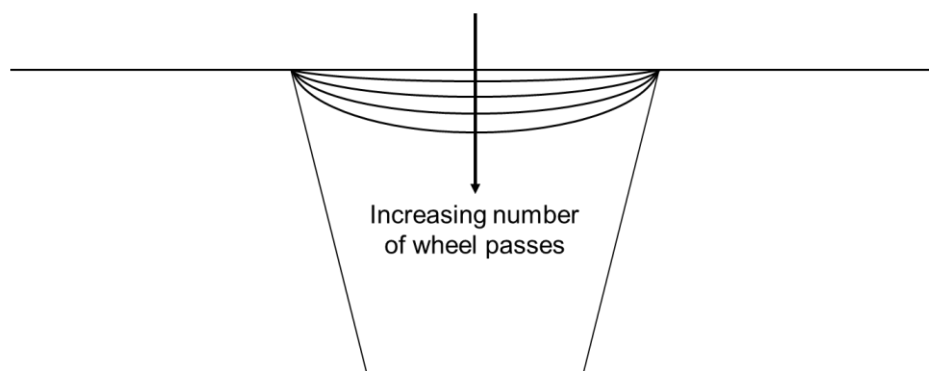


Figure 28 - Development of the dip over the trench with increasing number of wheel passes

On the other hand, if for the initial slope the shear strength is below the curve, subgrade beyond the downward edge of the trench will fail. This will lead to a downward slope forming during one-wheel cycle, as shown in tests 2 and 6. Whilst each wheel pass does cause failure of the subgrade close to the surface, the wheel also compacts the subgrade below. Therefore, for

subsequent wheel passes, the strength of the subgrade increases. After a certain number of passes the strength of the subgrade beyond the trench will have increased enough that failure will no longer occur after the downward edge. This then leads to the flattening of the slope beyond this point.

The failure mechanism identified shows that the subgrade used for test 1 must have had greater shear strength than the subgrade used in test 2 and 6. This is likely due to the extended time that was spent between construction and testing for the structure used in test 1. Information on the properties of the KW15 subgrade in test 1 are not known, yet the construction method used was the same as performed throughout this research project. It is therefore assumed that at construction the moisture content of the subgrade was close to optimum and that a high level of compaction was achieved. After construction, the pavement was left for 5 months during the English summer. Over this period, water within the voids will have evaporated leading to the menisci of water droplets located at particle contacts becoming more curved. This results in an increase in pore-suction, and therefore an increase in effective stress. Consequently, the shear strength available in the subgrade is increased.

4.2 Pavement Structures with Base Course

Tests 4 and 5 were performed to investigate the influence of base course on rutting development of a pavement structure. The pavement structure in test 5 consisted of a base course layer which was approximately two times thicker than the layer used in test 4.

4.2.1 Surface Rutting

In the early stages of both tests substantial shoving of the upper base course layer was witnessed in the longitudinal direction. Shoving occurs due to the embedment of the wheel into the upper base course, therefore showing that the compaction achieved was not great enough for the load application (see section 3.7). Whilst the base course close to the surface underwent shear deformation during the early wheel passes, the material below became more compact. Eventually, the strength of the base course reached a high enough level that shoving was prevented.

Agisoft Metashape has been used to create models of pavement surfaces at the start and end of tests 4 and 5. The models have been compared so that surface displacement can be measured. Figure 29 displays a 3D model of the pavement surface at the end of test 4. Contours indicate the vertical displacement between the initial and final surfaces, whilst red lines have been used to show the location of the trench.

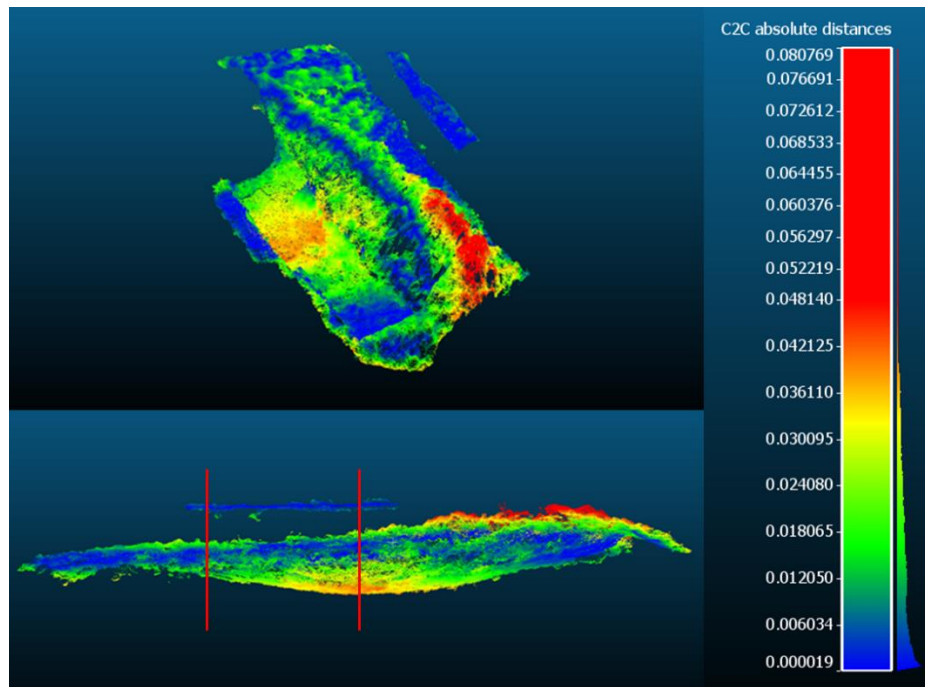


Figure 29 - 3D model of the final pavement surface of test 4 with contours used to show vertical displacement of the surface in metres

The reconstruction shows that surface rutting increases from the upward edge of the trench to a maximum displacement of around 40mm at the trench's downward edge. A decrease in deformation is then shown when moving away from the downward edge to the end of the test section. The substantial increase in surface deformation across the trench is similar to that witnessed in the tests on the single-layered pavements. Therefore, it is likely that failure of the subgrade layer has occurred.

A 3D model of the final pavement surface from test 5 is presented in Figure 30. Contours have been used to show surface displacement and red lines added to show the position of the trench.

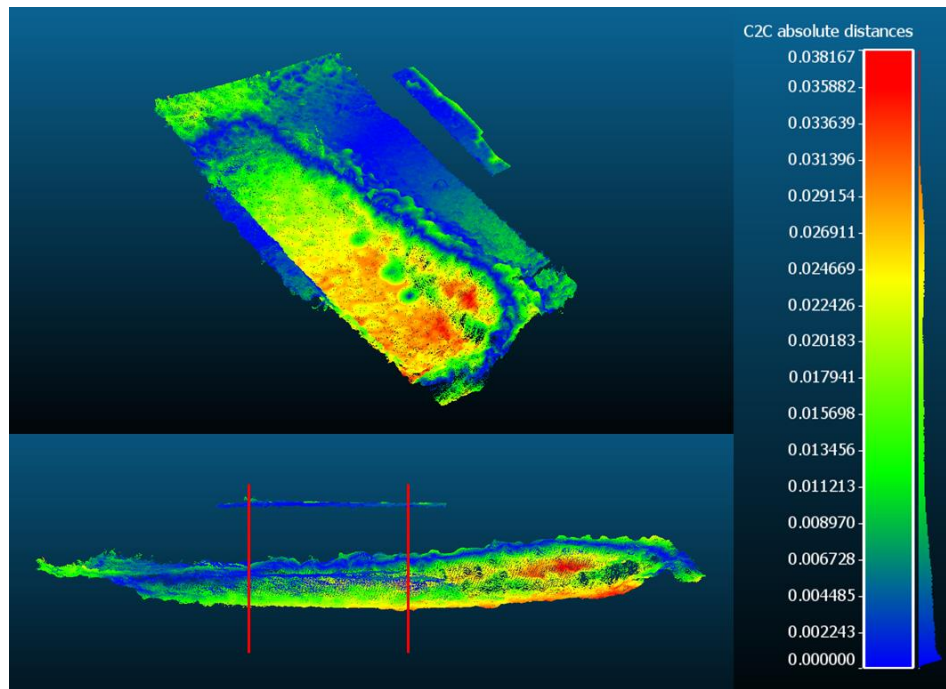


Figure 30 - 3D model of the final pavement structure of test 5 with contours used to show vertical displacement of the surface in metres

A sharp increase in deformation is shown at the position where wheel loading commences. However, thereafter deformation increases very gradually along the wheel path to the downward edge of the trench. After the trench, the surface level is shown to be relatively constant with a maximum displacement of around 38mm.

4.2.2 Subgrade Deformation

PIV has been used to determine the subgrade movement over the course of tests 4 and 5. Subgrade displacement from the start to end of test 4 is presented in Figure 31, with a grey-shaded area showing the location of the trench.

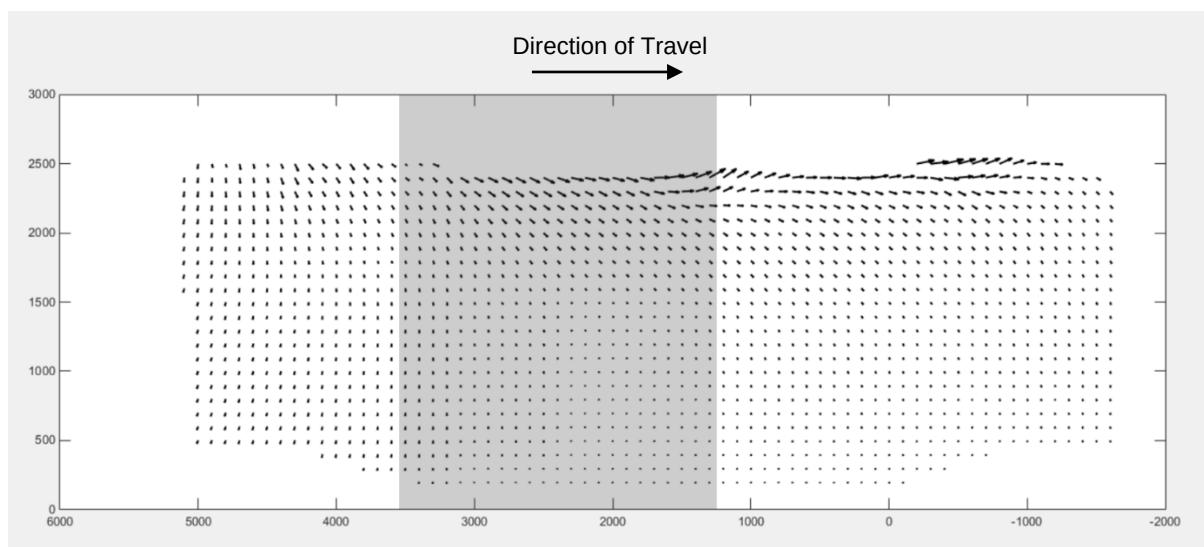


Figure 31 - Movement of subgrade below the pavement surface in test 4

Within the trench significant horizontal movement of the subgrade is shown, suggesting that the weaker subgrade within the trench is failing due to shear. A consequence of this is a reduction in the surface level within the trench, as shown in Figure 29. Vertical movement of the subgrade is seen to change from downwards to upwards when moving across the trench. The change in vertical displacement is likely due to the transitions between the original structure and the trench. The subgrade outside the trench is both stronger and stiffer and therefore has greater resistance to wheel loading. As a result, it is likely that failure of the subgrade leads to the formation of a dip, like seen in test 1. After the downward edge of the trench, further horizontal movement is witnessed within the original subgrade, indicating it also experiences shear failure. The subgrade at this section is the same as that before the trench, where minimal horizontal movement was witnessed. Consequently, a wheel load applied to a flat surface is not expected to cause shear failure of this subgrade. Failure of the subgrade beyond the trench is therefore expected to be due to loading of a sloped surface.

Figure 32 shows that during test 5 the subgrade experiences mostly downward displacement with minimal horizontal movement. This suggests the base course is able to distribute the wheel load over a large enough area in the subgrade layer to prevent shear failure of the material inside or outside the trench. As a result, rutting produced at the surface must be predominantly due to base course failure. The downward subgrade movement is likely to be due to compaction as a result of repetitive wheel loading.

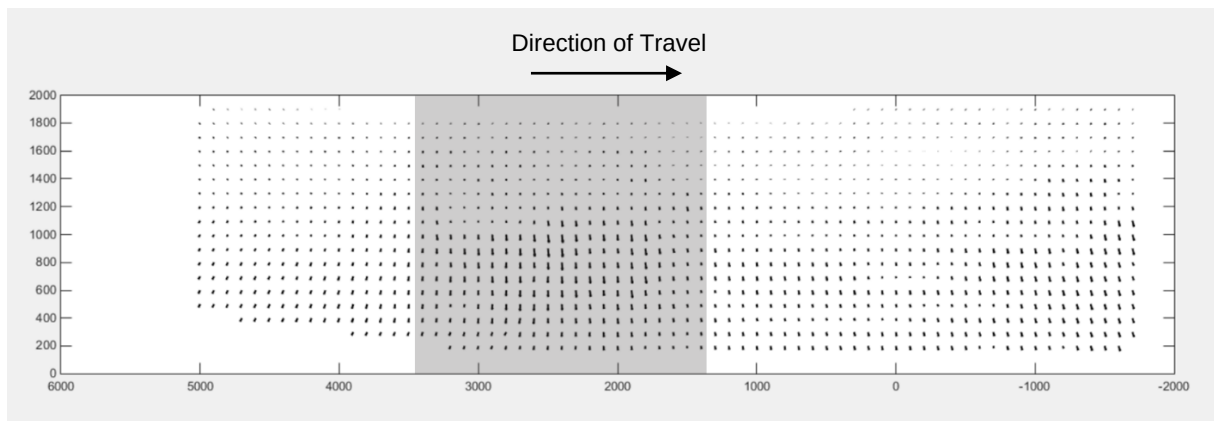


Figure 32 - Movement of subgrade below the pavement surface in test 5

4.2.3 Failure Mechanism

Shoving witnessed in both tests indicated that the shear failure of base course in the longitudinal direction was contributing to rutting development at the surface. Unlike the subgrade, the base course layers did not include any localised weaknesses. Consequently, the strength and stiffness were approximately uniform throughout the layer. The uniform properties mean that failure of the base course happens relatively evenly over the whole wheel path. Therefore, if the base course layer is thick enough to reduce the stress on the subgrade so that failure is

avoided, only base course failure will occur and rutting will be relatively constant at the surface. This was the case for the thicker base course layer used in test 5. As the movement of the base course was not tracked during testing, a mechanism attributed to base course failure cannot be determined.

In test 5, both the subgrade and base course layers are expected to have experienced shear failure and therefore contributed to the final rutting profile. Failure in the base course occurred in the form of shoving due to the low level of compaction achieved during construction. During the early stages, this resulted in a reduction in thickness of the base course layer over the whole wheel path. Though the base course close to the surface was displaced due to shear failure, the lower levels became more compact with each wheel pass. Eventually, the base course gained enough strength to prevent further shoving. Failure of the subgrade in a two-layered pavement is expected to happen in a similar fashion to that described for a single-layered pavement in section 4.1.3. Subgrade failure is first thought to occur in the weakened subgrade inside the trench. Previously, Tse (2019) determined a deformation mechanism for subgrade below a base course layer for an incremental wheel step (Figure 5(b)). The magnitude of deformation associated with the mechanism is expected to increase as the wheel moves from the edge to the centre of the trench. Therefore, the superposition of this mechanism will lead to downward displacement increasing towards the trench's centre. The mechanism for the failure of the subgrade beyond the downward edge of the trench is anticipated to be the same as for the single-layered pavement. However, the stress acting at the subgrade slope is reduced due to the assumption that the stronger base course spreads the resultant load over the weaker subgrade layer. For the same reasons has stated in section 4.1.3, the subgrade is treated as undrained and the resultant load is assumed to act perpendicular to the surface.

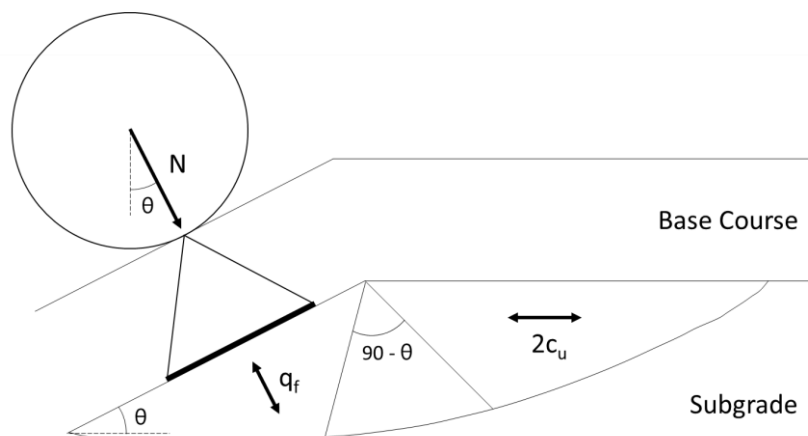


Figure 33 - Failure mechanism at downward edge of trench for two-layered pavement structure derived from lower bound analysis

The spreading of the wheel load means that a larger slope angle is required than for a single-layered pavement to reduce the bearing capacity to below the stress acting at the interface. Therefore, the two-layered pavement has greater resistance to deformation beyond the downward edge. This explains why the surface profile after the trench rises in test 4 but remains relatively constant for the single-layered pavements.

4.3 Pavement Structures with Cold Lay Macadam

The application of cold lay macadam over a subgrade layer proved to be unsuccessful. From the first wheel pass the wearing course layer was seen to fail, with large amounts of shoving in front of the tyre. After only a handful of wheel passes, the cold lay macadam had been removed from the wheel path exposing the surface of the subgrade layer below (Figure 34). The substantial failure of the wearing course was due to the low level of compaction achieved during construction (see section 3.7). A result of this was that the wearing course did not have the required stiffness and strength to prevent embedment and then shoving of the cold lay macadam. Due to the removal of the wearing course, the final deformation seen at the pavement surface was very similar to that witnessed for a single-layered pavement.



Figure 34 - Surface rutting present at the end of test 7

4.4 Failure Mechanism in the Field

4.4.1 Wheel Loading with Surface Traction

For all tests performed, the wheel was programmed to move at a constant speed. However, in the field, cars regularly need to accelerate or decelerate. To be able to change the speed of a vehicle, a moment must be applied to the wheel. In turn this causes surface traction at the interface between the wheel and the surface. The addition of a tractive force changes the angle,

α , at which the resultant wheel force acts at the surface. The change in loading inclination influences the bearing capacity of the subgrade for the failure mechanisms identified in the previous sections. Analysing the failure mechanism for the subgrade beyond the downward edge of the trench in a single-layered pavement (Figure 25) shows that the bearing capacity is reduced when the wheel is decelerating. This is because surface traction leads to the resultant load being applied more horizontally (Figure 35). Consequently, the rotation of the slip plane in the mechanism is smaller, and therefore bearing capacity is reduced.

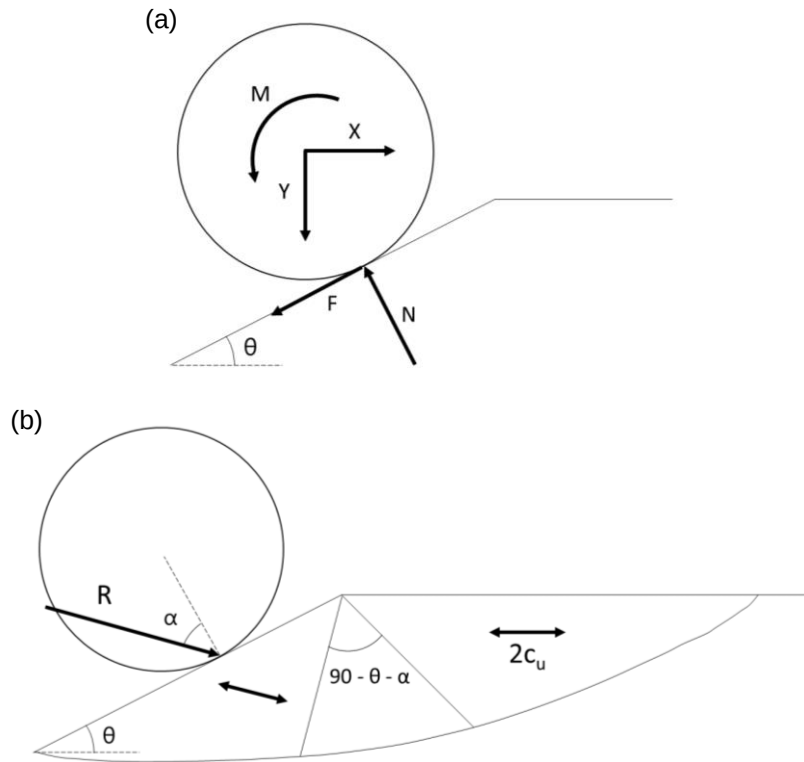


Figure 35 - Failure mechanism at downward edge of trench in a single-layered pavement for a decelerating wheel load

For the analysis of the mechanism at the downward edge it has been assumed that the subgrade is undrained (see section 4.1.3), whilst it has also been assumed that deceleration of the wheel acts parallel to the pavement surface. As slope angles stay relatively small this has a minimal impact on the bearing capacity. Using these assumptions, a lower bound for the bearing capacity is calculated using:

$$q_f = \frac{R \cos \alpha}{A} = \frac{N}{A} = c_u [1 + \pi - 2(\theta + \alpha) + \cos(2\alpha)] \quad (4)$$

N is assumed to be unchanged from when the wheel was moving at constant speed and so can be expressed using equation (2). Inserting equation (2) into equation (4) and then rearranging for c_u gives:

$$c_u = \frac{4.5}{[1 + \pi - 2(\theta + \alpha) + \cos(2\alpha)]A \cos \theta} \text{ kPa} \quad (5)$$

Using the relationship between N and A shown in Figure 26, the minimum required c_u to avoid failure can be determined for any θ and α . Figure 36 expands on Figure 27 to show how α influences the required shear strength for any given slope angle.

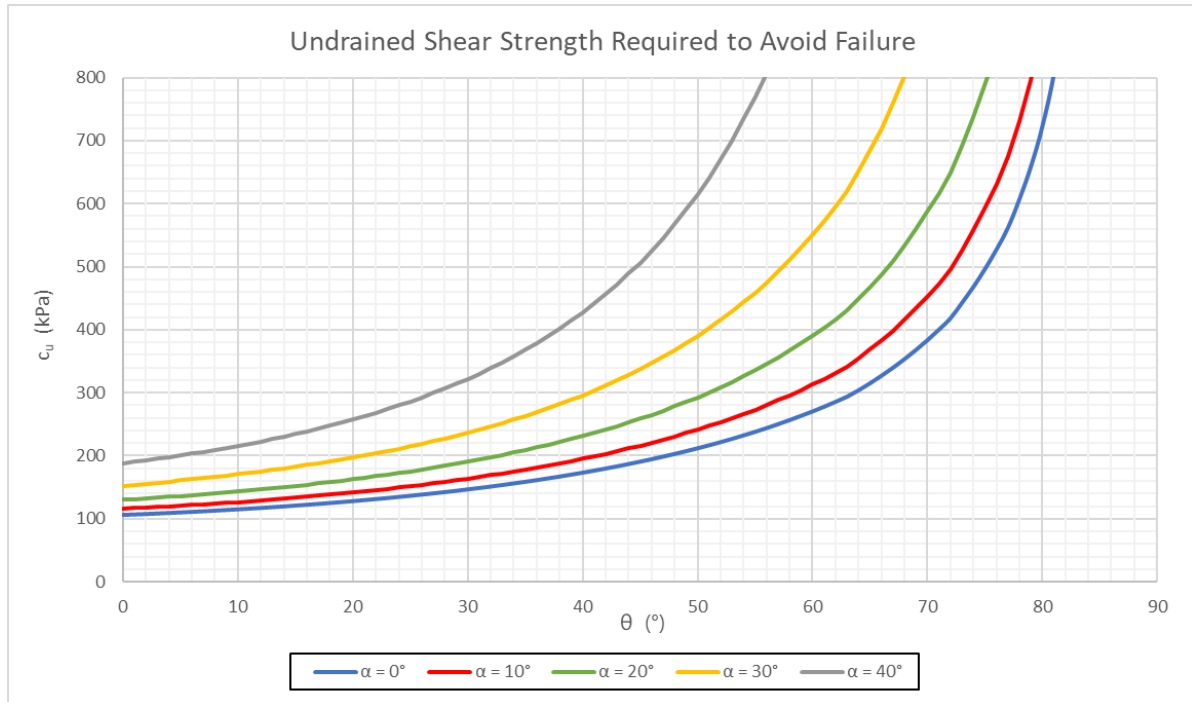


Figure 36 - Minimum undrained shear strength required to avoid failure for varying slope angles and load inclinations

For larger values of α , higher shear strength is required in the subgrade to avoid failure. α is dependent on the amount of surface traction, with a larger tractive force leading to a greater value of α . Therefore, deceleration of the wheel at the downward edge of the trench increases the chances of the subgrade failing. The effects of deceleration on failure of subgrade in a single-layered pavement are expected to be similar for thin multi-layered flexible pavements.

Whilst the mechanism above provides an understanding as to the effect's deceleration can have on pavement failure, it does have quite a few limitations. The mechanism assumes that deceleration occurs parallel to the surface, however in the field deceleration is applied horizontally to a vehicle. In addition, the analysis only focuses on a single wheel and does not consider how vehicle dynamics, such as suspension, influence wheel loading at the surface. In the field, vehicles move at a much faster pace than in the experiment which can result in impact forces at the slope of a dip. This is another area which is not considered in the mechanism presented.

4.4.2 Examples of Failure Mechanism in the Field

Pavement failures around the small town of Highworth, Swindon were examined to compare results in the field to the experimental results obtained using the APT. Figure 37 shows examples of pavement failures located over trench reinstatements. The reinstatements have been ordered in terms of interpreted age, with the oldest, most damaged first. Arrows have been added to each image to show the direction of traffic.

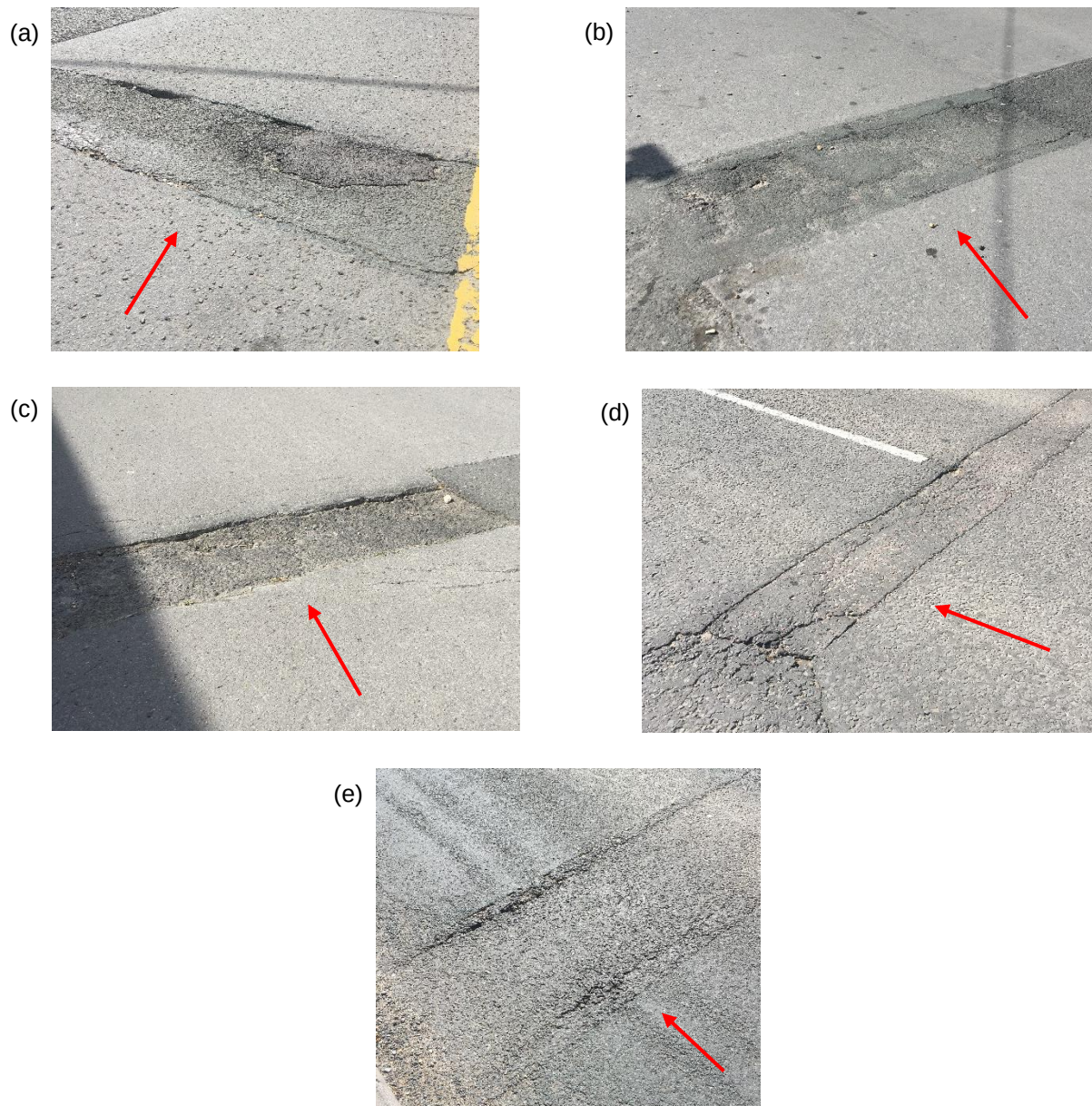


Figure 37 - Examples of pavement failure over trench reinstatements in Highworth, Swindon

The Figure shows each trench to be at a different stage of the same failure mechanism. Rutting, localized over the location of the trench, is first seen to occur, indicating that the backfill materials used has a lower strength and stiffness than the surrounding structure. As a result of the settlement in the trenches, a step is formed at both of the trench's edges. The step in the

surface at the trench's downward edge will experience an impact force when a vehicle moves across the trench. The older trenches displayed in Figure 37 show failure in the form of cracking of the wearing course at the downward edge. It is likely that the impact forces acting at the step at this edge cause accelerated cracking of the top pavement layer. In Figure 37(a) cracking of the trench wearing course looks to have been reinstated. However, this has not prevented failure from occurring, with cracks continuing to form at downward edge of the trench reinstatement.

The mechanisms discussed in the previous sections are not clearly identifiable in the examples evaluated in the field. This is likely due to the thickness of the pavements investigated being large enough to prevent failure of the underlying subgrade layer. For this reason, the mechanisms proposed are more likely to be discovered on not as well constructed dirt roads, where subgrade failure is common.

5. Conclusions

Testing of single- and two-layered pavements using the Cambridge APT has allowed the visualisation of the development of subsurface deformations across a trench reinstatement. Previous research has been performed to identify deformation mechanisms beneath a moving wheel load on uniform soils. This project extends this existing knowledge to cover deformations beneath a moving wheel load over a poorly constructed trench reinstatement. The results have suggested deformation mechanisms which could be used to explain the progression of rutting over the weaker trench and beyond its downward edge. In reality the subsurface mechanisms at work are complex, but by using 3D surface modeling, subsurface PIV data and field results, the following conclusions can be drawn:

- For a single-layered pavement, the presence of a poorly compacted trench resulted in increased rutting over the trench's location. The introduction of a base course layer helps spread the wheel load over a greater area of the subgrade, resulting in a lower increase in rutting over the trench.
- Base course layer thickness alters deformation behaviour. For the structure with a thin base course layer, failure of the weakened subgrade within the trench resulted in increased rutting over the trench's location. For a thicker base course layer, failure was restricted to the uniform base course and as a result a relatively even rut formed over the whole wheel path.
- Deformation of the subgrade beyond the downward edge of a trench is thought to resemble the mechanism for a vertically loaded footing on sloping ground. If the

bearing capacity for the mechanism is greater than the load acting on the slope, then increased rutting will only be witnessed over the area of the trench. However, if the bearing capacity is lower than the load applied to the slope, then increased rutting will continue into the surrounding subgrade.

- Resistance to deformation beyond the downward edge of a trench is greater for a two-layered pavement than a single-layered pavement due to the spreading of the wheel load through the base course layer. Consequently, the increased rutting caused by trench failure will not propagate as far beyond the trench's downward edge for a two-layered pavement.
- Trench reinstatements observed in the field show similar aspects of the damage patterns observed for the single- and two-layered pavements tested, with settlement in the trench causing traffic to have to climb up onto the existing road surface, leading to concentrated damage at the trench's downward edge.

6. Future Work

The research carried out in this project has focused on the development of rutting over many wheel cycles. However, to gain greater understanding of the deformation mechanisms present, soil movement for incremental wheel steps across the trench should be analysed. The Cambridge APT can be used to achieve this by reducing the wheel speed and intervals between images captured. Particular attention should be made to soil movement for an incremental wheel step at the downward edge of the trench to evaluate the accuracy of the lower bound mechanisms presented within this research. To be able to compare actual and predicted rutting measurements, the subgrade's undrained shear strength will need to be measured.

The friction between the wheel and the axle of the Cambridge APT could be increased to simulate braking. Performing tests with increased axle friction would present a first step to clarifying whether deceleration does accelerate failure of the subgrade beyond the trench. 3D surface models and PIV data from tests with varying axle friction could be compared to show the impact deceleration has on the development of surface rutting.

The experimental methods used in this study are not necessarily the best methods available to evaluate the impact of trench reinstatements on pavement failure. The Cambridge APT applies loads to the pavement surface via a single wheel moving at a slow constant speed. In the field, wheel loading of the surface is much more complex, due to dynamic wheel forces generated by vehicles, and much greater speeds leading to impact forces at surface slopes. A better

approach for assessing trench failure would be to perform tests at field-scale using real-life traffic loading. An issue with this method is that it is not possible to continually monitor subsurface soil movement over the course of testing. This therefore makes it more difficult to identify deformation mechanisms within the layers. To help identify subsurface deformation, strain gauges could be placed within each pavement layer. In addition, the change in layer heights from the start to end of testing can be used to determine soil movement. The original layer heights are known from construction. However, to obtain the final layer heights, a trench would need to be cut adjacent to the wheel path.

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8. Appendix

Risk Assessment

The risk assessment carried before the start of the project was found to be suitable. A compulsory health and safety briefing was conducted at the Schofield Centre prior to being allowed to use the facilities to establish the risks present. The following measures should be added to the risk assessment, should a similar experiment be performed. Moving of the APT in between testing is to be performed by technicians using appropriate lifting equipment, such as forklift. The pit should be kept covered up using wooden beams whilst not in use, whilst the barrier around the experimental setup needs to be closed whilst the test is running. When moving and compacting base course, significant amounts of dust are created, and so face masks should be worn and a dust extractor turned on within the area. Lifting of the plate compactor and digging of the soil should be performed using the correct manual handling procedures.

Covid-19 Disruption

A final test on a single-layered pavement was to be run in the week commencing 13th April. The structure was constructed at the end of lent term, with the hope that the month and a half between construction and testing would result in evaporation of some of the water in the subgrade, therefore producing a stronger material. The results of this test would have then been compared with test 1, 2 and 6 to clarify whether the baking of the subgrade did in fact alter the progression of rutting in and around the trench. The test would have also been run at a slower speed with shorter intervals between images captured to allow subsurface deformation for an incremental wheel step to be monitored at the downward edge. This would have likely provided more conclusive evidence on the accuracy of the lower bound failure mechanism proposed in this research project. Even though the final test was not performed, the previous seven tests provided enough detail to discuss the influence of trench reinstatements on the progression of rutting at a pavement surface.