Effects of water on chipseal and basecourse on high-volume roads

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D Alabaster, NZ Transport Agency, Wellington
J Patrick, Opus International Consultants, Wellington
J Hussain, Auckland University, Auckland
T Henning, Auckland University, Auckland

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NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

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The NZ Transport Agency initiated this research in 2008.

Keywords: accelerated pavement testing, CAPTIF, chipseal, unbound pavements, water.

An important note for the reader

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Abbreviations and acronyms

CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
ESA	equivalent standard axles
FE	finite element
FWD	falling weight deflectometer
MDD	maximum dry density
MESA	millions of equivalent standard axles
OMC	optimum moisture condition
OWC	optimum water contents
pph	parts per hundred
PTR	pneumatic tyre roller
RLT	repeated load triaxial
SWCC	soil-water characteristic curves
TDR	time domain reflectometry (method)
XRD	x-ray diffraction

Contents

Executive summary

The purpose of this research was to ensure that chipsealed unbound pavements remain sufficiently waterproof for use on today's and tomorrow's road networks. These are environments of high traffic volumes and high tyre pressures where pavement designers increasingly have to use marginal materials and/or recycled materials.

The hypothesis for this research at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) was that the risk of premature pavement failure would be a function of the amount of water entering the pavement and the reaction of the pavement materials to that water.

The amount of water entering the pavement through the sealed surface would be determined by:

- the waterfilm thickness around and above the surfacing aggregate particles
- the permeability of the seal and the basecourse
- the frequency and intensity of heavy loading.

The permeability of chipseals is a function of the chipseal design, eg single-coat first-coat vs two-coat first-coat. Rainfall intensity, drainage path length and degree of rutting control the waterfilm thickness. The frequency of heavy loading is determined by the volume of heavy commercial traffic.

How a pavement reacts to the amount water present is a function of the moisture sensitivity of the basecourse. The moisture sensitivity is considered to be related to the quantity and quality of the finer fractions of the basecourse.

The basic laboratory tests and repeated load triaxial (RLT) tests suggested that the three different basecourse materials used at CAPTIF had significantly different behaviour under saturated conditions. Geological testing suggested the aggregates used were for all practical purposes identical. The permeability tests suggested there was a significant range of permeabilities in the samples prepared in the laboratory – the permeability did not correlate with the RLT results. The field permeability tests suggested that (at low heads) after surface preparation for sealing, the permeabilities were nearly identical.

Before deriving a direct use of the outcomes, the research had to take into account that the CAPTIF testing is carried out at an extremely high frequency, with the vehicles travelling at 11m/s and a load applied roughly every three seconds. To reduce the intensity of loading, the vehicles were loaded as lightly as possible at 0.3 equivalent standard axles (ESA)/vehicle. The NZ Transport Agency design guidance suggests the 'average' truck has 2.4 heavy axle groups loaded to 0.6 ESA per heavy axle group. To achieve a load pulse on average every three seconds would require a truck fleet 3*2.4=7.2 seconds apart. This equates to eight trucks a minute, which in turn would be 500 an hour and thus 12,000 a day. Assuming the percentage of trucks was 10% that would be an annual average daily traffic of 120,000 in one direction. Allowing for the lighter load and slower speeds at CAPTIF could be considered a way of compensating for the high frequency – but with the results to hand that would seem a little dubious. A better approach might have been to apply small groups of non-reduced loads with rest periods in between.

The testing at CAPTIF showed it was relatively easy for pavements with high water film thicknesses and rapid loading to fail. Previous tests at CAPTIF in the mass limits projects had shown that chipseals could be trafficked to over 100,000 cycles before a bleeding failure occurred (bitumen would pick up on the tyres as the texture lowered) if the surface water film thickness was kept low. During the first test, the first 1,000 load cycles were applied with only enough water on the surface to prevent bitumen picking up on the tyres. This was done by spraying a light application of water on the tyres. As soon at the film thickness was increased by using the manifold system and a 9mm restrictor nozzle, the first failure in the unprimed two-coat chipseal occurred after 132 'wet' load cycles in the M/4 basecourse. This was attributed to the poor first coat of the unprimed two-coat seal. The second failure occurred after 347 'wet' laps in the fines added basecourse (with the densest grading) and the dense grade AP20 failed at 921 wet laps. The primed two-coat sections failed once the nozzles were changed to 12mm to increase the film thickness. The M/4 failed first at 1,190 wet laps followed by the fines-added section at 2,447 wet laps and finally the AP20 failed when the nozzle was increased to 18mm and a total of 3,863 wet laps were applied.

In the second test, surfaced by an unprimed two-coat and an unprimed racked-in seal, the first failure occurred in the racked-in surfaced M/4 after 300 wet laps under a 16mm nozzle at 27km/h. The loads were applied 100 laps at a time. One cycle of 100 laps each under 0, 8 and 16mm nozzles was applied at 20km/h. Only minor problems were observed with the sealing of this surface. The next failure occurred at 400 wet laps in the racked-in fines-added basecourse section under the 16mm nozzle at 40km/h. After this the loading intervals were increased to 500 laps. The two-coat M/4 failed at 1,192 wet laps in a 500 lap cycle of 8mm nozzle watering. The remaining section of racked-in fines-added basecourse and both AP20 sections failed at 3,386 wet laps during a 1,000 lap loading interval using a 16mm nozzle. However, the two-coat seal in section C appeared to have been damaged when the vehicle was parked on it. A repeat of that test required an additional 6,000 wet laps to fail the pavement. Review of all the tests showed that the second failure on each section generally took much longer than the first, perhaps suggesting some conditioning occurred under traffic.

The hypothesis that how a pavement reacts to the amount of water present is a function of the moisture sensitivity appeared to be disproved – the conventional testing of grading, fines quality, permeability and RLT laboratory testing all suggested that the M/4 should have performed the best. Yet in all cases it was the worst performer. The RLT testing suggested that the fines-added basecourse would be the worst performer, yet it was consistently the middle performer. And finally, the only test that ranked the materials was the laboratory permeability; however, it was in the reverse order to what had been expected. The lowest permeability performed the best.

The behaviour of the two-coat seal in the second experiment suggested that priming only allowed a better seal to be created; it did not add to the waterproofness of a well-laid seal. The racked-in seal appeared to be less waterproof than the two-coat seal, but pin-holes had formed in the racked-in seal which may have contributed to its performance. It certainly did not provide a better performance as had been thought likely.

The project aimed to create a number of outputs. These are listed below together with the project findings against each of them:

- An understanding of the effects of changing the permeability of the surface, waterfilm thickness, basecourse moisture sensitivity and heavy traffic volumes on pavement performance. This has certainly been advanced – surface permeability appears to be a function of construction quality and basecourse permeability. Waterfilm thickness is crucial but moisture sensitivity would appear (as defined by the RLT test) to be less of an issue. High heavy-traffic volumes running on a sufficient water film thickness will drive failure.
- A determination of when surfacing permeability becomes an issue. CAPTIF results suggest that a poorly constructed seal can fail very rapidly, or at least between 1/4 and 1/10 of the load cycles a well-sealed pavement will fail at. Defining when exactly surfacing permeability will become an issue is clouded by the loading frequency of the tests and what appears to be some sort of conditioning effect prior to wet loading.

- A validated method for assessing the moisture sensitivity of basecourse. Surprisingly, first-coat seal failure appeared to be a function of basecourse permeability, which went against the traditional concept of lower permeability being better at guarding against a first-coat seal failure.
- A validated hydraulic model for chipseals, which would also lead to better environmental contaminant transport modelling. It would appear that complex unsaturated modelling is the only way to provide sensible hydraulic models for pavements.
- Improved pavement deterioration models to cater for surfacing and moisture variations. Applying a prime coat would reduce the probability of failure. But assuming the surface survives the defects liability period, the surfacing and moisture variations in the pavement are not likely to change noticeably.
- A validated finite element pavement design model based on RLT testing capable of considering moisture conditions; however, the rapid changes in behaviour appeared to be driven by permeability.

The research produced some surprising results in that the traditional M/4 basecourse was the worst performer in all cases. However, it must be borne in mind that this research applied only to first-coat seals, with high water film thicknesses at very high traffic volume.

Moving away from the traditional M/4 envelope for basecourse production to denser gradations used in Australia has considerable construction benefits in that these are easier to lay. But denser gradations are harder to dry back before sealing and this trade-off needs to be considered before implementing wide use of denser gradations. The additional long-term benefits of denser gradations are that they should also be more rut resistant but that comes with the price that they may also draw more water in from the edges of the pavement in the long term. Suffice to say if this path is followed, a number of field trials will be required to validate the long-term implications of this project.

The recommendations resulting from the research are to:

- prime all new pavements before first-coat sealing to reduce the risk of early failure
- condition new seals before they are loaded in wet conditions, ie avoid the practice of sealing just before it rains as this is likely to increase the probability of failure
- avoid geometric designs that generate large water film thicknesses
- not delay in placing second-coat seals on high-volume roads
- use unsaturated hydraulic models for modelling moisture movement in pavements
- review first-coat seal failures for the factors observed in this report
- undertake field trials of lower permeability M/4 alternatives.

Abstract

The objectives of this study were to investigate the relationship between permeability of chipseals, waterfilm thickness, basecourse moisture sensitivity, heavy traffic volumes, and premature pavement failure following construction through the use of accelerated pavement testing at CAPTIF.

The research has produced some surprising results in that the traditional M/4 basecourse was the worst performer in all cases. However, it must be borne in mind that this research can only be considered applicable to first coat seals, with high water film thicknesses at very high traffic volume.

The recommendations resulting from the research are to:

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- use unsaturated hydraulic models for modelling moisture movement in pavements
- review first-coat seal failures for the factors observed in this report
- undertake field trials of lower permeability M/4 alternatives.

1 Introduction

1.1 Origin of the research

The purpose of this research was to ensure that chipsealed unbound pavements remained sufficiently waterproof for use on today's and tomorrow's road networks. These are environments of high traffic volumes and high tyre pressures where pavement designers increasingly have to use marginal and/or recycled materials.

Three distinct areas for this research included investigating:

- the permeability characteristics of the most commonly used surface type in New Zealand, compared with alternative sealing practices
- the performance of selected materials in relation to changing moisture contents
- the hydraulic modelling issues related to run-off and infiltration water, which would be an additional benefit in improving environmental contaminant modelling.

Recent failures on major roads have concerned the NZ Transport Agency (the Transport Agency) and the roading industry that current techniques for chipsealing are not controlling water ingress enough to prevent early failures on high-volume roads with unbound granular pavements. Recent examples are McKay's Crossing (Wellington) on State Highway (SH) 1 where a relatively good quality basecourse was used, and rehabilitation failures around Taupo (also on SH1) where traffic volumes are lower but the marginal basecourse material was moisture sensitive. Some difficulties experienced in the construction of passing lane pavements may also be attributable in part to chipseals being more permeable than expected.

1.2 Seriousness of the problem

A number of factors combined to give seriousness and urgency to this research, such as the diminishing availability of quality aggregates and a drive to use non-traditional marginal and recycled materials. These trends have been moving the industry away from using known materials. Other recent research has only calibrated non-traditional material testing under dry conditions. Consequently we could only use anecdotal evidence to look at issues of moisture sensitivity, with no clear understanding of where moisture-sensitive materials could or could not be used or, for that matter, what moisture conditions should be used for assessing moisture sensitivity. Traffic volumes are increasing, leading to more frequent high traffic loadings. Truck tyre pressures are higher, possibly leading to greater water pressure in wet conditions. Pavements are frequently wider, leading to longer drainage paths and higher waterfilm thicknesses. Recent failures suggest we may be driving our traditional materials too hard. As well, the move to use alternative materials that may be more moisture sensitive requires that we understand the road pavement moisture environment fully.

As an outcome of the research, clear guidelines have been developed for the industry regarding best practice for surfacing construction and maintenance planning. For example, the guidelines will specify how to determine to what degree certain materials are moisture sensitive, and how to better utilise them without compromising the performance of the pavement.

New Zealand is running out of premium aggregates in a number of locations, and Auckland in particular is a source of concern. There is also a strong desire for the roading industry to be more sustainable and use marginal roading materials that would otherwise be wasted, or to recycle materials, rather than import fresh material.

Using alternative materials or alternative construction practices means we must fully understand the effects of chipseal permeability on pavements. The aim of this project was to play an important part in allowing industry to successfully use marginal and recycled materials, which would in turn demonstrate to the public that the roading industry is truly interested in sustainable construction.

1.2.1 Links to previous and international research

This research built on an interesting range of research already conducted in New Zealand. Hanson first documented the permeability of chipseals in 1956. Research by Patrick (2009) in the research report 'The waterproofness of first coat chipseals' showed that although seals are permeable in some situations this did not necessarily lead to premature pavement failure. This is supported by earlier research by Dodds et al (1998), which suggested some completely saturated unbound materials could perform relatively well, and by Ball et al (1999), which showed that water could flow through a seal at a pressure as low as 100 kPa. Previous testing at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) as part of the Foundation for Research, Science and Technology's high performance roading project showed that moisture entering from the side of a pavement dramatically increased rutting, while the Transfund NZ mass limits projects showed that lightly watered chipseals could be trafficked almost continuously without failure. These projects all suggest that permeability, waterfilm thickness and moisture sensitivity are critical issues.

Moisture movement within pavements has been the subject of much recent research internationally. The focus of international research has typically been on the transport of road contaminants rather than on structural performance. The Apul et al (2002) report *A review of water movement in the highway environment: implications for recycled materials use* provides a very good summary of recent research and modelling capability. The European Co-operation in Science and Technology Programme action COST 351 *Water movement in road pavements and embankments*, is about to publish an entire book on the subject. However, draft material supplied by its Chairman Andrew Dawson indicates that, while they have considered the structural performance of pavements, they have not considered the performance of chipsealed pavements to this degree of accuracy. The COST 351 Chairman described this work as essential.

Previous research clearly identified the issues, but did not identify the combinations of conditions that brought about failure. Practically, to do this would require two accelerated pavement tests testing a range of factors that combined to cause failure. These tests would provide the opportunity to look at advanced prediction and mitigation strategies. For example, this research project planned to assess the value of using prime coats in surfacings as a simple mitigation strategy.

1.3 Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF)

CAPTIF is located in Christchurch, New Zealand. It consists of a circular track, 58m long (on the centreline) contained within a 1.5m deep x 4m wide concrete tank so that the moisture content of the pavement materials can be controlled and the boundary conditions are known. A centre platform carries the machinery and electronics needed to drive the system. Mounted on this platform is a sliding frame that can move horizontally by 1m. This radial movement enables the wheel paths to be varied laterally and can be used to have the two 'vehicles' operating in independent wheel paths. An elevation view is shown in figure 1.1.

At the ends of this frame, two radial arms connect to the vehicle units shown in figure 1.2. These arms are hinged in the vertical plane so that the vehicles can be removed from the track during pavement construction, profile measurement etc, and in the horizontal plane allow for vehicle bounce.

Figure 1.1 Elevation view of CAPTIF

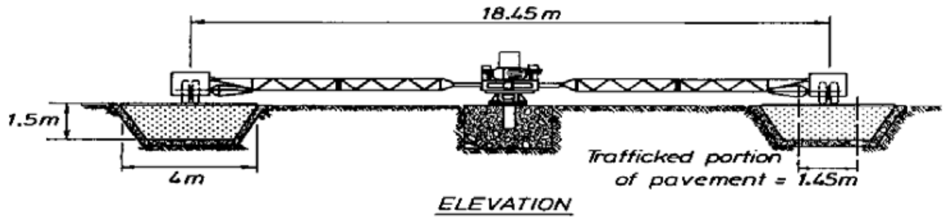
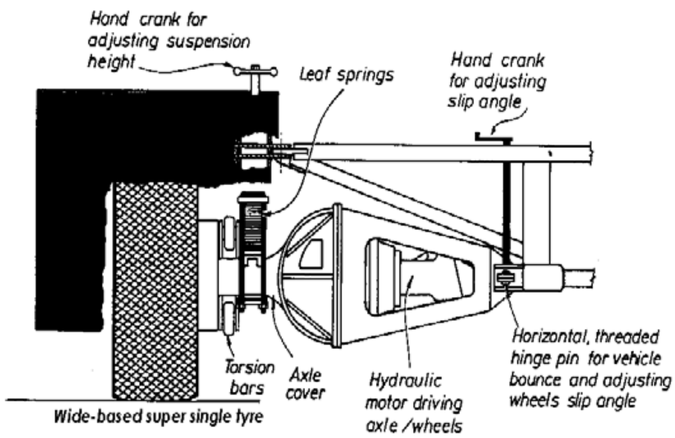


Figure 1.2 The CAPTIF vehicle unit



CAPTIF is unique among accelerated pavement test facilities in that it was specifically designed to generate realistic dynamic wheel forces. A more detailed description of CAPTIF is provided by Pidwerbesky (1995).

1.4 Description of the methodology

1.4.1 Hypothesis for the research

The hypothesis for the research was that the risk of premature pavement failure is a function of the amount of water entering the pavement and the reaction of the pavement materials to that water.

The amount of water entering the pavement through the sealed surface is determined by:

- the waterfilm thickness around and above the surfacing aggregate particles
- the permeability of the seal and the basecourse
- the frequency and intensity of heavy loading.

The permeability of chipseals is a function of the chipseal design, eg single-coat first coat vs two-coat first coat. Rainfall intensity, drainage path length and degree of rutting control the waterfilm thickness. The frequency of heavy loading is determined by heavy commercial traffic volume.

How a pavement reacts to the amount of water present is a function of the moisture sensitivity of the basecourse. The moisture sensitivity is considered to be related to the quantity and quality of the finer fractions of the basecourse.

1.4.2 Objectives of the research

The objectives were to investigate the relationship between the permeability of chipseals, waterfilm thickness, basecourse moisture sensitivity, heavy traffic volumes, and premature pavement failure following construction. A review of the local and international literature and discussion with the Chairman of the European COST 351 project showed that this research had not been considered elsewhere and needed further investigation. The methodology proposed for the study was to conduct two accelerated pavement tests to study these parameters.

The two tests were as follows:

Test 1 tested a two-coat first-coat grade 3 and 5 chipseal over a range of basecourses, and also tested a pavement constructed using a prime coat applied to the aggregate;'

Test 2 tested an improved surfacing or a moisture-removal technology under the same conditions used for test 1.

1.4.3 Technology for the tests

Surface permeability was estimated from existing laboratory data and an initial hydraulic model was developed. Testing during loading was used to confirm the assumed permeabilities. Initial moisture sensitivity was estimated from the repeated load triaxial (RLT) test using the draft TNZ T/15 specification (in press) and that data was also used to develop the pavement design using the University of Birmingham's ROSTRA finite element package. This is the next generation to their DEVPAV package that has been used with great success locally in New Zealand in developing the T/15 specification.

Test 1: Traditional surfacing technology

In test 1, a traditional two-coat first-coat grade 3 and 5 chipseal was tested over three basecourses and then tested using a prime applied to the same aggregate.

The first loading plan started with 1,000 passes of each waterfilm thickness, which were then raised to 10,000 passes and finally 100,000 passes. Moisture conditions for test 1 are shown in table 1.1.

Table 1.1 Moisture conditions for CAPTIF testing

Film thickness	Grade 3 and 5 – not primed			Grade 3 and 5 – primed		
	BC1	BC2	BC3	BC1	BC2	BC3
Dry	✓	✓	✓	✓	✓	✓
Low film	✓	✓	✓	✓	✓	✓
Medium	✓	✓	✓	✓	✓	✓
High film	✓	✓	✓	✓	✓	✓

Where

BC1 = moisture-sensitive basecourse

BC2 = average basecourse

BC3 = Non-sensitive basecourse

Test 2: Improved surfacing technology

In the second accelerated pavement test an improved surfacing or moisture-removal technology was applied and the tests used in test 1 were repeated.

1.4.4 Project outputs

The accelerated pavement tests were used to calibrate the initial finite element analysis and hydraulic models. The pavements were:

- monitored for moisture content changes by the installation of time domain reflectometry (TDR) gauges
- measured for the effects on elastic performance by the installation of Emu strain gauges to determine the effect on resilient strains.

Their overall performance was measured by rutting and surface failure.

The outputs from the project were to include:

- an understanding of the effects of changing the permeability of the surface, waterfilm thickness, basecourse moisture sensitivity and heavy traffic volumes on pavement performance
- a determination of when surfacing permeability became an issue
- a validated method for assessing the moisture sensitivity of basecourse
- a validated hydraulic model for chipseals that would also lead to better environmental contaminate transport modelling
- improved pavement deterioration models to cater for surfacing and moisture variations
- a validated finite element pavement design model based on RLT testing capable of considering moisture conditions.

2 CAPTIF experiment 1

2.1 Experiment 1 objectives

Test 1 tested a two-coat first-coat grade 3 and 5 chipseal over a range of basecourses and also tested a pavement constructed with a prime coat applied to the aggregate. Table 2.1 lists the design parameters for the experiment, which predominately looked at the change in behaviour of a grade 3 and 5 two-coat first-coat surface placed on three different basecourse materials that were either primed or unprimed. The theory field provides the conventional view of how the pavements would perform.

Table 2.1 Design parameters

Section	Theory	Primed	Surfacing	Basecourse
A	Unprimed least sensitive (UP-L)	Unprimed	3 and 5 two coat	M/4 AP40
B	Primed least sensitive (P-L)	Primed	3 and 5 two coat	M/4 AP40
C	Primed medium sensitive (P-M)	Primed	3 and 5 two coat	Dense graded AP20
D	Primed most sensitive (P-H)	Primed	3 and 5 two coat	Fines added AP40
E	Unprimed most sensitive (UP-H)	Unprimed	3 and 5 two coat	Fines added AP40
F	Unprimed medium sensitive (UP-M)	Unprimed	3 and 5 two coat	Dense graded AP20

Figures 2.1 and 2.2 provide a plan view and a cross section of the constructed experiment. The plan view shows the locations of the TDR sensors and the surface and subsoil sumps. It also provides the locations of the test sections and wheel paths. The cross section shows the depths of the pavement and subsoil drains and the 3% crossfall on the pavement.

Figure 2.1 CAPTIF track plan layout

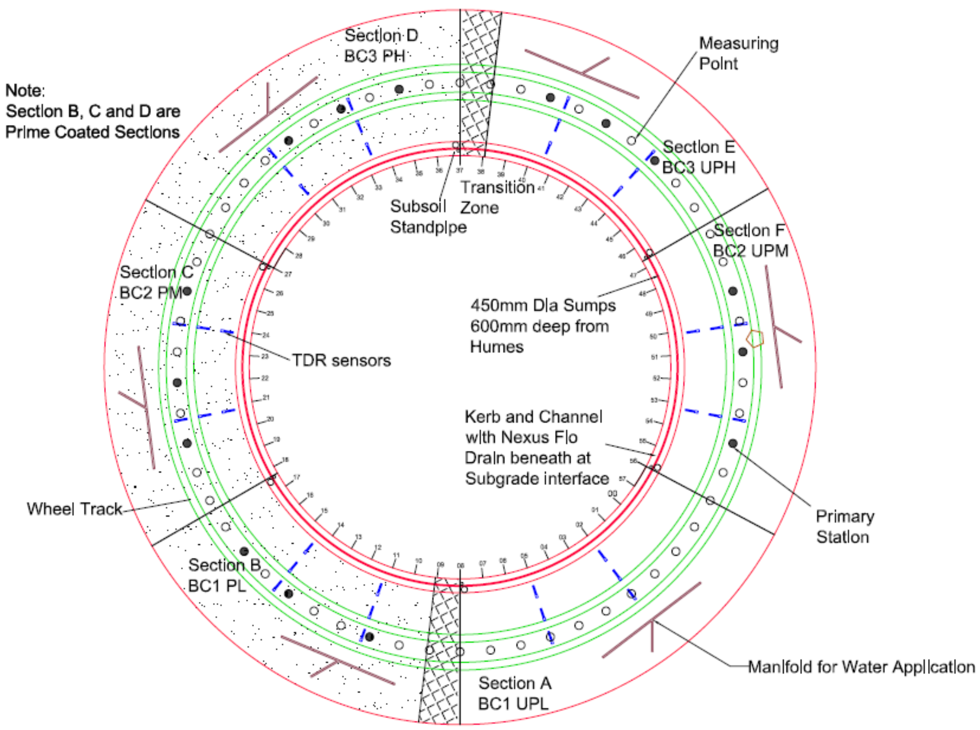
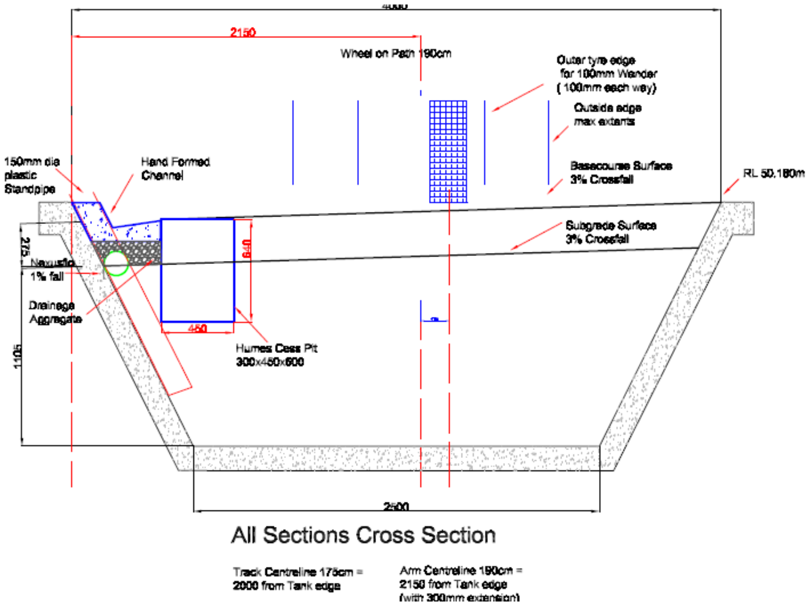


Figure 2.2 CAPTIF track cross section



2.2 Laboratory mix design

2.2.1 Aggregate characterisation

The industry steering group assisted in the selection of suitable basecourse aggregates for the project. It was decided that the geological origin of the parent aggregate should remain constant to limit the number of variables being tested and only the grading should be altered. A local AP40 NZTA M/4 basecourse was set as the 'good' control material, fines were added to the M/4 to create what was considered a 'poor' low permeability material and finally a dense AP20 with an intermediate grading was selected as the 'average' material.

The particle size distributions are summarised in figure 2.3. The Talbot values of 'n' for M/4, AP20 and fines added materials were approximated as 0.5, 0.43 and 0.37 respectively.

Figure 2.3 Material particle size distribution curves

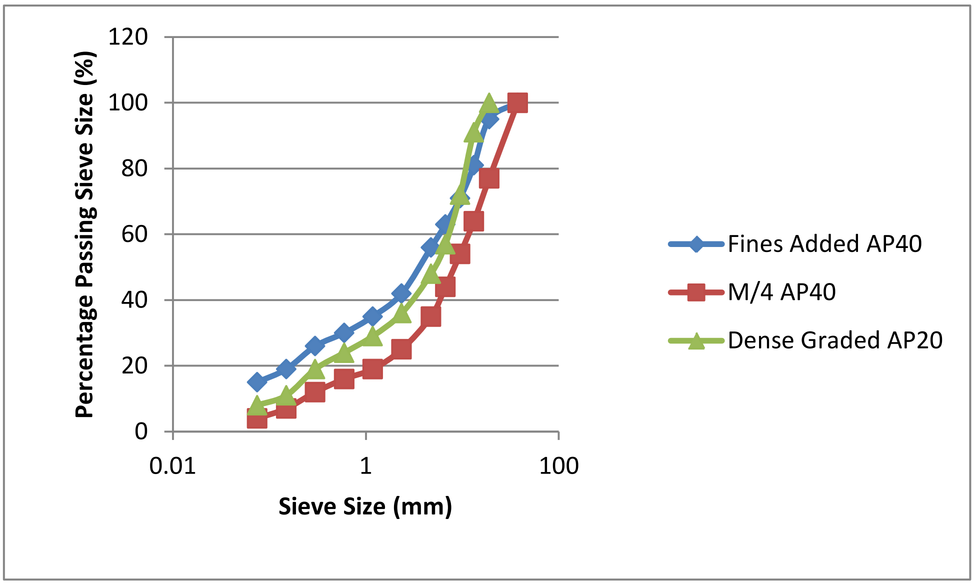


Table 2.2 summarises the Transport Agency M/4 fines quality tests and broken faces content for the materials.

Table 2.2 Fine quality and broken faces

Material	PI	CI	SE	PL	CPL	Broken faces
Fines added AP40	NP	2.2	17	NP	21	52%
M/4 AP40	NP	2	24	NP	19	
Dense graded AP20	NP	1.4	36	NP	21	74%

The particle size distributions, broken faces content and fines quality tests followed the procedures in NZS 4407.

The maximum dry densities (MDD) and optimum water content (OWC) were determined following the New Zealand vibrating hammer compaction test NZS 4402:1986 Test 4.1.3 and are provided in table 2.3. The results are surprisingly close given the Talbot ‘n’ values of the materials. The test was carried out by the same technician in the same laboratory as it was known that it had a relatively poor reputation for reproducibility; in fact close inspection of the gradings suggested the presence of bumps in sand fractions that might help explain the closeness of the MDDs.

Table 2.3 Maximum dry densities and optimum water content

Material	Maximum dry density (t/m³)	Optimum water content (%)	Assumed solid density (t/m³)
Fines added AP40	2.36	4.8	2.68
M/4 AP40	2.34	4.2	2.68
Dense graded AP20	2.38	4.8	2.69

2.2.2 Geological aggregate characterisation

The basecourse materials used at CAPTIF were characterised geologically (Hussain 2013). Two types of tests were conducted in the laboratory to investigate the aggregate formation and the quality of fines in the three materials used in the CAPTIF experiment. Representative aggregates from the samples were selected for the thin sections, which were prepared in the laboratory and were generally less than 30 microns in thickness. The prepared thin sections were investigated under an electron microscope (under normal and polarised light) for their geological makeup and the identification of various constituent minerals.

The fines from these samples were put in an aluminium folder and x-ray diffraction (XRD) tests were performed on multiple samples from each of the three materials. The conditions for the XRD tests were:

- copper anode X-ray tube running at 40kV, 20mA
- divergence slit: 1 degree
- receiving slit: 0.2mm
- scatter slit: 1 degree
- scanning speed 2 or 3 degrees 2-theta per minute, range 2 degrees per minute
- typical step size 0.02 degrees per step.

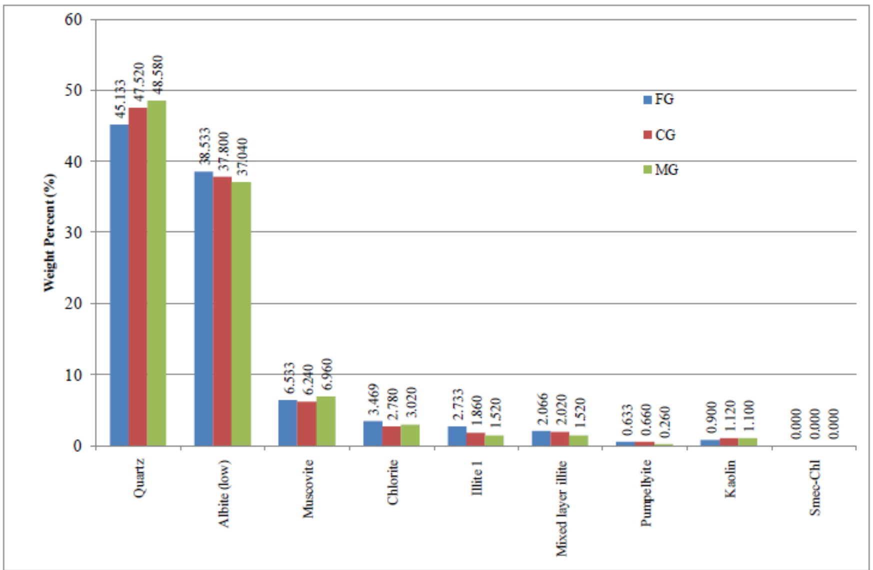
Thin sections were made of representative chips taken from coarse aggregate portions for each of the samples representing the three material types used in this study. The coarse aggregate chips all conformed to the available descriptions of Rakaia sub-terrane sediments in that they were monotonous quartzofeldspathic sandstones classified as arkosic arenites under the Pettijohn sandstone classification scheme (Folk et al 1970; Pettijohn et al 1987). The sandstones contained lithic fragments of felsic volcanics and rare basic volcanics. Detrital mica grains were relatively common. The sandstones had been metamorphosed to prehnite-pumpellyite facies. Thin veins of quartz and less commonly prehnite and calcite were common.

Each of the thin-sectioned rock chips and representative splits of fine sand fractions of the aggregates were subject to x-ray diffraction analysis. Diffractogramms of each of the rock chip and fines samples were obtained from bulk random samples packed into aluminium holders and the minerals present were identified using an automised search/match programme and powder diffraction data files. The weight percentages of the minerals present in the samples were also calculated using SIROQUANT XRD software (Sietronics (Pty) Ltd). In the case of the fines up to three duplicates were run for each sample.

The clay-size fractions of each of the fines samples were also sedimented onto a glass slide to enhance the basal spacings of any sheet silicates and clay minerals present and the oriented samples were also glycolated to determine if any swelling clays were present.

The major minerals in all the sandstone chips and the fine sand fraction of the three aggregates were quartz and feldspar (albite) shown in figure 2.4. Other minerals detected in the samples were chlorite, illite, mica (biotite and muscovite), a mixed layer illite – chlorite, kaolinite and pumpellyite; these in total constituted less than 10% of the sample by weight. Smectites were not found in detectable amounts in any of the bulk diffractogrammes. Figure 2.4 shows that the variations in percentages for each material were within 4% of the weight percentage.

Figure 2.4 Weight percentages of minerals in fine contents of aggregate mixes



Results indicate that the three aggregate materials were almost identical in terms of the geological and mineralogical compositions and that the observed differences between the three samples could not be expected to affect the performance of the aggregate. Further, the fines present in these aggregates were non-expanding and non-plastic. The high quartz content in clasts and matrix cement of the aggregate source rock sandstones gave the material high strength (crushing resistance to produce 10% fines were found at loads greater than 400kN).

2.2.3 RLT aggregate characterisation

The basecourse materials used at CAPTIF were tested in the RLT test. Each material was tested in three conditions: saturated and undrained, saturated and drained, and optimum moisture condition (OMC) drained (table 2.4).

Table 2.4 Detail of RLT test specimens

Description/sample no.	Specimen no.	MDD t/m3	Moisture (%)	Specimen density (95% of MDD)	Test conditions
Ex. Fulton Hogan, Miners Rd, M4 AP40 Christchurch, no. 2-09/021	Af	2.34	**4.3**	**2.223**	Saturated, undrained
	Bf	2.34	**4.3**	**2.223**	Saturated, drained
	Cf	2.34	**4.3**	**2.223**	OMC
Isaac quarry, M/4 + fines, Christchurch, no. 2-09/205	A	2.36	**4.8**	**2.242**	Saturated, undrained
	B	2.36	**4.8**	**2.242**	Saturated, drained
	C	2.36	**4.8**	**2.242**	OMC
Miners Rd, AP20 Christchurch, no. 2-09/206	A	2.38	**4.8**	**2.61**	Saturated, undrained
	B	2.38	**4.8**	**2.261**	Saturated, drained
	C	2.38	**4.8**	**2.261**	OMC

The tests followed the draft TNZ T/15 except for the saturation procedure. One of the objectives of the project was to analyse the pavement performance when the road was saturated by water penetrating through a surface crack in the seal. Water is expected to infiltrate at high pressure through the crack under the vehicle tyres. Therefore the method adapted in these experiments differed from T/15 and is described below.

De-aired water was slowly percolated through the bottom of the specimen and out from the top to atmospheric pressure. This process continued overnight (>12 hours) when the specimen was in the triaxial cell. Then the pore pressure of the specimen was raised to 700kPa in 50kPa steps, with the cell pressure 15kPa greater than the pore pressure at all times. The upper 700kPa condition was maintained for six hours. After this the pore pressure was dropped back by steps of 50kPa to atmospheric pressure, with a cell pressure of 15kPa. The specimen was maintained at this condition for two hours, at which point it was considered to be fully saturated.

The permeability measurements were made on the saturated undrained specimens (nos 2-09/021 Af, 2-09/205 A and 209/206 A). The permeability test results measured with a 5kPa head before testing are provided below in table 2.5. The table also provides the abbreviations used in the RLT testing figures.

Table 2.5 Laboratory permeability's (5kPa head)

Material	RLT name	Lab k m/s
M/4 AP40	CG	10.00E-06
Fines added AP40	FG	6.00E-06
Dense graded AP20	MG	2.00E-06

The RLT permanent strain results are provided in figures 2.5 to 2.7. All three test conditions in the RLT ranked the materials as expected, with the M/4 providing the best RLT results and highest permeability followed by the dense grade AP20 which actually had the lowest permeability and finally the M/4 with fines added providing the worst RLT result with the intermediate permeability.

Figure 2.5 RLT saturated undrained permanent strain results

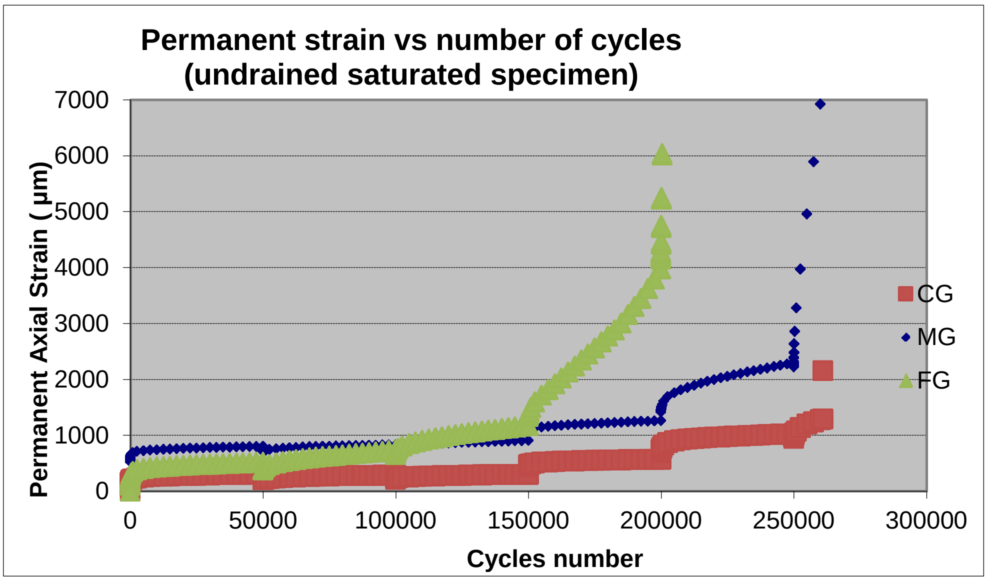


Figure 2.6 RLT saturated drained permanent strain results

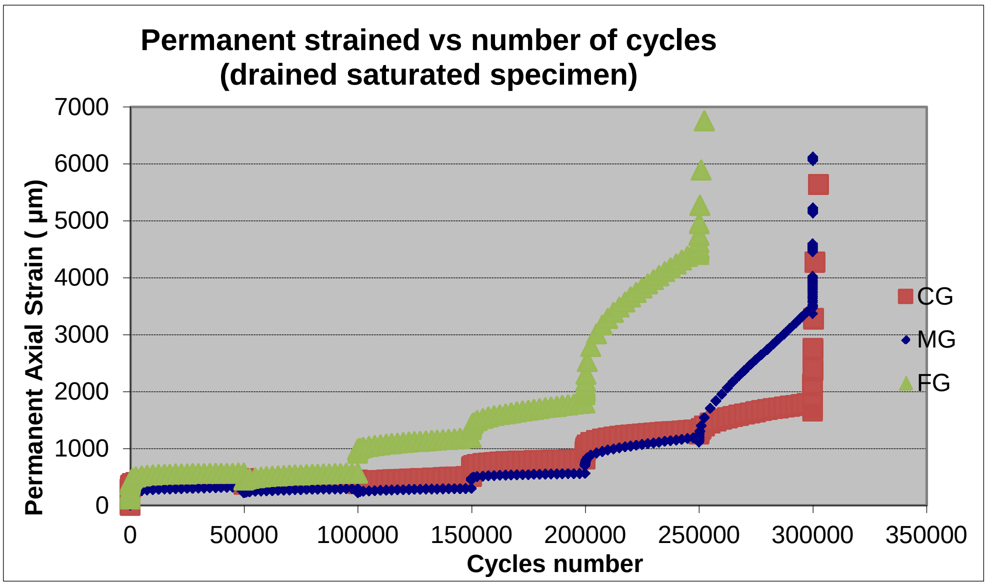
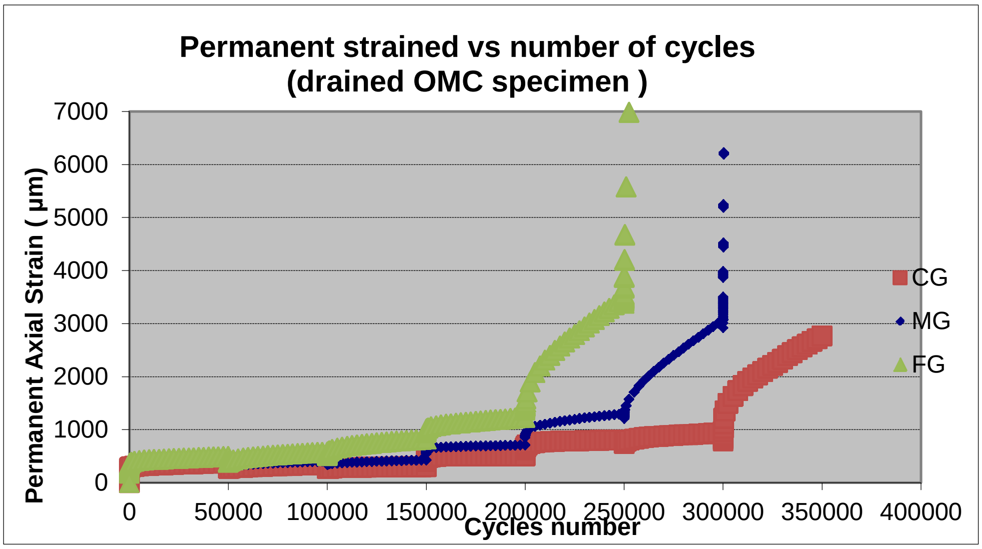


Figure 2.7 RLT OMC drained permanent strain results



2.3 Pavement design

The pavement design was based on experience from previous CAPTIF pavements that suggested 300mm of basecourse would be suitable for the experiment.

2.4 CAPTIF pavement construction

2.4.1 Subgrade

The pavement layers from the previous project were removed and the tank's subgrade was excavated to allow room for the new pavement. The top 450mm of the clay subgrade at CAPTIF was replaced for this project and remaining Waikari silty clay subgrade from previous CAPTIF projects was left undisturbed in the concrete tank. The top 450 mm of Tod clay was placed in three 150mm lifts and compacted using CAPTIF's pivot steer trench roller. Quality control was maintained with layer-by-layer density and moisture-content testing. Once the construction of the subgrade was finished, falling weight deflectometer (FWD) deflections of the subgrade surface were measured to verify the layer homogeneity.

2.4.2 Basecourse construction

The three basecourses were all sourced from Christchurch. They were placed in two 150mm layers and compacted.

Before sealing, layer profiles and density and moisture measurements were taken on 5 October 2009. The percentage of maximum dry density (%MDD) and saturation (%Sat) results are provided in table 2.6 and layer thicknesses in table 2.7. The mosaic surface finish can be seen in figure 2.8. The densities are lower than would be expected in the field but are typical of CAPTIF construction where the circular track makes it difficult to achieve field compaction levels as the rollers need to turn continually. Previous research (Henning et al 2007) in comparing the long-term pavement performance (LTPP) programme with CAPTIF suggested the rate of rutting at CAPTIF was typical of New Zealand pavements. The current study in particular is a comparative study and thus the densities should not impact on the results.

Table 2.6 Percentages of maximum dry density (%MDD) and saturation (%Sat)

Section	Min %MDD	Avg %MDD	Avg %Sat	Max %Sat
A	93.1	96.2	29.4	37.3
B	94.1	97.4	32.0	44.9
C	93.1	96.3	33.4	44.6
D	95.2	96.9	40.2	53.9
E	93.4	95.5	39.0	58.3
F	92.6	95.7	35.8	42.1

Table 2.7 Final depth of pavement

Section	Primed/unprimed	Surfacing	Basecourse	Depth (mm)
A	Unprimed	3 and 5 two-coat first coat	M/4 AP40	296
B	Primed	3 and 5 two-coat first coat	M/4 AP40	298
C	Primed	3 and 5 two-coat first coat	Dense graded AP20	287
D	Primed	3 and 5 two-coat first coat	Fines added AP40	286
E	Unprimed	3 and 5 two-coat first coat	Fines added AP40	285
F	Unprimed	3 and 5 two-coat first coat	Dense graded AP20	294

Figure 2.8 Basecourse surface finish

2.4.3 Sealing

The prime coat was applied to sections B, C, and D on 14 October 2009 (see figure 2.8). The target application rate was 0.5 l/m^2 and actual application rate was 0.4 l/m^2.

The prime was Fulton Hogan's EP-55 emulsion that had been manufactured the day before. Testing to BS 434 pt 1 1984, appendix F, showed the average binder content was 55%. Testing to ASTM D2196-05 method A with a Brookfield HSDV-I+ viscometer with a 01 spindle showed at 24.5°C the viscosity at 100RPM was 54mPas and the torque at 100RPM was 27%.

The final two-coat first-coat surfacing was constructed 11 days after the basecourse layers were tested for density and moisture content on 21 October 2009. It was typical of a Canterbury seal based on a 180/200 bitumen with a grade 3 chip first layer and a grade 5 second layer.

The bitumen sprayer was fitted with the CAPTIF spray bar designed to spray a uniform bitumen film around the circular track at CAPTIF. The spray bar was checked for uniformity and calibration prior to spraying using standard pad tests at the CAPTIF radius.

The final blend of bitumen and cutters was based on a fairly standard Canterbury first-coat sealing blend of 180/200 bitumen with 0 parts diesel and 4 parts kerosene with 0.7 adhesion agent. However, there was a compromise between having a seal suitable to place over the primed sections and a seal suitable for the sections that were not primed. Testing to TNZ T/9:2003 suggested the kerosene content was 5.6 parts per hundred (pph). Adhesion agent was detected with testing to BCA9804. The kinematic viscosity was 12,200mm^2/s when tested to ASTM D 2170-06 and corrected to 60°C.

The target application rate was 0.9 l/m^2 for the first coat and 0.9 l/m^2 for the second coat on the primed sections and 0.9 l/m^2 for the first coat and 1 l/m^2 for the second coat on the unprimed sections.

The bitumen temperature on the external tank temperature gauge was 145°C at the start of spraying and 130°C at the end. The sprayer driver noted that the bottom of the tank temperature gauge, displayed in the truck cab, read 145°C when the sealing was finished.

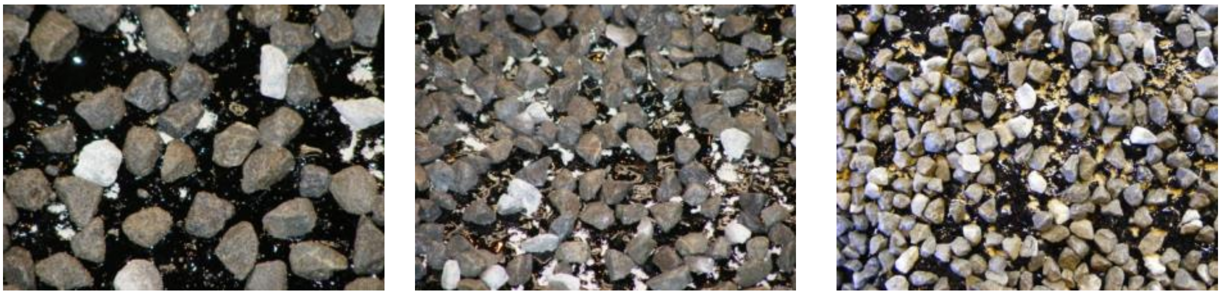
The sealing chip was sourced from Fulton Hogan's Miners Road quarry. The grade 3 (SC14) chip had a cleanness value of 92, 100% broken faces, an ALD of 8.94mm and an AGD/ALD ratio of 1.85. The grade 5 (SC10) chip had a cleanness value of 92. Both sizes passed the TNZ M/6:2004 grading requirements. The chip used was damp but dried well.

The first coat was sprayed and chipped in two halves. The first half started on two sheets of paper at station 41 and ended on station 4 on three sheets of paper, seen in figure 2.9, and the tank was dipped.

Figure 2.9 Chipsealing

The grade 3 chip was applied immediately after the spraying – with noticeable gaps between chips – but may have been a little over chipped. Some minor bitumen dripping was noted about station 2 while waiting for the next run. The second half started at station 4 on three sheets of paper and ended on station 41 on three sheets of paper and the tank was dipped. There was a little bit of hand spreading of chip at the join. There was noticeable blistering in the first-coat seal in unprimed sections (figure 2.10). No blocked jets were observed and the surface was dry when sealed. Discussion with the sealing staff suggested that the surface should have been slightly dampened prior to sealing.

Figure 2.10 Blistering in unprimed sections



The second coat had some over spray past the paper on the first half, and there was possibly a blocked jet between stations 11 and 6 (note spraying is anticlockwise; review of the results suggests this section did not perform abnormally). The application looked patchy (some unsealed chip in centre of track). The jets were checked but the end paper looked normal. On the second half there was a blocked jet on the centre of the track, which was not easy to see, but which became visible when looking back across the track.

The track was rolled with a Sakai TW41, a steel and rubber tyred combo, for 10 minutes and was followed by a Ingersoll-Rand pneumatic tyre roller (PTR) for a further 30 minutes (figure 2.11).

Figure 2.11 Rollers

An average texture depth of 4.1mm for the entire track was measured following NRB T/3:1981 prior to trafficking. Timings and actual application rates are given in table 2.8.

Seal quality is paramount to a pavement's behaviour but we did see blistering in the field. The blistering in test 1 was in some ways a useful outcome as it allowed investigation of both primed good and unprimed poor two-coat seals. Test 2, where the unprimed two coat was applied well, allowed investigation of a good quality unprimed two-coat seal.

Table 2.8 Chipsealing details

Run no.	Station no.		Application rate (l/m2)		Spray time		Chip time		Rolling time	
	Start	Stop	Target	Actual	Start	Stop	Start	Stop	Start	Stop
1	41	4	0.9	0.9	10.50	10.50	10.50	10.51		
2	4	41	0.9	0.9	11.08	11.08	11.08	11.08		
3	42	6	0.9	0.9	11.27	11.27	11.27	11.29		
4	6	42	1	0.8	11.55	11.55	11.55	11.55		
Sakai									12.14	12.24
Ingersoll									12.24	12.57

2.4.4 Falling weight deflectometer testing

The constructed pavement was tested with a FWD to check it would be of a suitable strength for testing. Table 2.9 suggests that a suitable pavement was prepared. Comparison with the design charts of Austroads (2011) indicates that all the test sections should carry at least 1 million load cycles.

Table 2.9 FWD tests

Section	FWD central deflection (micron)		FWD drop stress (kPa)	
	Average	Standard deviation	Average	Standard deviation
A	604	38	611	4
B	645	48	613	9
C	610	50	617	5
D	547	51	617	9
E	494	71	620	8
F	486	56	620	15

2.4.5 In-pavement instrumentation

The pavement instrumentation included 3D CAPTIF soil-strain transducers for measuring vertical, transverse and longitudinal strains in the pavement, TDR moisture sensors for measuring moisture changes in the pavement basecourse, and tensiometers measuring changes in suction in the subgrade.

The 3D CAPTIF soil-strain measuring system determines strains with good resolution (±50μm/m). The sensors use the principle of inductance coupling between two free-floating, flat, circular wire-wound induction coils coated in epoxy, with a diameter of 50mm. Details of the system can be found in Greenslade et al (2012). The strain coils were installed during the formation of the subgrade and the basecourse layers, to minimise the disturbance to the materials.

The CAPTIF strain coils were located coaxially at a spacing of 75mm. The reported depth of the vertical strains corresponded to the midpoint between two coils, while the reported depth of the longitudinal and transversal strain corresponded to the coil depth. The 3D CAPTIF stacks were located at stations 2, 11, 21, 31, 40 and 50.

The TDR gauges used to determine moisture content were Campbell Scientific's CS625. Proof testing of a number of gauges at CAPTIF suggested that these would be ideal. The gauges were installed under the wheel paths in upper and lower vertical locations, and across the track to try to detect moisture changes as water reached the subsoil drain. The gauges were installed at two stations in each track section; there was a main location near the CAPTIF coils with a high water film thickness where the water was applied and a secondary location with low water film thickness where the water was tracked.

Figure 2.12 Instrument location cross section

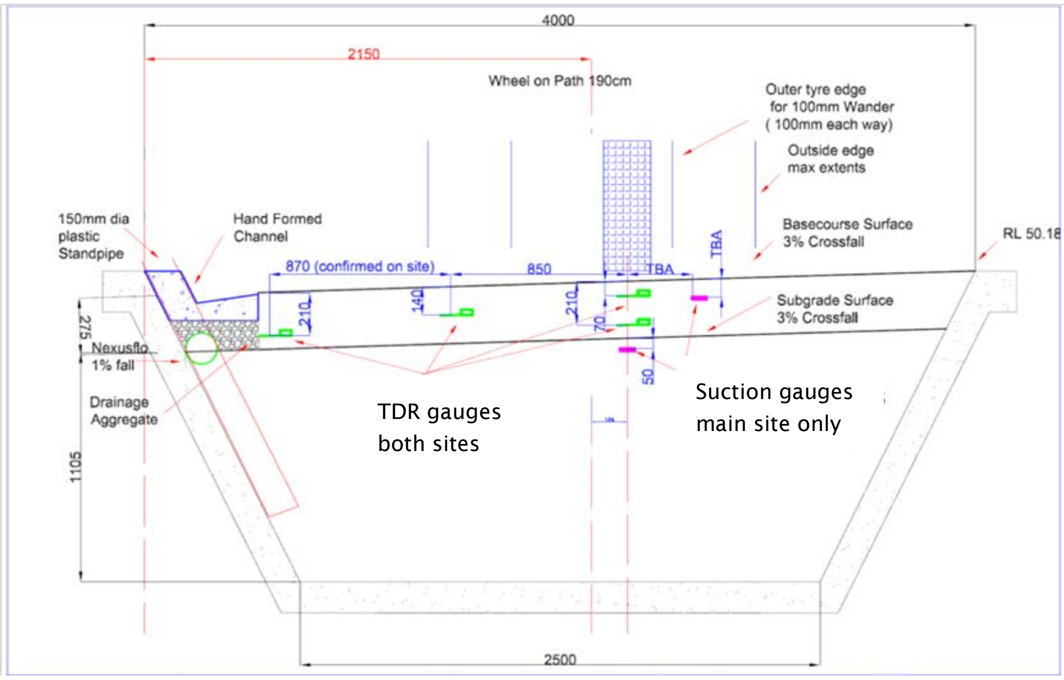
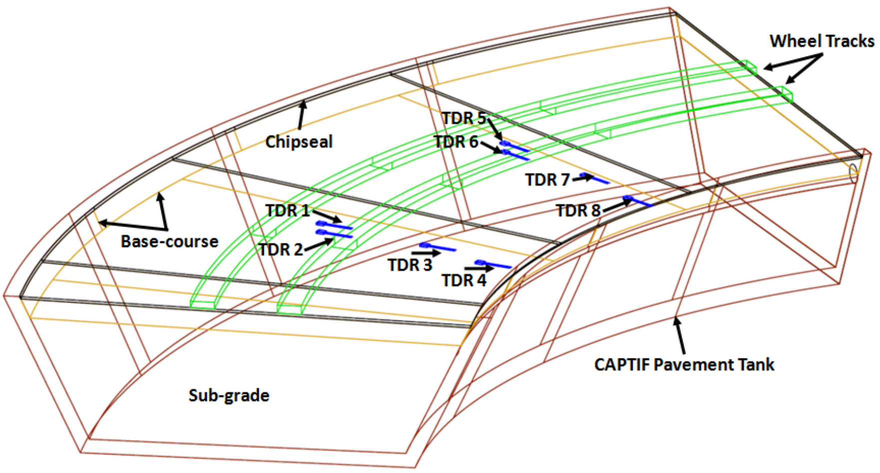


Figure 2.13 TDR locations 3D



2.4.6 Permeability testing

Permeability tests were also undertaken at CAPTIF on the surface of the basecourse that had been prepared for sealing (figure 2.14). As can be seen from table 2.10, the results were significantly lower than those obtained in the laboratory under saturated conditions and a 5kPa head. This conforms to the traditional expectations of saturated vs unsaturated permeabilities but the fact that the permeabilities in the field were so similar was a surprise.

Figure 2.14 Field permeability test

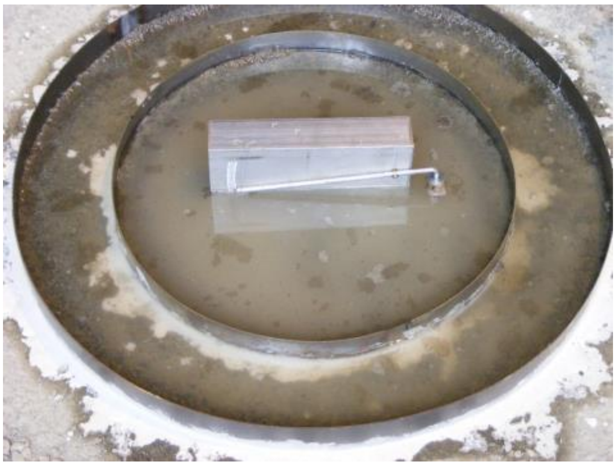


Table 2.10 Field permeability results

Material	Short-term field k m/s	Average field k m/s	Long-term k m/s	Opus Lab k m/s
M/4 AP40	7.9E-07	2.8E-07	1.5E-07	10.00E-06
Fines added AP40	7.7E-07	3.0E-07	1.4E-07	6.00E-06
Dense graded AP20	7.4E-07	3.2E-07	1.6E-07	2.00E-06

2.5 Accelerated pavement testing

2.5.1 Loading arrangement

The CAPTIF loading vehicles were arranged with single tyres inflated to 700kPa without any additional loading plates – thus the applied load was 20kN on each tyre. The original project contemplated loading the pavement on a single wheel path with 100mm of wander. The final loading was on two separate wheel paths as the pavement suffered some stripping in hot weather prior to the water application beginning and an asphalt patch was placed on the centreline.

The speed of the vehicles was kept constant at 40km/h during most of the project.

2.5.2 Water application

Water was applied across the track at discrete locations in each test section. The water was applied from a 1m long manifold placed on the outside of the track (figure 2.15). Each manifold had its own 5,000 litre storage tank. The water flowed across the track, into the kerb and channel where it was collected in a sump and pumped back into the storage tanks. Losses were continuously topped up from the mains water supply using a valve controlled by a float.

The water film thickness was adjusted by placing sized restrictors in the pipe supplying the manifold. The restrictors were disks with different sized holes drilled in them.

Figure 2.15 Watering manifold

The rate of flow from each sized disc was estimated by measuring the volume of water applied over a set time and the film thickness was estimated by measuring the water film thickness above the chips and creating a regression relationship between disc size and film thickness (table 2.11).

Table 2.11 Disc flow rates

Disc	mm	8	9	10	11	12	14	16	18
Estimated flow	litres/s	0.15	0.25	0.27	0.31	0.36	0.6	0.74	1.1
Film thickness	mm	2.3	2.9	3.6	4.2	4.9	6.2	7.5	8.7

2.5.3 Testing

The estimates of the load cycles required in the original testing plan, described in table 2.12, were developed from CAPTIF testing of chipseals in the mass limits project undertaken in the early 2000s. Those chipseals lasted over 100,000 cycles when tested with a damp surface (the damp surface was used to prevent bitumen collecting on the tyres).

Table 2.12 Planned loading sequence

Film thickness	**Load cycles**		
	1,000	**10,000**	**100,000**
Dry	✓	✓	✓
Low film	✓	✓	✓
Medium	✓	✓	✓
High film	✓	✓	✓

Early testing suggested the unprimed sealed sections were significantly more permeable than the primed sections. An 8mm restrictor was used to control the flow water across the track with no loading applied for 2.75 hours (only 1.5 hours on section A) and the subsoil drains were monitored. Table 2.13 provides the results measured from the subsoil drains and figure 2.17 shows the TDR gauge results at the manifold locations and at the downstream positions.

Table 2.13 Subsoil drain water volumes in unloaded test

Date	Time	Section A volume (mils)	Section B volume (mils)	Section C volume (mils)	Section D volume (mils)	Section E volume (mils)	Section F volume (mils)
24 Feb 2010	11.45	0	0	0	0	0	0
	12.45	0	0	0	0	0	0
	13.10	3,000	0	0	0	0	damp
	13.35	4,000	0	0	0	400	<100
	13.50	4,250	0	0	0	850	200
	14.15	4,250	0	0	0	2,400	400
	14.30	4,250	0	0	0	4,000	500
	15.30	4,250	1,200	0	0	6,800	650
	16.40	4,250	1,650	0	0	1,300	650
25 Feb 2010	9.30	4,250	2,200	0	0	1,600	650
1 Mar 2010	8.30			250			

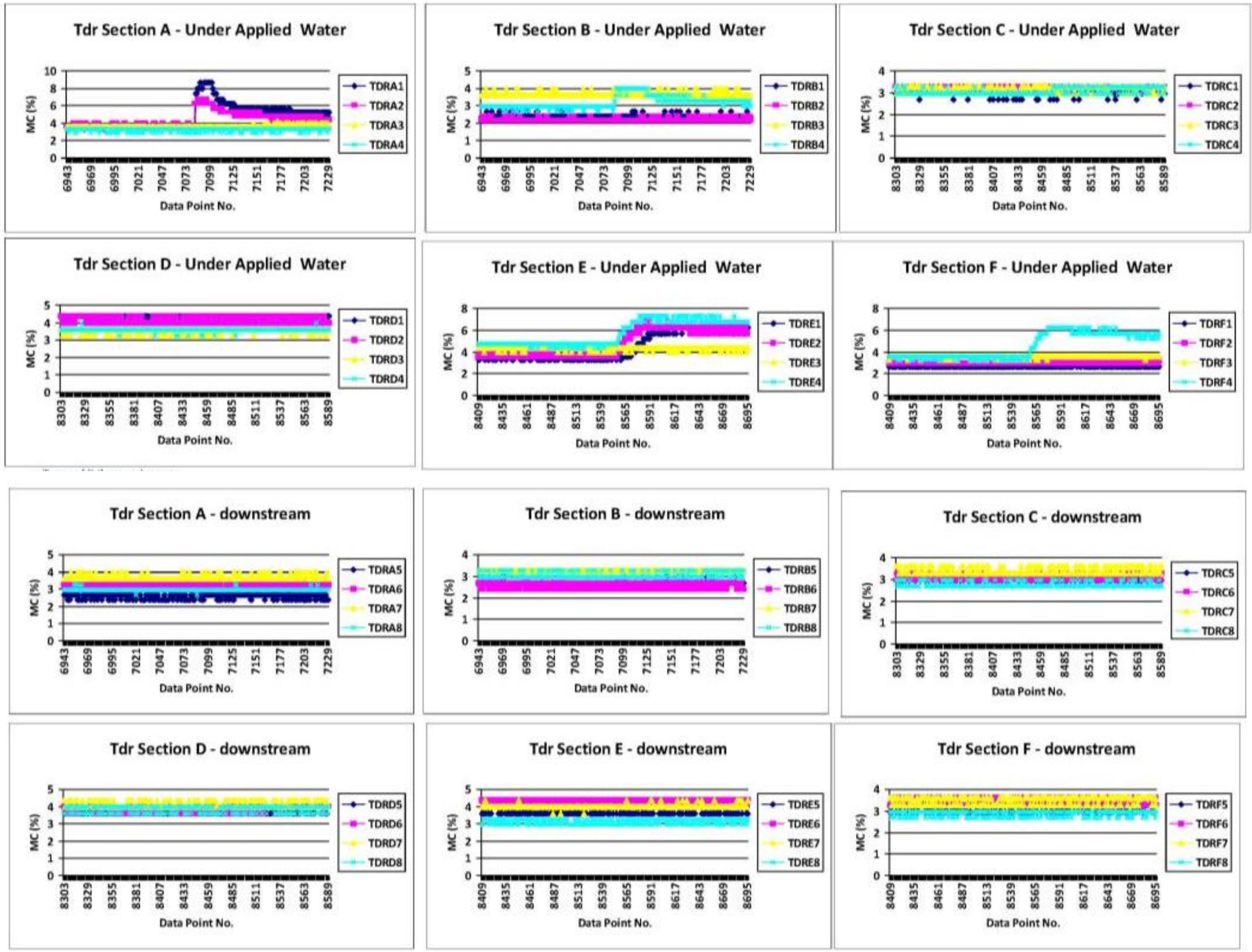
While the results in table 2.13 agree with the traditional view of priming improving waterproofing (in sections B, C and D), the volumes of water being extracted from the unprimed sections were a concern. The change in results between surfacing type and basecourse also suggested that the experimental design was implemented in construction. However, significant effort was made to check and ensure that these results were correct, and that additional seal was applied to the kerb and channel interface, hose fittings checked, pumps installed in the subsurface drains and repeats of these tests carried out.

The TDR results in figure 2.17 follow what we would generally expect to see; however, it was apparent the flow paths to the drain were more complex than we had expected. Often the TDR gauges at the intermediate and edge locations did not measure any increase and occasionally the central TDR also measured no increase. Additional efforts were made to understand these readings, from surface resistivity measurements, back scatter nuclear density measurements and the air launch ground penetrating radar shown in figure 2.16 below. Unfortunately none of these methods assisted in understanding the flow paths.

The key information from table 2.13 and figure 2.17 is that the blistering seen in the sealing process in sections A, E and F most likely compromised the surface in section A and E as TDRs 1 and 2 in each section were in the centre of the track. Section F appeared fine in the centre but water was entering the edge, TDR 4. The water entering the drains in sections B and C was possibly entering the edge (section B, TDR 4).

Figure 2.16 Air launched ground penetrating radar

Figure 2.17 Initial static test TDR results



2.5.4 Failure

The first failure occurred in section A after 1,186 laps of loading had been applied at the manifold. The basecourse started to pothole and eventually failed in shear as seen in figure 2.18. At this point only 132 laps had been applied with water flowing across the surface, and with a 9mm restrictor in place.

Figure 2.18 Test 1 – first failure

The TDR gauges in figure 2.20 show there was certainly enough water to saturate the basecourse in section A – but very little change in moisture was recorded in the other test sections and where it was recorded, it appeared to be at the edges of the track.

Table 2.14 shows that the failures continued at a rapid rate. The table shows:

- whether the test was loaded or not (some tests were just water flowing across the track with no loading)
- whether the test was dry or not (some tests had no water film applied at the manifolds)
- the total number of loading laps applied since the experiment began
- the stations (chainages) in each section that required repair after each test
- the total number of loading laps that had been applied with a water film applied at the manifolds
- the nozzle was the diameter of the restrictor in the manifold and controlled the film thickness.

By the time 1,000 wet laps at the low-flow setting were reached all the unprimed sections had failed. The order they failed in was not what had been expected – the M/4 AP40 material in section A failed first followed by the M/4 AP40 with fines added to it and the best performer was the dense grade AP20. The primed sections failed in the same order but under higher numbers of load applications and higher film thicknesses. The final failure was the primed dense graded AP20 at 3,863 laps of wet testing, the last 2,700 of which were at the 18mm restrictor nozzle film thickness.

Table 2.14 Loading and failure test 1

Test	Loaded	Wet /dry	Laps	Station repairs by section						Wet laps	Nozzle
				A	B	C	D	E	F		
0	Yes	Dry	1,054								
1-5	No	Wet									8-12
6	Yes	Wet	1,186	0-5						132	9
7	Yes	Wet	1,401	5-8				37-43		347	9
8	Yes	Wet	1,975	57-0				43-47	47-56	921	9
9	No	Wet									12
10	Yes	Wet	2,244		9-11.5					1,190	12
11	No	Wet									18
12	Yes	Wet	3,501		11.5-18		28-37			2,447	18
13	Yes	Wet	4,917			19-27				3,863	18
Surface parameter				Un	Prime	Prime	Prime	Un	Un		
Basecourse parameter				M/4	M/4	AP20	Fines	Fines	AP20		

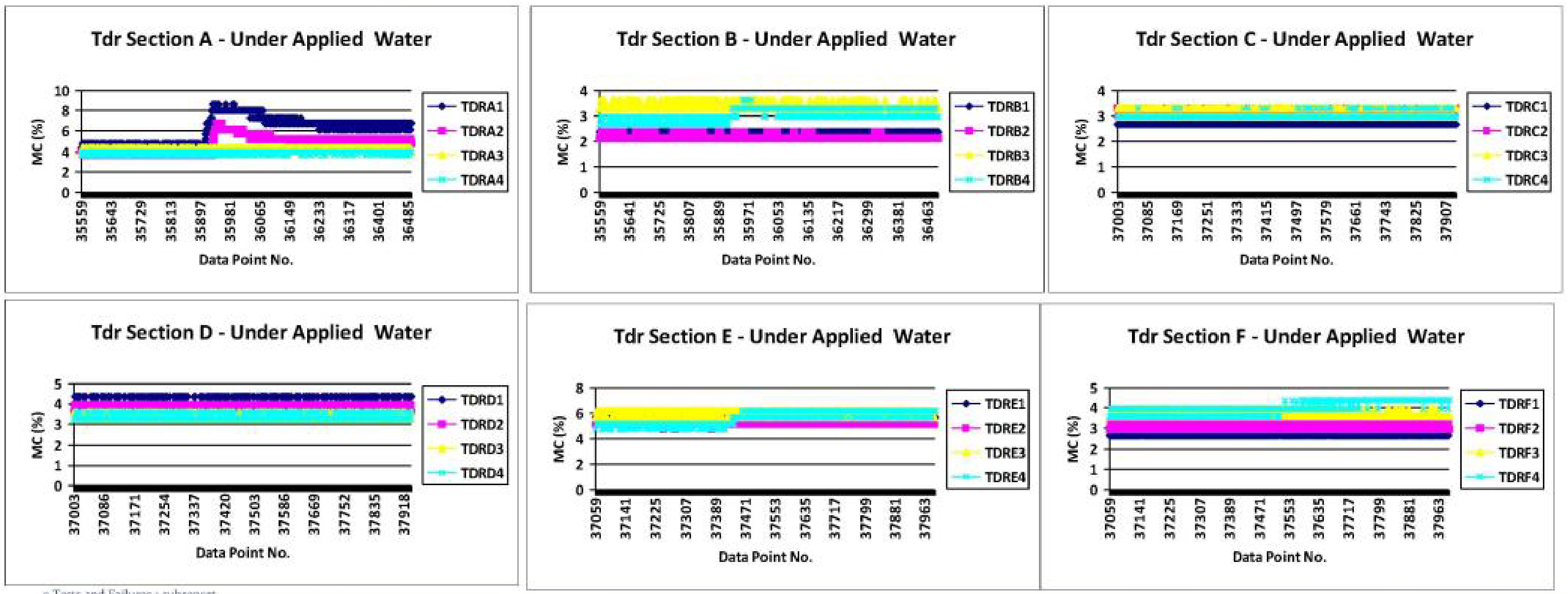
Figure 2.19 illustrates that there were different failure modes present. The left-hand photo is of the M/4 basecourse and it failed in shear; the middle photo is of the M/4 plus fines that potholed as did the dense graded AP20. The rate and mode of failure that meant the CAPTIF soil strain transducers did not provide additional data for the analysis and the tensiometers appeared to have measured constants suctions in the subgrade, and had failed during construction of the basecourse.

Figure 2.19 Failure modes

A final layout for the failures is shown in figure 2.21. As can been seen from the timeline of failures and the initial values of the TDR readings in appendix A, the moisture in the test sections was allowed to stabilise after each test.

Figure 2.20 TDR gauge response at first failure

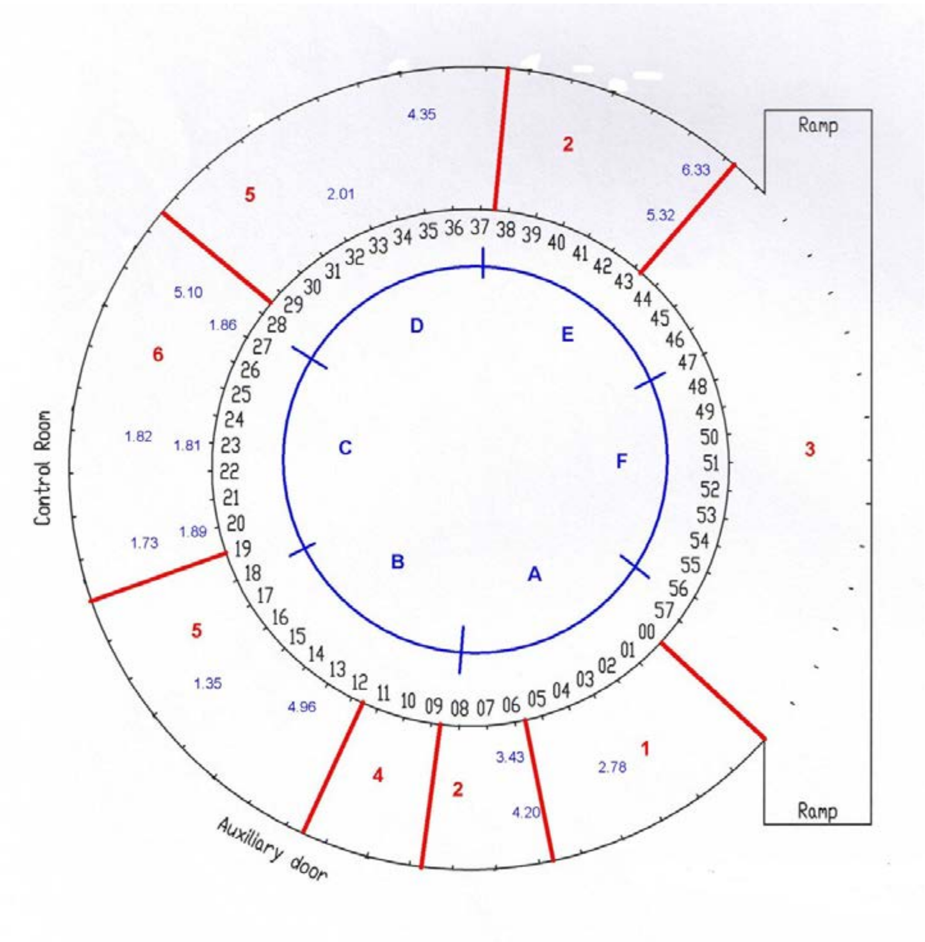
6 26/05/2010 9 DA Notes: 1st Dynamic



0 Tests and Failures 1 subreport

Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
6	26/05/2010	9	1st Dynamic	A=un-primed least sensitive (UP	########	1186	Unprimed	3/5 Two Coat First Coat	M/4 AP40	0	6

Figure 2.21 Failure map test 1



Initial laps = 1,054 before water applied

1 Failed 26 May: 1,186 laps
Digout 10 June (FH)
Sealed 14 June

2 Failed 17 June: 1,401 laps
Digout 22–24 June
Sealed 30 June

3 Failed 12 July: 1,975 laps
Digout 26–28 July
Sealed 3 August

4 Failed 30 August: 2,244 laps
Digout 1 September
Sealed 15 September

5 Failed 21–27 September
Sealed 30 September

6 Failed 5 October: 4,917 laps
Digout 11–12 October
Sealed 18 October (asphalt contractors)

2.6 Interpretation and discussion of results

Seal and basecourse quality along with good structural design are traditionally seen as vitally important in pavement performance. The traditional New Zealand view is that a more permeable basecourse is preferable to a low permeable basecourse and that the prime coat before sealing improves water proofing. In this experiment three basecourses were tested, the major difference between them being grading and this was reflected in the laboratory permeabilities. Surprisingly the change in permeability was not noted in the field permeability tests (which were low head) and permeability did not relate to performance in the RLT test as was expected.

The construction of the pavement raised two issues. The first was that the basecourse was not constructed to the densities typically seen in the field. However the densities were typical of previous construction at CAPTIF and previous research suggests that those densities were suitable to simulate field performance. The study was also a comparative study which alleviated these concerns to some extent. Earlier work at CAPTIF studies suggested that chipsealed pavements could be trafficked to over 100,000 vehicle passes before a bleeding failure occurred and this was with a light application of water.

Seal quality is paramount to a pavement's behaviour and the experimental design was to compare two good quality seals in experiment 1 but half the track was sealed poorly. In some ways this was a useful outcome as it expanded the range of parameters tested and allowed investigation of both primed good and unprimed poor two-coat seals. Experiment 2 at CAPTIF, where the unprimed two coat was applied well, still allowed investigation of a good quality unprimed two-coat seal. This test 2 surface was originally selected to link the two CAPTIF tests and that was certainly made more difficult.

The failures occurred consistently at the manifold locations (refer to the photos in appendix B) confirming two things – one that water film thickness was driving the failures and two, that the stripping repair was in fact water proof. The fact that moisture was able to enter the edge of the pavements did not appear to be driving failure in other locations on the track.

The primed sections performed better than the unprimed sections; however, there was doubt that unprimed chipseal was built as well as it could have been and this was confirmed in the testing without loading and the performance of the second experiment at CAPTIF.

3 CAPTIF experiment 2

3.1 Experiment 2 objectives

The second test pavement was constructed to study an improved surfacing technology; the steering group felt a study of traditional two-coat first-coat seals vs racked-in seals was appropriate. The racked-in seal, in providing a single layer of bitumen on the basecourse rather than one coat on the basecourse and one on the first layer of chips, was thought likely to improve performance. Given the difficulties of measuring moisture in the first project, the instrumentation locations were re-evaluated in an effort to improve detection and allow modelling.

3.2 Pavement construction

3.2.1 Pavement design

The pavement design for these test sections followed the design of the first test: 300mm deep basecourse test sections were used.

3.2.2 Subgrade

The pavement layers from the previous test were removed and the top 300mm of the clay subgrade was also replaced as Scala Penetrometer and Prima testing indicated it had been weakened by the last test, suggesting the suction testing in test 1 was not correct. The remaining subgrade from the previous test was left undisturbed in the concrete tank. The top 300mm of Tod clay was placed in two 150mm lifts and compacted using CAPTIF's pivot steer trench roller. Quality control was maintained with layer-by-layer density and moisture-content testing. Once the construction of the subgrade was finished, FWD deflections of the subgrade surface were measured to verify the layer homogeneity.

3.2.3 Basecourse construction

The three basecourses had all been sourced for the previous test. And again they were laid in two 150mm layers and compacted.

Before sealing, layer profiles, density and moisture measurements were taken on 22 June 2011. The %MDD and %Sat results are provided in table 3.1. As noted in the experiment 1 section on density, these results are not as high as would be expected in the field but are typical for CAPTIF and should be sufficient for the comparative nature of the experiment.

Table 3.1 Percentages of maximum dry density (%MDD) and saturation (%Sat)

Section	Min %MDD	Avg %MDD	Avg %Sat	Max %Sat
A	93	96	29	37
B	94	97	32	45
C	93	96	33	45
D	95	97	40	54
E	93	96	39	58
F	93	96	36	42

3.2.4 Sealing

The first-coat surface was constructed on 30 June 2011, eight days after the basecourse layers were tested for density and moisture content. It was typical of a Canterbury seal being based on a 180/200 bitumen with a grade 3 chip first layer and a grade 5 second layer. However, half the track was sprayed as a racked-in seal rather than a traditional two-coat seal.

The bitumen sprayer was fitted with the CAPTIF spray bay, which is designed to spray a uniform bitumen film around the circular track at CAPTIF. The spray bar was checked for uniformity and calibration prior to spraying using a standard pad test at the CAPTIF radius.

The final blend of bitumen and cutters was based on a standard Canterbury first-coat sealing blend of 180/200 bitumen with 0 parts diesel and 4 parts kerosene with 0.6 adhesion agent.

Testing TNZ T/9:2003 suggested that kerosene content was 5.1pph and the adhesion agent was detected by testing to BCA9804. The kinematic viscosity was 13,700 mm^2/s when tested to ASTM D 2170-06 and corrected to 60ºC.

The target application rates for the two-coat seal were 1.0 l/m^2 hot for the first coat and 1.0 l/m^2 for the second coat. The application rate on the racked-in sections was 2.0l/m2 hot. Tank dipping records suggested that the application targets were met.

The sprayer driver noted that the temperature of the bitumen at the start of spraying was 158ºC. The air temperature in the track was 10ºC.

The sealing chip was sourced from Fulton Hogan’s Miners Road quarry. The grade 3 (SC14) chip had a cleanness value of 93, 100% broken faces, an ALD of 9.39 mm and an AGD/ALD ratio of 1.97. The grade 5 (SC10) chip had a cleanness value of 89, 100% broken faces, an ALD of 5.83 and an AGD/ALD ratio of 1.96. Both sizes passed the TNZ M/6:2004 grading requirements. The chip used was wet.

The two seal types were sprayed separately. The two-coat seal was applied first starting at 1.48pm. The first coat of bitumen achieved good coverage and no blistering or streaking of the seal was observed. The chip application started immediately and the grade 3 chip application was perhaps a little high. The chip was wet. Rolling started at 2.04pm with a roller with a rubber covered steel front drum and pneumatic rear roller. There was some hand sweeping of the inner track to remove excess chip but it was not in the wheel path. Twelve passes were applied with the roller and rolling stopped at 2.15pm. The chip adhesion was not good, but after the second coat the chip appeared to adhere well when dry.

The second coat started at 2.19pm. Again coverage was good. Chipping was completed at 2.22pm and rolling started at 2.28pm and was maintained for 18 minutes. The first four passes were with a PTR roller and the final six were with the combo roller vibrating.

The construction of the racked-in seal started at 2.55pm. Pinholes were noted in the seal from stations 53 to 38. They were approximately 5mm pinholes rather than blistering and not as bad as in test pavement 1. The spray tank was still at 158ºC. The grade 3 chipping was completed by 2.59pm. Rolling started with the combo roller at 3pm with one pass static, followed by a pass on vibration and then two passes static. Rolling ceased at 3.05pm. The grade 5 chipping started at 3.06pm and was completed by 3.08pm. The PTR roller was applied for 20 minutes from 3.30pm. CAPTIF staff took over and rolled the entire track with the PTR until 4.30pm. Most of the chip had dried and was sticking well.

3.2.5 FWD testing

The constructed pavement was tested with a FWD to check the pavement would be of a suitable strength for testing. Table 3.2 suggests a suitable pavement was prepared and table 3.3 suggests a consistent depth was constructed. Comparison with the design charts of Austroads (2011) indicated all the test sections should carry at least 1 million load cycles.

Table 3.2 FWD readings

Section	FWD central deflection (micron)		FWD drop stress	
	Average	Standard deviation	Average	Standard deviation
A	592	35	621	14
B	641	81	639	7
C	532	85	636	5
D	450	73	632	11
E	392	56	634	11
F	459	69	632	9

Table 3.3 Final depth of pavement

Section	Primed/unprimed	Surfacing	Basecourse	Depth (mm)
A	Unprimed	3 and 5 racked-in first coat	M/4 AP40	364
B	Unprimed	3 and 5 two-coat first coat	M/4 AP40	366
C	Unprimed	3 and 5 two-coat first coat	Dense graded AP20	355
D	Unprimed	3 and 5 two-coat first coat	Fines added AP40	358
E	Unprimed	3 and 5 racked-in first coat	Fines added AP40	358
F	Unprimed	3 and 5 racked-in first coat	Dense graded AP20	363

3.2.6 In-pavement instrumentation

The pavement instrumentation included the new TDR arrangement, an Equitensiometer, and 3D CAPTIF soil-strain transducers for measurement of vertical, transverse and longitudinal strains in the pavement.

The TDR gauges were all placed in the upper under-tyre position shown in figure 2.13 at the locations shown in figure 3.4. The naming convention was the section name (A to F) followed by the location number, ie E2 denotes the second TDR in section E between stations 41 and 42.

The TDR and 3D CAPTIF transducers are described in chapter 2. The Equitensiometer is a Delta-T Devices EQ2 device, placed 50mm below the subgrade surface at station 5 (figure 3.1) to measure changes in suction in subgrade that would indicate changes in moisture content and a lowering of the subgrade's strength.

The EQ2 Equitensiometer is an innovative sensor for measuring soil matric potential. Based on the ML2x ThetaProbe soil sensor, the EQ2 Equitensiometer avoids the problems of water-filled tensiometers. The ThetaProbe pins are embedded into a specially formulated porous matric material. Being maintenance free (ie no refilling, degassing or topping up required) and low power, the EQ2 Equitensiometer can be conveniently used at remote sites. It is not harmed by frost, nor by long-term burial.

The EQ2 Equitensiometer's full range is 0 to -1000 kPa but best accuracy is achieved between -100 and -500kPa. This makes it well suited to studies, even in very dry soils. However, the EQ2 Equitensiometer should not be seen as a rapid response, high-accuracy device covering the full range of matric potentials, for which a sensor does not yet exist. The EQ2 Equitensiometer's equilibration time is typically several days and extension tubes can be used to position it at depth.

Figure 3.1 Equitensiometer

3.3 Pavement testing

3.3.1 Loading arrangement

The CAPTIF loading vehicles were again arranged with single tyres inflated to 700kPa without any additional loading plates – thus the applied load was 20kN. Loading of the pavement was on a single wheel path with 100mm of wander. The speed of the vehicles was kept constant at 40km/h during most of the project.

3.3.2 Water application

Water was applied across the track in the same manner as the first test.

3.3.3 Testing

After the early failures in the first test, the second test loading plan was revised and is provided in table 3.4. The moist film thickness was simply a light spray of water on the vehicle tyres to prevent bitumen pick up. The low film thickness would be applied with an 8mm restrictor and the high film thickness with a 16mm restrictor.

Table 3.4 Planned loading sequence

Film thickness	Load cycles			
	100	500	1,000	2,000
Moist	✓	✓	✓	✓
Low film	✓	✓	✓	✓
High film	✓	✓	✓	✓

3.3.4 Failure

The first failure occurred in section A at 736 laps of loading at the manifold. The basecourse started to pothole and eventually failed in shear, as seen in figure 3.1. At this point only 300 laps had been applied with water flowing across the surface in 100 lap increments. The first 200 wet laps had been applied at 20km/h, with 8mm and 16mm restrictors in place. The remaining laps had been applied moist.

Figure 3.2 Test 2 – first failure

The TDR gauges in figure 3.3 show there was no change in moisture content observed in the basecourse in section A during the first failure.

Table 3.5 shows where and when the failures occurred. It lists:

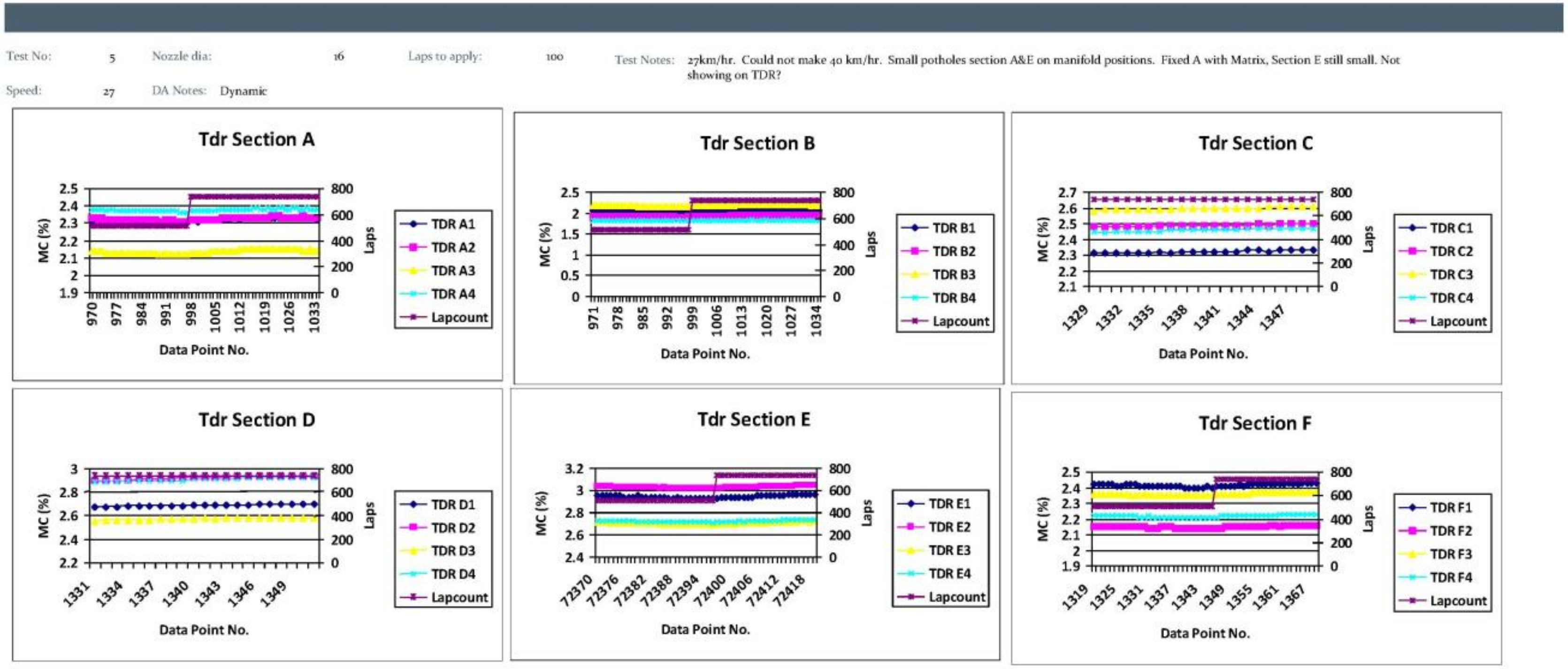
- whether the test was wet or moist (some tests had no water film applied at the manifolds, just a light spray on the tyre, these were classed as moist)
- the failure number – most tests had no failure
- the number of laps to apply in the test
- the total number of loading laps applied since the experiment began
- the stations (chainages) in each section that required repair after each test
- the total number of loading laps that had been applied with a water film at the manifolds
- the incremental number of loading laps that had been applied with a water film at the manifolds.

The right-hand column of table 3.5 gives the dimensions of the nozzle. This is the diameter of the restrictor in the manifold and controls the film thickness.

Table 3.5 shows that the failures continued at a rapid rate; by 5,900 laps every section had experienced failure. Again the M/4 AP40 failed first this time with a racked-in seal, followed by the fines-added M/4 with a racked-in seal, then the M/4 with the two-coat seal and finally the remaining sites all failed by 5,900 laps. However, the AP20 in section C did appear to be damaged only because the vehicle was accidentally parked on it.

Figure 3.4 maps the locations of the failures; it can be seen that M/4 had the most extensive failures, followed by the fines added M/4. The repairs noted in section F without failures were a result of damage to the surface by an excavator while other repairs were being performed.

Figure 3.3 Test 2 – first failure TDR readings



o Tests and Failures 2 subreport

Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
5	23/08/2011	100	27	16	Dynamic	736	3	4	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat

.

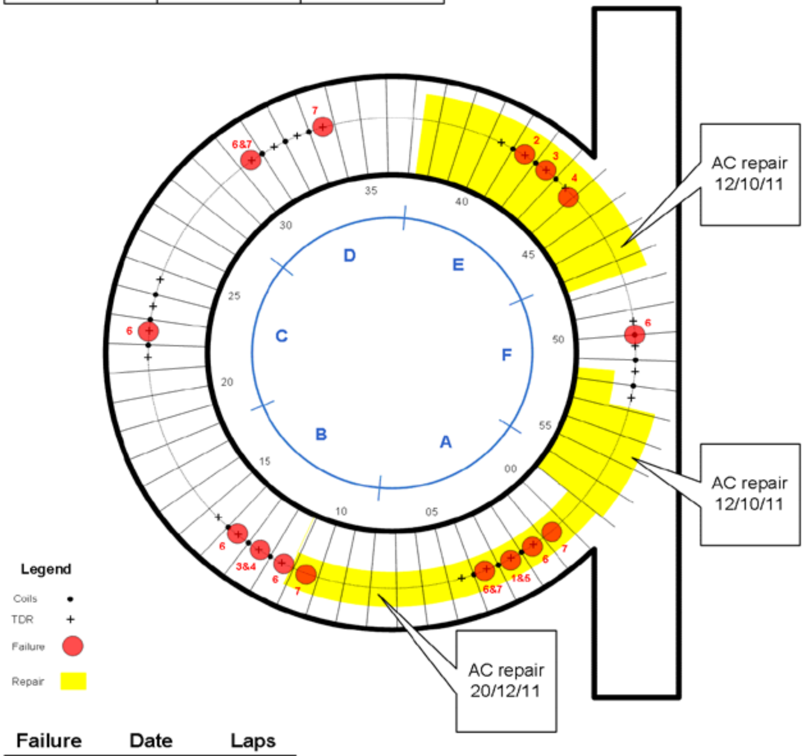
Table 3.5 Loading and failure test 2

Test	Wet /dry	Failure	Laps to apply	Laps	Station repairs by section						Wet laps	Inc laps	Speed	Nozzle
					A	B	C	D	E	F				
0	Moist	0		236										
1	Moist		100	336									20	0
2	Wet		100	436							100	100	20	8
3	Wet		100	536							200	100	20	16
4	Moist		100	636									20	0
5	Wet	1	100	736	3-4						300	100	27	16
6	Moist		100	914									40	0
7	Wet	2	100	1,014					41-42		400	100	40	16
8	Wet		500	1,514									40	0
9	Moist		300	1,814									20	0
10	Wet	3	500	2,606		12-13			42-43		1,192	1,192	40	8
11	Wet	4	500	3,005		12-13			43-44		1,591	399	40	16
12	Wet		1,000	4,005									40	0
13	Moist		100	4,105									20	0
14	Wet	5	1,000	4,871	3-4						2,357	2,357	40	8
15	Wet	6	1,000	5,900	2-3&4-5	11-12&13-14	22-23x	30-31		49-50	3,386	1,029	40	16
16	Wet		2,000	7,900									40	0
17	Wet	7	2,000	10,002	0-1&3-4	10-11		30-31,33-34			5,488	5,488	40	8
18	Wet		2,000	12,002							7,488	2,000	35	16
19	Wet		2,000	14,002			Shear				9,488	2,000	35	16
Surface parameter					Racked	Two	Two	Two	Racked	Racked				
Basecourse parameter					M/4	M/4	AP20	Fines	Fines	AP20				

X - Section C failed when vehicle was parked on it.

Figure 3.4 Test 2 failure map

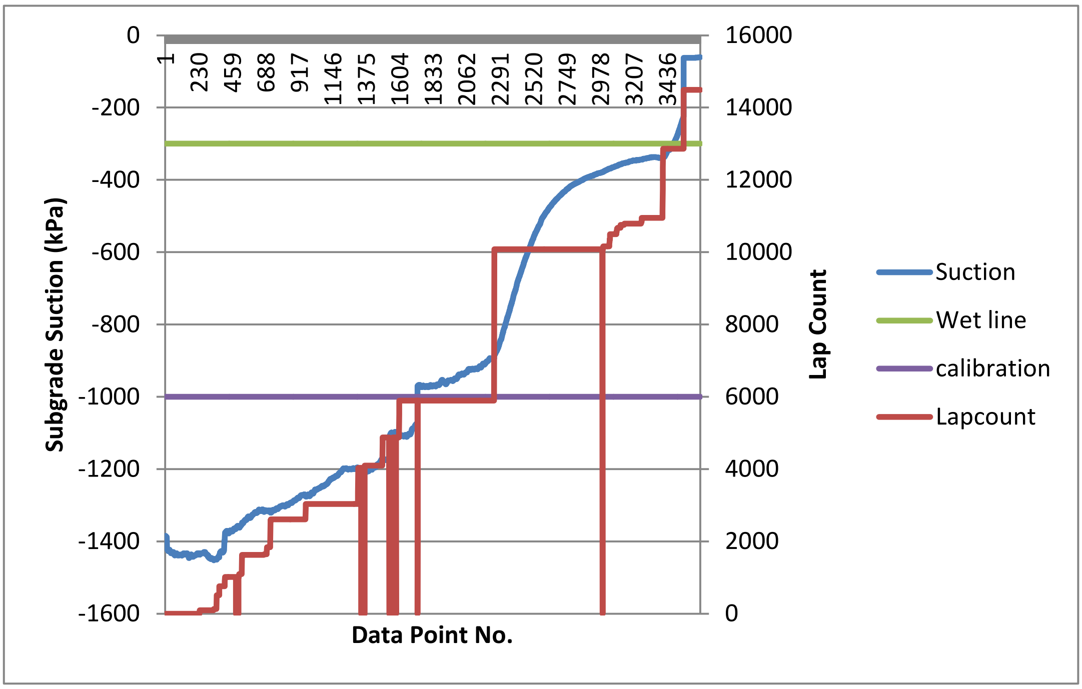
PROJECT: WATER 2		
Segment	**Basecourse**	**Surface**
A	M4 AP40	3/5 Locked-in
B	M4 AP40	3/5 2 Coat
C	DGB AP20	3/5 2 Coat
D	SAP40	3/5 2 Coat
E	SAP40	3/5 Locked-in
F	DGB AP20	3/5 Locked-in



Failure	Date	Laps
1	23/08/2011	736
2	30/08/2011	1014
3	16/09/2011	2606
4	26/09/2011	3005
5	25/10/2011	4871
6	3/11/2011	5900
7	6/12/2011	10002

The results of the EQ2 Equitensiometer at station 5 (figure 3.5) show that the moisture entering the pavement was being sucked towards the subgrade as well as exiting via the subsoil strain system and that potentially explains why the non-wheel path TDRs in test 1 were not reading the moisture changes.

Figure 3.5 EQ2 Equitensiometer at station 5



3.4 Interpretation and discussion of results

As with experiment 1, the construction of the pavement raised two issues. The first was that the basecourse was not constructed to the densities typically seen in the field. However, the densities were typical of previous construction at CAPTIF and previous research suggests that those densities are suitable to simulate field performance. The study was also a comparative study which alleviated the concerns to some extent. Earlier work at CAPTIF studies suggested that chipsealed pavements could be trafficked to over 100,000 vehicle passes before a bleeding failure occurred and this was with a light application of water.

Again the second issue was seal quality which is paramount to a pavement's behaviour. The experimental design was to compare two good quality seals as in experiment 1 but half the track was sealed in such a way as to leave some doubt about its quality. In some ways this was a useful outcome as it expanded the range of parameters tested and allowed investigation of another fault involving a racked-in seal with pin holes.

The failures again occurred consistently at the manifold locations (refer photos in appendix D) confirming that water film thickness was driving the failures. In this experiment, outflows from the subsoil drains had not been reported as there was uncertainty about their accuracy and relevance and a decision was made to base the modelling on the point-specific TDR readings directly under the failure locations.

4 Modelling

An attempt was made to understand the data from the tests by modelling the seepage mechanism and the way this seepage could affect the pore pressure profile within the pavement, in the event that water managed to penetrate the pavement seal. To this end, Opus carried out two separate seepage analyses to investigate the overall drainage performance of the CAPTIF testing setup.

The first analysis assumed that the basecourse and subgrade layers in the pavement were under fully saturated conditions and that steady-state seepage had been reached. The second analysis was a transient seepage analysis where the basecourse layer was assumed to be under unsaturated soil conditions. Both analyses were carried out using the finite-element (FE) software package Seep/W.

These two analyses served to provide an understanding of the drainage mechanism within the pavement structures which complemented a broader study aiming to investigate the influence of waterproofness quality of surface coatings on pavement performance in New Zealand. The outcomes from the seepage analyses and the CAPTIF TDR readings were used to check the consistency of the mathematical model and the experimental results. Additionally, there was a motivation behind the analyses that the model outputs could identify possible trigger event(s) that could be used to signify impending pavement failure.

4.1 Saturated flow model

4.1.1 Assumptions in saturated flow model

It was envisaged in the Seep/W models that water would infiltrate the pavement where the wheel had been travelling but the pavement surface would be impermeable elsewhere. This is based on the assumption that infiltration occurs as a result of small cracks developing in the chipseal due to repeated traffic loading thus compromising the quality of its waterproofness. Alternatively, Patrick (2009) reported on the possibility of water being forced through a pavement seal when it was subjected to a pressure level that was similar to that generated by a rolling tyre. Both of these mechanisms point to the possibility of water ingress near areas where frequent traffic loading is encountered. And these assumptions, while not absolutely correct according to experiment 1 observations, are substantially correct as not all the failures occurred under moist test conditions in experiment 2.

It was assumed that the area of infiltration in the model would be limited to the width of the wheel path plus a 100mm wander measured from the outer edges of the tyre. The infiltration dimensions are based on the drawing details that were provided, which label the width of the wheel on the track as 190cm.

Both the basecourse and subgrade layers were assumed to operate at their saturated state in the model for this part of the study. The coefficient of permeability of the basecourse adopted was 3x10-7 ms-1 which was based on the field permeability data provided (average term field permeability for M4, table 2.10). The permeability of the subgrade was assumed to be 1x10-9 ms-1.

The saturated seepage analysis is a steady-state analysis which means the flow rate and material states do not change over time in the model. The infiltration rate in the model is adjusted until positive pore pressure starts to build up underneath the chipseal surface. As pushing extra water into the pavement through the infiltration boundary beyond this point would result in additional pore pressure beneath the pavement surface, it does not seem likely that the infiltration rate during the CAPTIF testing could have been larger than this value under the assumed seepage conditions. It was not possible to validate this flow rate since data on the actual amount of water that infiltrated into the pavement layers could not be isolated to a single section as water was dragged around the track.

4.1.2 Saturated flow model geometry

The model geometry used in the Seep/W programme is an axisymmetric cross section (ie the cross section is revolving about the y-axis) with a cross-fall of 3% for both the basecourse and subgrade layers. The cross section is shown in figure 4.1 below. The infiltration boundary representing water ingress is input as a unit flux boundary and is shown as a pink line in figure 4.1.

The blue boundary of the cross section is a flow line which has been modelled as a unit flux boundary with a zero flow rate. The red boundary is where the water is collected via a Nexusflo drain and is modelled as a line with a constant pressure head equal to zero.

4.1.3 Saturated flow model outputs and discussions

Figure 4.2 below shows the pore pressure contour outputs from our steady-state, saturated flow Seep/W model. The magnification of the vector arrows shown in the figure is proportional to the velocity of the seepage and can serve as an indicator of the relative flow quantity within the various parts of the pavement. Figure 4.2 shows that much of the seepage due to infiltration was confined to the basecourse layer of the pavement. This was mainly due to the large contrast in the permeability values between the basecourse and subgrade layers. When the infiltration rate was increased to above 4 × 10-8 m3/m2/sec, positive pore pressure would begin to build up underneath the chipseal surface and a small part of the seepage would also be diverted towards the subgrade layer, although the majority of which was still occurring within the basecourse layer. This indicates that beyond this threshold further infiltration could result in the formation of pot holes on the pavement surface (excessive pore pressure causing pavement materials to be pushed out, and combined with nearby traffic load would make the pavement particularly vulnerable).

When reviewing the TDR readings it was noted that there was generally little change in the readings during the CAPTIF tests. The gravimetric water content remained at a level between 2% and 2.5% for much of the tests, although one of the TDR gauges began to show a noticeable increase in reading to above 6% just when the pavement started failing. This reading came from the TDR gauge installed in the sector under test at the time. What was not conclusive from the readings, however, was the direct cause for the increase in water content: whether this was due to seepage gradually finding its way within the pavement from the infiltration source or due to cracks opening up abruptly when the pavement materials failed providing easy seepage conduits in the vicinity of the cracks.

Figure 4.1 Saturated flow model setup in Seep/W

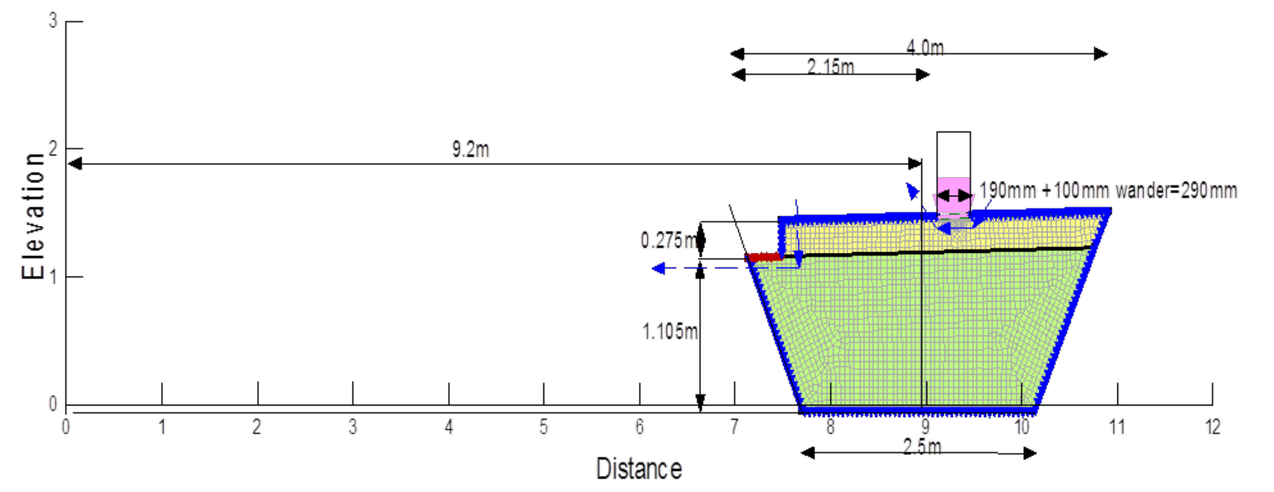
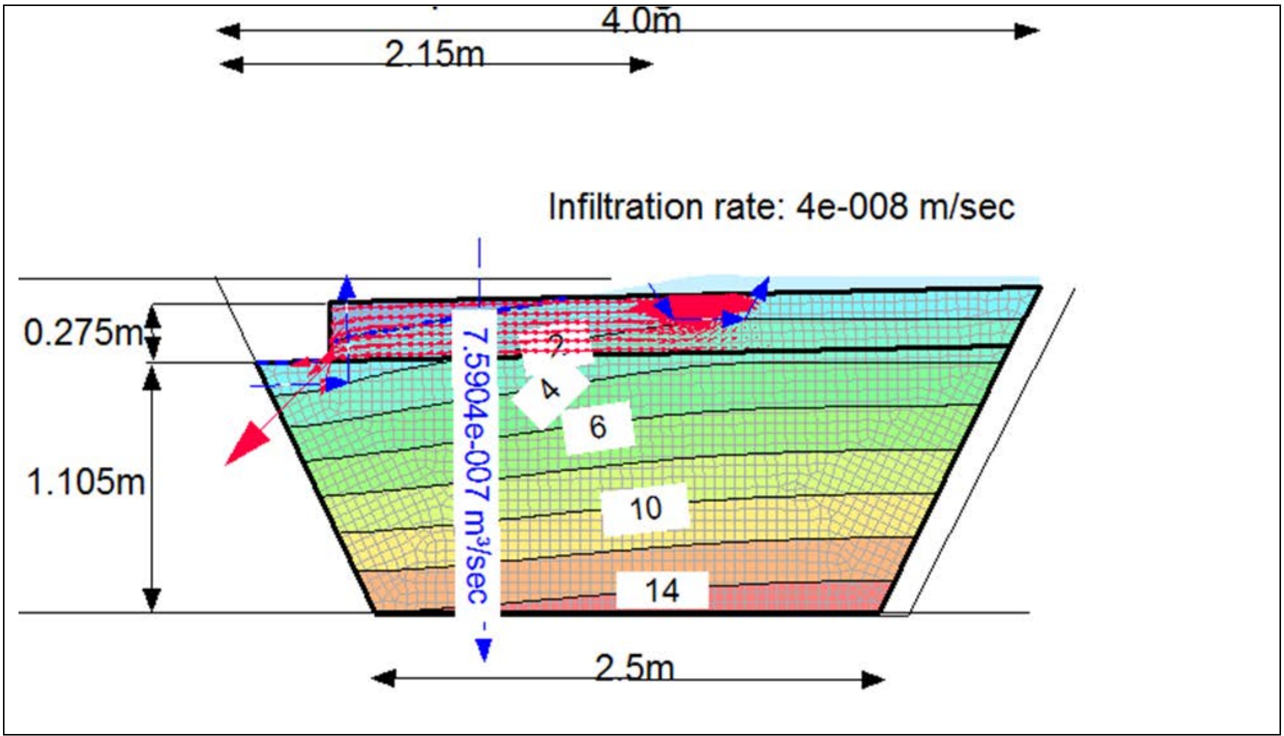


Figure 4.2 Saturated flow Seep/W model outputs



It was noted that the assumption of full saturation in this analysis is far removed from the actual conditions of pavement in reality. Traditional pavement design is based upon the risk-averse approach that construction materials will encounter the worst possible moisture conditions, but pavement design practitioners have long noted that many pavements have performed extremely well despite being composed of materials regarded as substandard when in-situ moisture conditions are less than saturated (Arampamoorthy and Patrick 2010). In fact, a major function of surface coatings is to provide the seal that prevents infiltration from entering the pavement structure. While the saturated seepage analysis has offered us a deeper understanding and prediction of the pavement structure's drainage performance at an ultimate steady state, the model could be further enhanced if unsaturated flow is incorporated in the analysis which better simulates the actual field conditions.

Modelling unsaturated flow requires the basecourse and subgrade layers' soil-water characteristic curves (SWCC) to be included as part of the model inputs. The findings in Arampamoorthy and Patrick (2010), which contains references to SWCCs of other soils derived from research studies overseas, were a good starting point for assuming the SWCCs for this study. The methodologies and findings of the transient, unsaturated seepage analysis are described in the following sections.

4.2 Unsaturated flow model

4.2.1 Overview

Two different models for the unsaturated seepage analysis were produced:

- Model A – The geometry in model A was the same as the one used in the saturated seepage model. Unsaturated soil conditions were assumed for the seepage model. A transient analysis was carried out to study how the pore pressure changed over time as a constant flow of water infiltrated the pavement. As in the saturated seepage model, water was able to infiltrate the pavement where the wheel had been travelling but elsewhere the pavement surface was impermeable.
- Model B – In model B the infiltration boundary in model A was replaced by a flow line. This resulted in the model geometry being almost entirely encapsulated within an impermeable boundary, save for a small segment towards the inner part of the circular track where the exit drainage operated in the model. A small initial value of pore pressure (10kPa) was assumed in a small region underneath the previous infiltration boundary and a transient, unsaturated seepage analysis was carried out to investigate how this initial pore pressure would dissipate to other parts of the pavement over time.

4.2.2 Further assumptions on soil water characteristic curve and permeability of unsaturated soil

In general, the permeability of a porous material decreases as the matric suction in the soil increases. Careful experimental work is required to establish the form of this relationship accurately but it is possible for Seep/W to make an estimate if the SWCC of the material is provided as a model input. The estimation method chosen for the unsaturated seepage analysis is from Fredlund and Xing (1994).

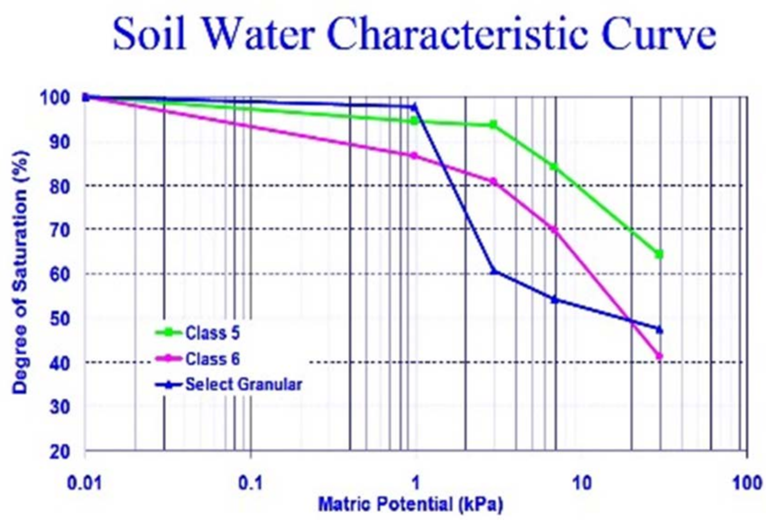
The SWCC is a graphical representation of the water retention characteristics of a particular soil. It relates the water content of the soil to its matric suction, which is the part of the pore water suction derived from the concavity of the menisci. SWCC can be established from pressure plate testing in the laboratory but great care is required during the test to achieve quality results, and depending on the suction range of interest the test can be time consuming to complete. A research report by Arampamoorthy and Patrick (2010) contains references to SWCC profiles derived from the work of Roberson (2001) and makes the suggestion that the curve designated as class 6 in figure 4.3 may be used to approximate the SWCC for M4 material in New Zealand, given the similarity between the particle gradation of the two materials. We followed the report's suggestion and used figure 4.3 as the SWCC reference for our Seep/W analysis.

The SWCC given in figure 4.3 has an ordinate representing the degree of saturation. The SWCC input for Seep/W, however, is in the form of volumetric water content vs matric suction. To convert figure 4.3 for Seep/W input we needed to change the values on the y-axis to the soil's volumetric water content. The degree of saturation is related to the volumetric water content via the following formula:

$$\frac{V_w}{V} = S_r\left(1 - \frac{\rho_d}{\rho_s}\right) \qquad \text{(Equation 4.1)}$$

where V_w/V is the volumetric water content, S_r is the degree of saturation, ρ_d and ρ_s are the dry and solid densities respectively. For the analysis, an assumed value of 1,400kg/m3 and 2,650kg/m3 for ρ_d and ρ_s respectively has been used.

Figure 4.3 Soil water characteristic curve as derived by Roberson (2001)



4.2.3 Values of permeability at saturated state used for the unsaturated flow model

The relationship between permeability and the SWCC described above explains how the permeability of the material decreases as it becomes unsaturated but the assumed graph of permeability vs matric suction still needs to be based on the material's permeability at its saturated state. For the unsaturated flow part of this study we wished to investigate how the different permeability of the various basecourse materials used in the CAPTIF testing could have influenced the model outputs. The permeability values of the basecourse layer in the Seep/W model were changed systematically as part of the investigation.

The permeability used in saturated modelling of the basecourse (3x10-7 ms-1) was based on the 'average term' permeability reported for M4 in table 2.10.

As we can see from table 2.10, there was little difference between the field permeability of the various basecourse materials used in the CAPTIF testing but there was a larger difference between the short-term, average and long-term values. These three values for the M4 basecourse were selected for the Seep/W unsaturated flow model with the short-term value (7.9x10-7) being referenced as the base value in the following section.

4.2.4 Model A

4.2.4.1 Model descriptions

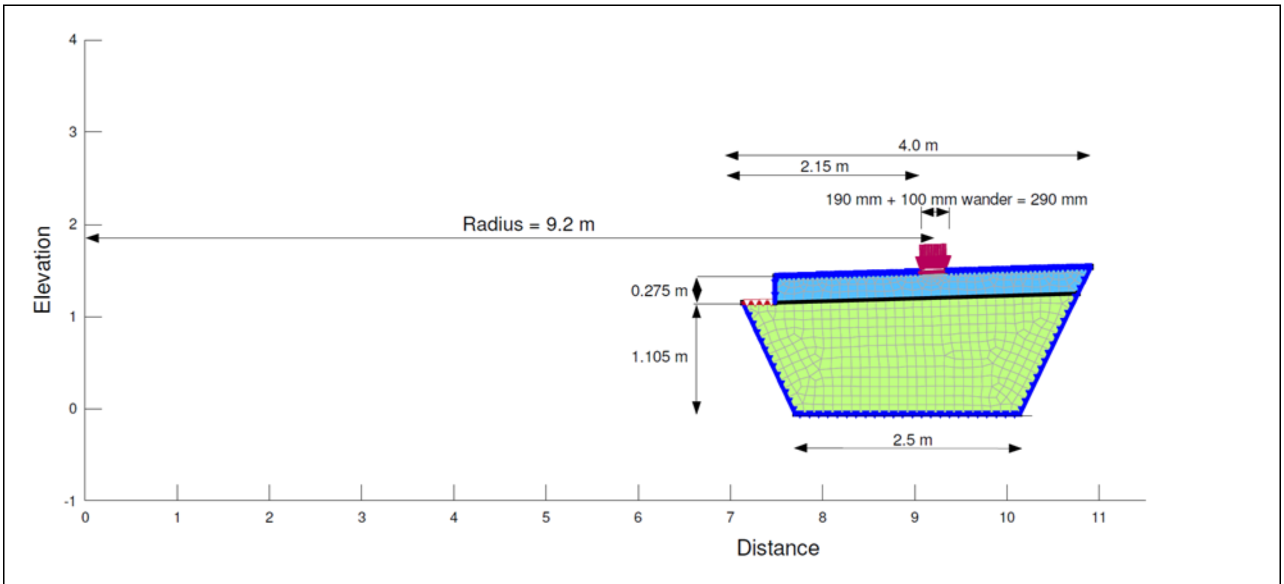
The geometry of model A is illustrated in figure 4.4 below. In SEEP/W, the model is set as axisymmetric and is essentially the same as the saturated seepage model other than the changes to the permeability values used as described above.

As with the saturated seepage case, the red/yellow boundary line in figure 4.4 represents a Nexusflo drain where exit drainage was facilitated in the CAPTIF testing. In the previous model this exit drainage was modelled as a line of zero pressure head which is appropriate since fully saturated conditions were assumed for that model. For the unsaturated case, however, this was no longer suitable, as a line of zero pressure head would present a higher total head than the unsaturated soil in its vicinity (pore water in unsaturated soil is in suction hence a negative pressure head) and would become a water source. This obviously contradicted with reality as water was only allowed to exit in these drainage areas. The technique we followed to model such exit drainage was to set the boundary with a unit flux of zero while selecting the 'Potential seepage face review' checkbox. This would prevent the drainage from acting as a water source while allowing water to exit the model when the value of pore pressure became positive.

The model geometry was divided into two regions with the basecourse layer overlaying the subgrade layer on the bottom as shown in figure 4.4. The subgrade was assumed to be in a saturated condition with an initial pore suction value (20kPa) similar to that of the basecourse to avoid an abrupt change in total head at the boundary which could complicate the initial drainage behaviour within the pavement during the early part of the transient analysis, and this certainly appeared to be correct towards end of the experiments. The initial suction value we assumed for the basecourse was 30kPa.

As with the saturated seepage analysis case we did not have any accurate information on the amount of water that actually infiltrated the pavement so the infiltration rate in Seep/W was revised until the pore pressure values given by the model became reasonable. Since model A was a transient analysis, the pore pressure values in the model changed over time so the adjustment criterion for infiltration rate was set as the value that would give a small pore pressure value close to the pavement surface at eight hours after water ingress had initially commenced. Using this adjustment criterion we found the infiltration rate to be 1 × 10-6 m3/m2/sec for the short-term permeability of M4 (7.9x10-7 ms-1). This was higher than the corresponding value for the saturated case but not unexpected since the materials in this model were unsaturated (hence under vastly different seepage conditions) and adsorption took place in addition to water seepage when infiltration occurred at the pavement surface.

Figure 4.4 Model A geometry



The same infiltration rate of 1 × 10-6 m3/m2/sec was then applied to the average and long-term basecourse permeability cases to study the effect of the basecourse permeability on the overall drainage performance of the pavement.

As noted previously, two different types of surfacings were used during each CAPTIF test. We assumed the effect of the different surfacings on water ingress was to change the infiltration rate into the pavement. To model this, we re-ran the Seep/W models with two additional infiltration rates – two thirds and one third of the base value of 1 × 10-6 m3/m2/sec – to study how the different surfacings could potentially affect the model outputs.

As noted in the Seep/W user manual, finding an appropriate time step size in a transient analysis is often a matter of trial and error. There are many theoretical factors that affect the ideal time step size such as the number and shape of elements in the FE mesh, but generally speaking a large rate of change would require a smaller step size at the expense of computation time, although it is possible for the step size to become so small it compromises the quality of the model outputs. For the transient analysis in model A, a duration of eight hours (28,800 seconds) was chosen and a constant step size was adopted at 24 seconds (ie Seep/W treats the events occurring within the 24-second increment as a mini-steady-state).

4.2.4.2 Results and discussion

The model results are presented in the graphs below representing the pore pressure (figure 4.5) and volumetric water content (figure 4.6) at a chosen point of interest which is 50mm below the surface in the middle of the pavement. In addition, the pore pressure contours at two-hour intervals for the short term permeability case are shown in figure 4.7. Only the top part of the pavement cross section is shown in figure 4.7. This is because, as was the case with the saturated seepage model, the model shows that many of the changes occurring were mostly limited to areas close to the surface and did not extend to the subgrade layer underneath. Also, the pattern of contours for the average and long-term permeability cases is very similar to that shown in figure 4.7 and has not been included here for brevity.

Figure 4.5 Pore water pressure over time at chosen point of interest in model A

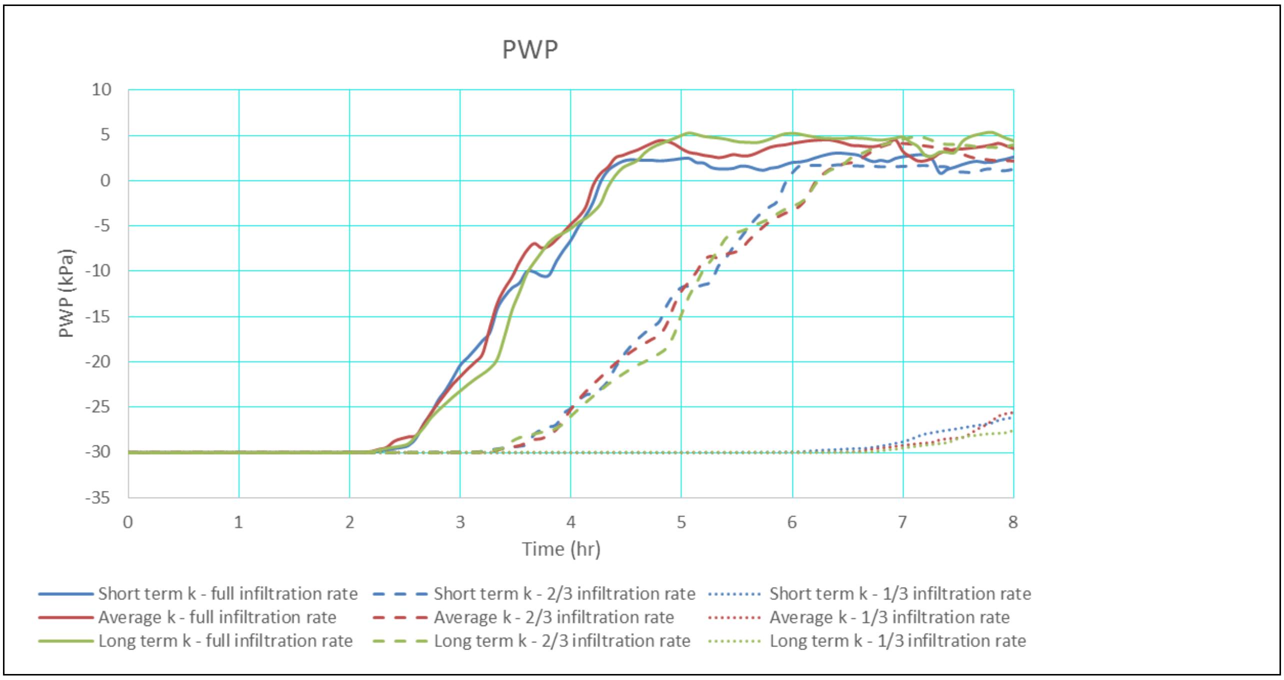
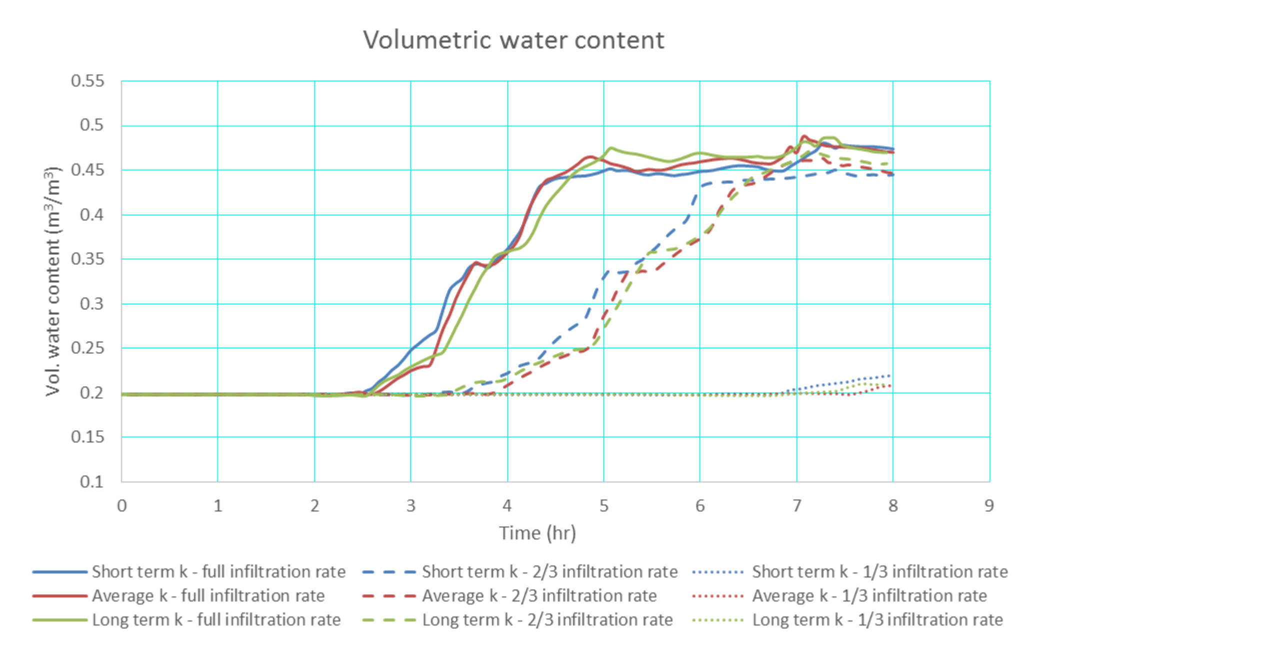


Figure 4.6 Volumetric water content over time at chosen point of interest in model A



The values of volumetric water content shown in figure 4.6 are indicative only and may not equate accurately to their gravimetric counterparts recorded by the TDR gauges during the CAPTIF testing, due to the assumptions made regarding the SWCC and initial dry density of the basecourse material. Nevertheless, the figure shows that the volumetric water content increased by about 2.3 times from its initial value towards the end of the modelling duration, which is comparable to the increase recorded in the CAPTIF TDR gauges not long after pavement failure was noted to have commenced.

As can be seen clearly from figures 4.5 and 4.8, changing the value of permeability at the saturated state produced little effect on the model outputs within the range of values studied. The effect of using different surfacings, however, could be potentially more significant. The two figures show that changes in pore water pressure and volumetric water content close to the pavement surface were relatively sensitive to the infiltration rate. Hence if a particular surfacing was able to significantly reduce the rate of water ingress it could increase the amount of time it took for pore pressure to build up close to the pavement surface and present an effective deterrence to pavement damage.

In figure 4.7, the area marked in red or pink signifies a region where the pore pressure value is zero or above. The figure suggests, based on the seepage conditions we assumed, that even eight hours after initial infiltration had commenced, the area where positive pore pressure had built up was still confined close to the infiltration source and was only spreading to the other parts of the pavement very slowly. This indicates that the basecourse layer’s drainage was not effective in carrying the water ingress away from its source and led it towards the exit next to the kerb. This could be explained by the dependence of the basecourse’s permeability on matric suction. As noted in section 4.2, the permeability of the basecourse decreased as the value of matric suction increased. According to the model outputs, it seems that the part of the basecourse closest to the surface would begin to absorb the water ingress and experience an initial decrease in matric suction in the model; however, for the part of the basecourse outside the absorption region the matric suction remained at a level that would keep the permeability relatively low. Although the absorption area would begin to slowly increase over time, the rate of this increase was ultimately not sufficient to prevent ponding (build-up of positive pore pressure) from occurring within the absorption region. So while the model showed there might still be a large area within the pavement cross section with a negative value of pore pressure, the part closest to the source of water ingress would start to build up positive pore pressure over time (assuming the infiltration rate into the pavement would remain constant) instead of dissipating this pore pressure build-up to the rest of the pavement. In short, it seems possible that the decrease in permeability due to the initial matric suction in the pavement prevented the basecourse from facilitating effective drainage within the pavement and caused localised pore pressure build-up.

The argument above is consistent with the low value of permeability estimated in Seep/W based on the initial values of matric suction we assumed. According to the permeability vs matric suction estimate in the current model, the permeability of the initial unsaturated part of the basecourse layer was in the order of 10–11 ms-1 or lower. This level is considered to be practically impermeable, although in our situation the material's water content would start to increase as soon as adsorption of the water ingress occurred and the permeability would increase accordingly; nevertheless, our FE model suggests that the rate of these changes took place in such a way that the very low permeability of the unsaturated materials surrounding the infiltration region still presented a significant obstacle which prevented the pavement drainage from performing effectively.

4.2.5 Model B

4.2.5.1 Model descriptions

As described above there was no major difference between the geometry of models A and B except for the replacement of the unit flux boundary on the pavement surface by a flow line. The initial value of positive pore pressure close to the pavement surface was chosen as 10kPa, where the initial suction of the surrounding basecourse material was 30kPa. The positive pore pressure region (shown in figure 4.8) had the same width as that of the infiltration boundary in model A and extended to 120mm depth from the surface. Judging from the model outputs in model A this depth was greater than what would likely result from water ingress on the surface, although the greater depth was chosen for ease of output presentation while not compromising the overall conclusion of the model.

There were two stages of time stepping in model B. The first stage, which lasted five minutes, contained 1,200 time steps. The second stage had 1,000 time steps and covered the model duration beyond the initial five-minute period through to 30 days. In both stages the increment of time step increased exponentially. These time step arrangements accounted for the rapid rate of change during the early parts of the transient analysis which would gradually slow down over time.

Other model inputs in model B were the same as in model A.

4.2.5.2 Results and discussions

The pore pressure and volumetric water content over time for model B at the same chosen point of interest are shown in figures 4.9 and 4.10. The figures show that aside from an initial drop in the pressure (much like the sudden decrease in excess pore pressure at time equals zero close to the drainage surface in a one-dimensional consolidation scenario) the rate of decrease in the pore pressure was very slow and some of the initial pore pressure took a long time to dissipate (note the time axis was in logarithmic scale). The rate of dissipation was such that part of the initial pore pressure had essentially been locked in. As an illustration the matric suction assumed in the basecourse layer outside the positive pore pressure region was 30kPa which gave an initial pressure difference of 40kPa (10 - (-30) = 40) within the basecourse layer. According to the model outputs, about half of this 40kPa difference was still locked in after 30 days. Most of the equilibration occurred within the first two minutes but the rate slowed down markedly when the material went from pressure to suction, which probably caused the permeability to decrease significantly.

Compared with figures 4.5 and 4.6, figures 4.9 and 4.10 show that changing the permeability value in the basecourse produces slightly more noticeable difference to the plots, with a larger rate of change to both the pore pressure and water content noted for the larger permeability values, although we should note that the difference in values as shown in the two figures is still relatively small.

Figure 4.7 Pore pressure contours at two-hour intervals in model A for short-term permeability

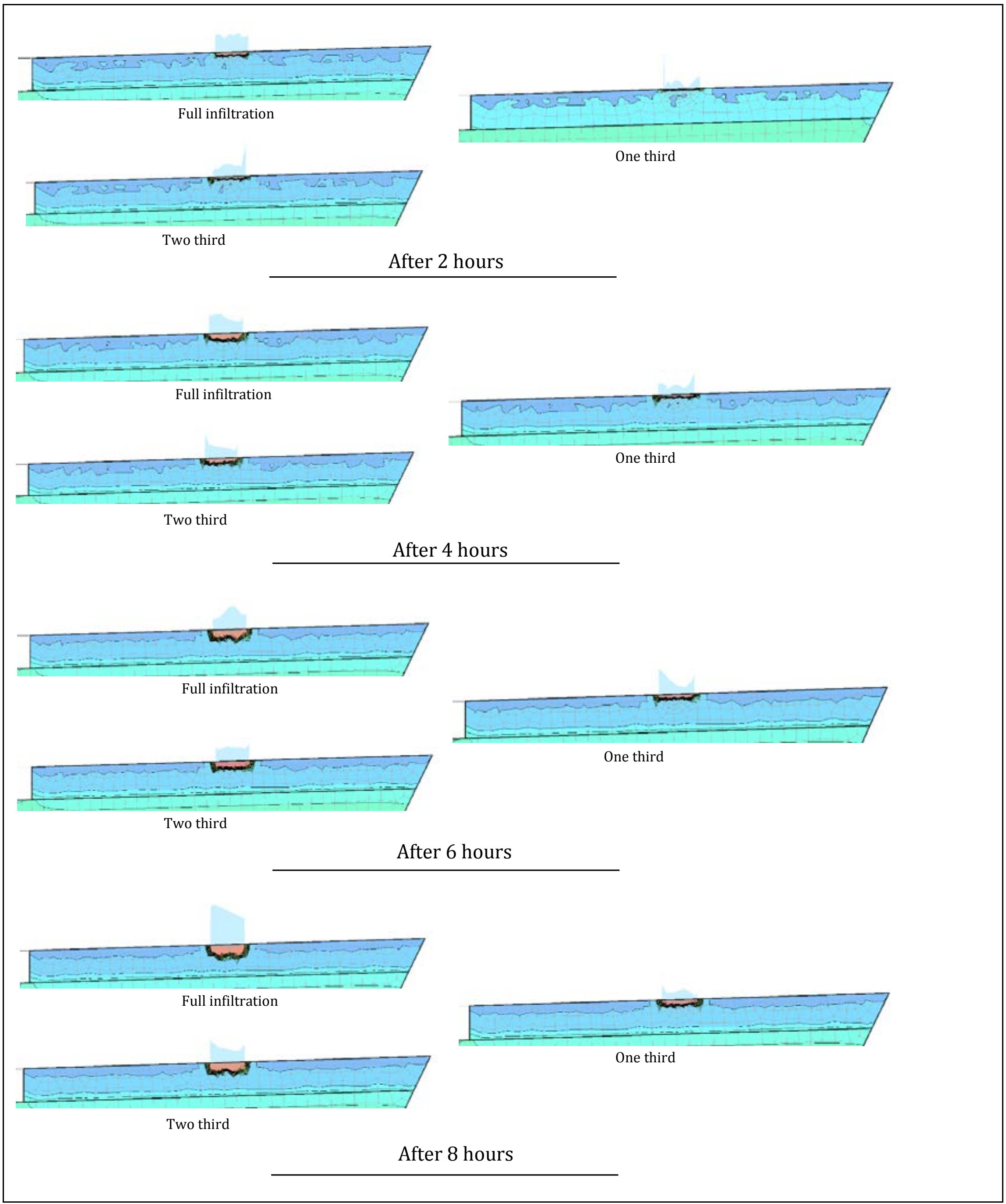


Figure 4.8 Area of positive pore pressure region in model B

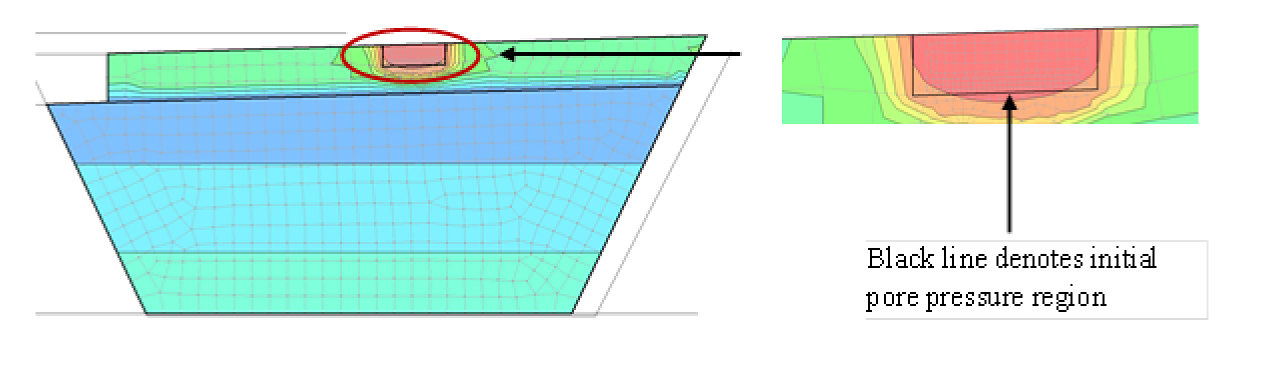
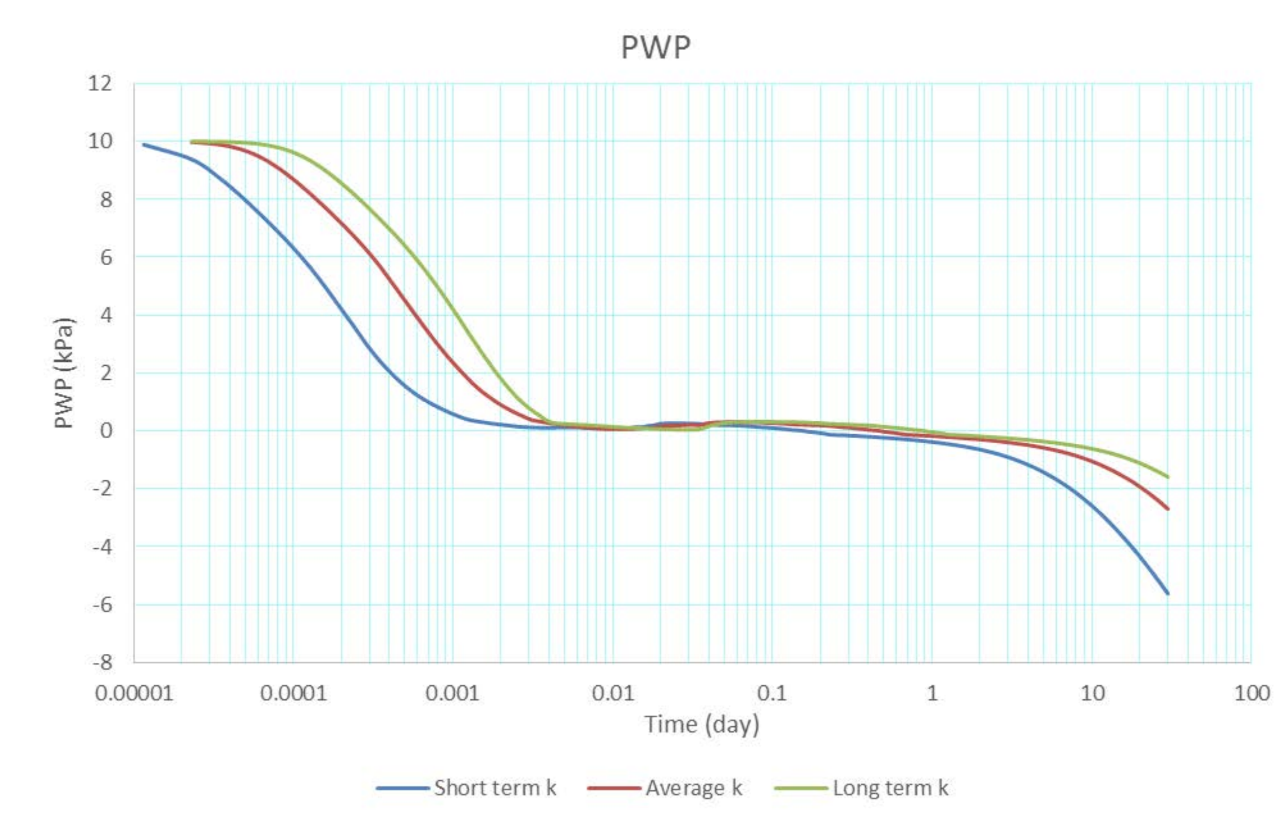
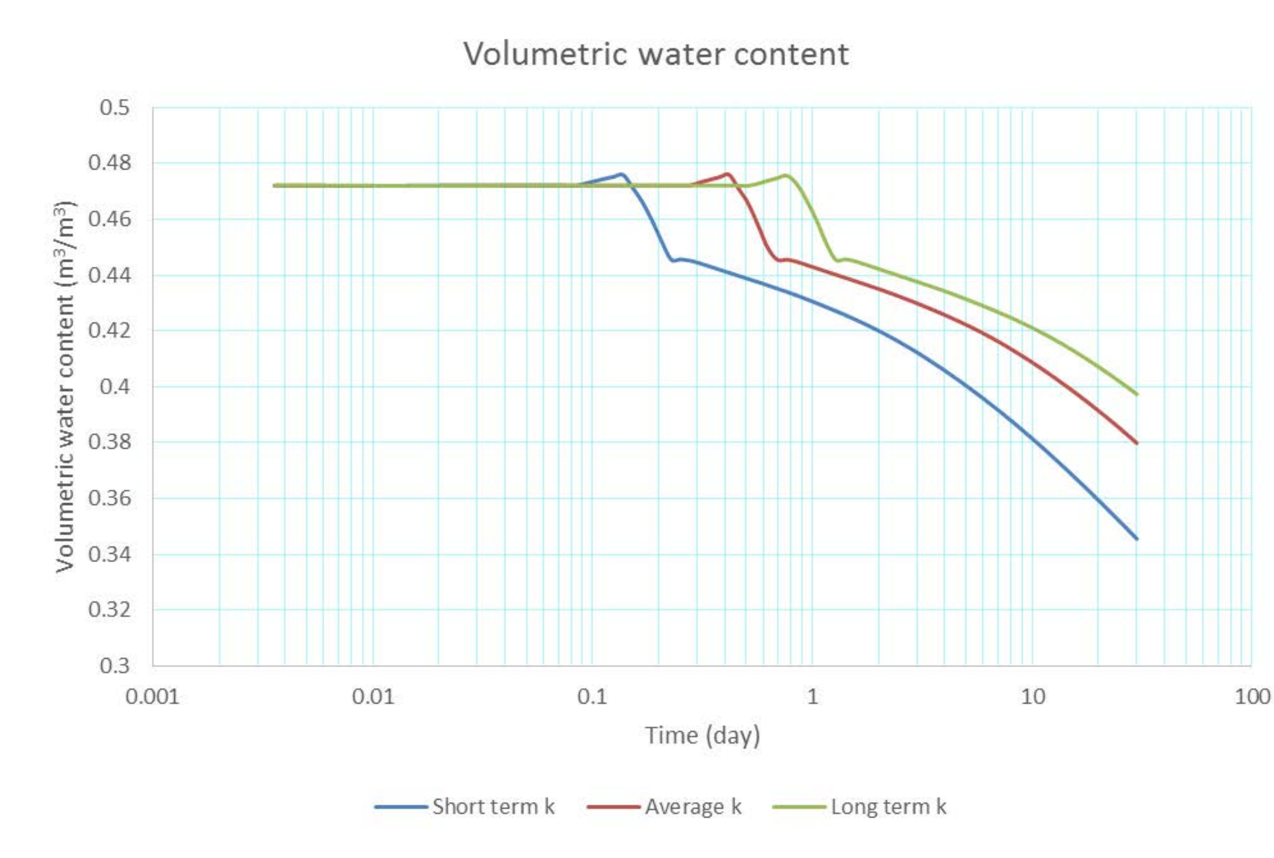


Figure 4.9 Pore water pressure at chosen point of interest in model B



The pore pressure contours followed a similar pattern to that of model A, where little change occurred in the overall pore pressure/suction profile of the pavement structure beyond the initial 10kPa pore pressure region. The initial pore pressure in the pavement again appeared to be trapped by the surrounding unsaturated material due to the low permeability. The pore pressure contour plots are not shown here.

Figure 4.10 Volumetric water content over time at chosen point of interest in model B



4.3 Modelling conclusions

The seepage analyses carried out in this study showed that should water ingress occur through the pavement seal, much of the ensuing water seepage would be confined within the basecourse layer and not extend to the subgrade. However this was not observed in the CAPTIF experiments. Figure 3.5 suggests that water was drawn into the subgrade via the suction in the clay suggesting the model was only broadly calibrated. The unsaturated seepage analysis in particular showed that the existence of matric suction in the basecourse could hamper its drainage performance due to the assumed inverse relationship between matric suction and permeability in unsaturated soil, and this could lead to the local build-up of pore pressure close to the ingress source. The increase in pore pressure could in turn lead to a decrease in material strength, making these areas more susceptible to failure when the pavement was subjected to heavy traffic loading.

With regard to the effect of basecourse permeability on the model outputs, our model showed that the influence from changing the permeability value did not seem to be readily apparent within the range of values studied in table 1. The effect of using a different type of surface on the other hand was potentially much more significant, since our models showed that altering the infiltration rate resulted in very noticeable changes to the outputs.

Although the outputs from the Seep/W models were not an exact quantitative match of the TDR readings due to a lack of accurate knowledge on the dry density and SWCC of the basecourse materials used in the CAPTIF testing, the results were by and large consistent with the general trend shown in the experimental data. The TDR readings were generally constant before the initiation of pavement failure, and according to our models changes in the pore pressure profile within the pavement were generally limited to the area in the vicinity of the infiltration source which was consistent with this observation. More importantly, our model suggested that a possible explanation for this behaviour could be due to the low permeability of the unsaturated basecourse materials.

The model also reported that an increase in volumetric water content of the basecourse from infiltration adsorption was of a similar order of magnitude to the TDR data. Noting the complexity of unsaturated seepage modelling and that the outputs were often highly sensitive to the input parameters (both estimates on the SWCC and permeability vs matric suction relationship were plotted against a horizontal axis that had a logarithmic scale, resulting in errors being magnified exponentially), we were quite encouraged by the quality of the model outputs.

Unfortunately, it was not possible to identify any trigger event from the model outputs that could be used to presage the initiation of pavement failure. Note that the model outputs often pointed to the pore pressure changing abruptly from negative to positive in areas close to the infiltration source after a certain period of time; however, it could not be concluded that such changes were necessarily related to the formation of potholes or rutting without an in-depth mechanistic analysis which would also include the effect of traffic loadings on the stress-strain behaviour within the pavement. The modelling of such mechanical behaviour is beyond the scope of a standalone seepage analysis such as carried out here, although commercial software packages exist which allow both the seepage and mechanical FE modellings to be combined into an integrated analysis. There is potential within these models to investigate the complex interaction between seepage and traffic loadings inside the pavement structure but at this stage with the RLT models not being able to rank the materials as observed at CAPTIF and permeability not being a great driver it is difficult to see how tying a drainage and structural model together would assist. The modelling seems to suggest that permeability (at least the laboratory permeability) is a driver but in an inverse fashion to that expected, as it perhaps simply lowers the infiltration rate.

5 Conclusions and recommendations

5.1 Conclusions

The hypothesis for the research was that the risk of premature pavement failure is a function of the amount of water entering the pavement and the reaction of the pavement materials to that water.

The amount of water entering the pavement through the sealed surface would be determined by:

- the waterfilm thickness around and above the surfacing aggregate particles
- the permeability of the seal and the basecourse
- the frequency and intensity of heavy loading.

The permeability of chipseals would be a function of the chipseal design, eg single-coat first-coat v two-coat first-coat. Rainfall intensity, drainage path length and degree of rutting control the waterfilm thickness. The frequency of heavy loading is determined by the volume of heavy commercial traffic.

How a pavement reacts to the amount water present is a function of the moisture sensitivity of the basecourse. The moisture sensitivity is considered to be related to the quantity and quality of the finer fractions of the basecourse.

The basic laboratory tests and RLT tests suggested that the three different basecourse materials used at CAPTIF had significantly different behaviour under saturated conditions. Geological testing suggested that the aggregates used were for all practical purposes identical. The permeability tests suggested there was a significant range of permeabilities in the laboratory prepared samples – the permeability did not correlate with the RLT results. The field permeability tests suggested that (at low heads) after surface preparation for sealing the permeabilities were nearly identical.

Before deriving a direct use of the outcomes, it also needs to be considered that the CAPTIF testing is carried out at an extremely high frequency with the vehicles travelling at 11m/s and a load applied roughly every three seconds. To reduce the intensity of loading, the vehicles were loaded as lightly as possible (0.3 ESA/vehicle). This reduction was made as an instinctive response to the rapid nature of the loading; in theory the tyre pressure rather than the load should drive the water pressure near the surface. Reducing the load would simply reduce the area under high water pressure. The Transport Agency design guidance suggests the 'average' truck has 2.4 heavy axle groups loaded to 0.6 ESA per heavy axle group. To achieve a load pulse on average every three seconds would require a truck fleet 3*2.4=7.2 seconds apart. This equates to eight trucks a minute, which would in turn be 500 an hour and thus 12,000 a day. Assuming the percentage of trucks was 10% that would be an annual average daily traffic of 120,000 in one direction. Allowing for the lighter load and slower speeds at CAPTIF could be considered a way of compensating for the high frequency – but with the results to hand that would seem a little dubious. A better approach may have been to apply small groups of non-reduced loads with rest periods in between.

The testing at CAPTIF showed that it was relatively easy for pavements with high water film thicknesses and rapid loading to fail. Previous tests at CAPTIF in the mass limits projects had shown that chipseals could be trafficked to over 100,000 cycles before a bleeding failure occurred (bitumen would pick up on the tyres as the texture lowered) if the surface water film thickness was kept low. During the first test, the first 1,000 load cycles were applied with only enough water on the surface to prevent bitumen picking up on the tyres. This was done by spraying a light application of water on the tyres. As soon at the film thickness was increased by using the manifold system and a 9mm restrictor nozzle, the first failure in the unprimed two-coat chipseal occurred after 132 wet load cycles in the M/4 basecourse. This was attributed to the poor first coat of the unprimed two-coat seal. The second failure occurred after 347 wet laps in the fines added basecourse and the dense grade AP20 failed at 921 wet laps. The primed two-coat sections failed once the nozzles were changed to 12mm to increase the film thickness. The M/4 failed first at 1,190 wet laps followed by the fines added section at 2,447 wet laps and finally the AP20 failed when the nozzle was increased to 18mm and a total of 3,863 wet laps were applied.

In the second test, surfaced by an unprimed two-coat and an unprimed racked-in seal, the first failure occurred in the racked-in surfaced M/4 after 300 wet laps under a 16mm nozzle at 27km/h. The loads were applied 100 laps at a time. One cycle of 100 laps each under 0, 8 and 16mm nozzles was applied at 20km/h. Only minor problems were observed with the sealing of this surface. The next failure occurred at 400 wet laps in the racked-in fines-added section under the 16mm nozzle at 40km/h. After this the loading intervals were increased to 500 laps. The two coat M/4 failed at 1,192 wet laps in a 500 lap cycle of 8mm nozzle watering. The remaining section of racked-in fines added and both AP20 sections failed at 3,386 wet laps during a 1,000 lap loading interval using a 16mm nozzle. However, the two-coat seal in section C appeared to have been damaged when the vehicle was parked on it. A repeat of that test required an additional 6,000 wet laps to fail the pavement. A review of all the tests showed that the second failure on each section generally took much longer than the first, perhaps suggesting that some conditioning occurred under traffic.

The hypothesis that how a pavement reacts to the amount of water present is a function of the moisture sensitivity appeared to be disproved – the conventional testing of grading, fines quality, permeability and RLT laboratory testing all suggested that the M/4 should have performed the best. Yet in all cases it was the worst performer. The RLT testing suggested that the fines-added basecourse would be the worst performer, yet it was consistently the middle performer. And finally, the only test that ranked the materials was the laboratory permeability; however, it was in the reverse order to what had been expected. The lowest permeability performed the best.

The behaviour of the two-coat seal in the second experiment suggested that priming only allowed a better seal to be created; it did not add to the waterproofness of a well-laid seal. The racked-in seal appeared to be less waterproof than the two-coat seal – but pin-holes had formed in the racked-in seal which may have contributed to its performance. It certainly did not provide a better performance as had been thought likely.

The project aimed to create a number of outputs. These are listed below together with the project findings against each of them:

- An understanding of the effects of changing the permeability of the surface, waterfilm thickness, basecourse moisture sensitivity, and heavy traffic volumes on pavement performance was desired. This has certainly been advanced – surface permeability appears to be a function of construction quality and basecourse permeability. Waterfilm thickness is crucial but moisture sensitivity would appear (as defined by the RLT test) to be less of an issue. High heavy traffic volumes running on a sufficient water film thickness will drive failure.
- A determination of when surfacing permeability becomes an issue. CAPTIF results suggest that a poorly constructed seal can fail very rapidly, or at least between 1/4 and 1/10 of the load cycles a well-sealed pavement will fail at. Defining when exactly surfacing permeability will become an issue is clouded by the loading frequency of the tests and what appears to be some sort of conditioning effect prior to wet loading.
- A validated method for assessing the moisture sensitivity of basecourse. Surprisingly, first-coat seal failure appeared to be a function of permeability. This went against the traditional concept that lower permeability would be better at guarding against a first-coat seal failure.

- A validated hydraulic model for chipseals, which would also lead to better environmental contaminant transport modelling. It would appear that complex unsaturated modelling is the only way to provide sensible hydraulic models for pavements.
- Improved pavement deterioration models to cater for surfacing and moisture variations. Applying a prime coat would reduce the probability of failure. But assuming the surface survives the defects liability period, the surfacing and moisture variations in the pavement are not likely to change noticeably.
- A validated finite element pavement design model based on RLT testing capable of considering moisture conditions; however, the rapid changes in behaviour appeared to be driven by permeability.

The research produced some surprising results in that the traditional M/4 basecourse was the worst performer in all cases. However, it must be borne in mind that this research applied only to first-coat seals, with high water film thicknesses at very high traffic volume.

Moving away from the traditional M/4 envelope for basecourse production to denser gradations used in Australia has considerable construction benefits in that these are easier to lay. But denser gradations are harder to dry back before sealing and this trade-off needs to be considered before implementing wide use of denser gradations. The additional long-term benefits of denser gradations are that they should also be more rut resistant but that comes with the price that they may also draw more water in from the edges of the pavement in the long term. Suffice to say if this path is followed, a number of field trials will be required to validate the long-term implications of this project.

5.2 Recommendations

The recommendations resulting from the research are to:

- prime all new pavements before first-coat sealing to reduce the risk of early failure
- condition new seals before they are loaded in wet conditions, ie avoid the practice of sealing just before it rains as this is likely to increase the probability of failure
- avoid geometric designs that generate large water film thicknesses
- not delay in placing second-coat seals on high-volume roads
- use unsaturated hydraulic models for modelling moisture movement in pavements
- review first-coat seal failures for the factors observed in this report
- undertake field trials of lower permeability M/4 alternatives.

5.3 Further research

The implications of this research are so far reaching for New Zealand's road building community it is suggested that key sections of the work be repeated, as it very important to confirm (or otherwise) this work. Apart from grading, it opens the door a crack for considering marginal aggregates.

Any further work should:

- prior to sealing, complete in situ permeability tests on the base (on the track)
- after sealing (and confirming that the seal has worked well) repeat the permeability tests

- recognise the transient dynamic nature of applied load and response. Look at some one-dimensional modelling – applied mathematics rather than FE programmes
- retain the loads and speeds used but provide rest periods between groups of loads to better simulate lower loading frequencies
- in addition to the measurements in these experiments, measure deflections and/or elastic strains in real time. The response may be slower with the less permeable base and conversely with traditional M/4.

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6 References

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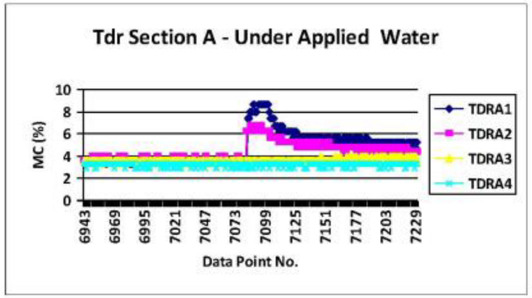
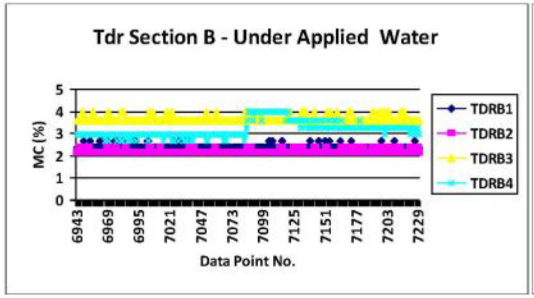
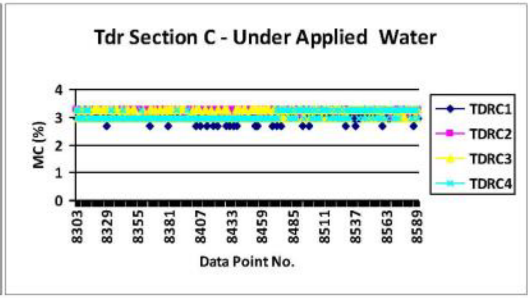
Appendix A: Test 1 TDR readings

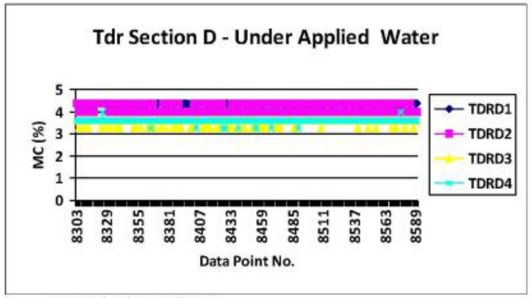
Test Dates2

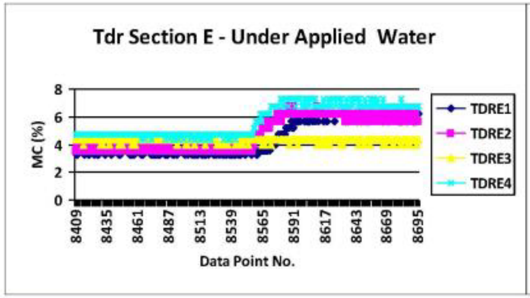
1 24/02/2010 3/03/2010 8 DA Notes: 1st Prelim Test

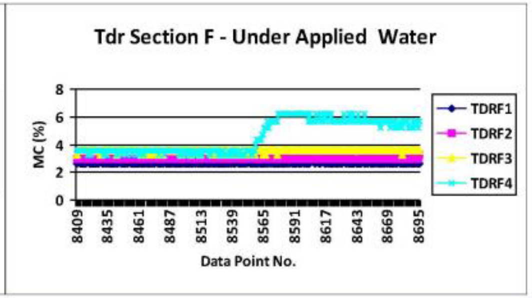












o Tests and Failures 1 subreport

Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
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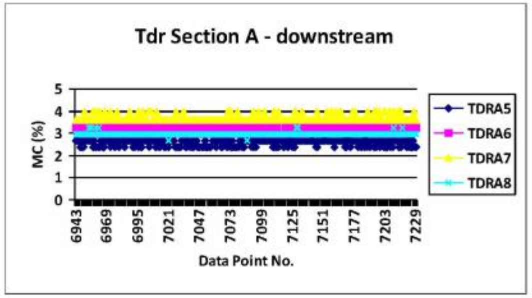
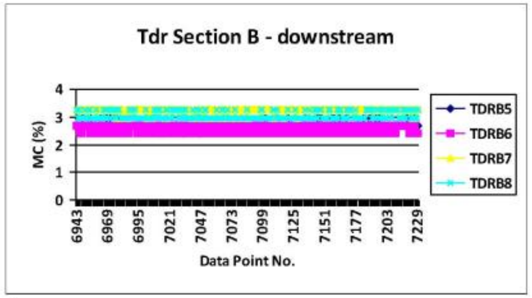
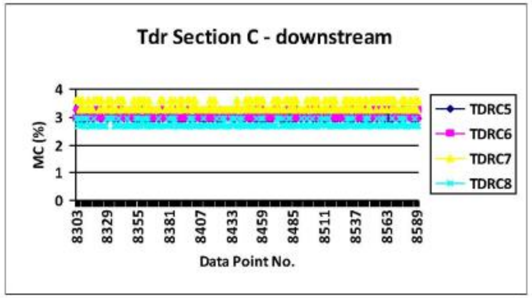
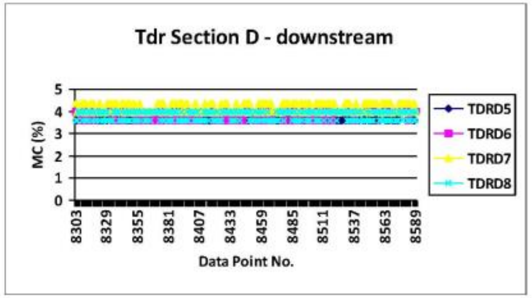
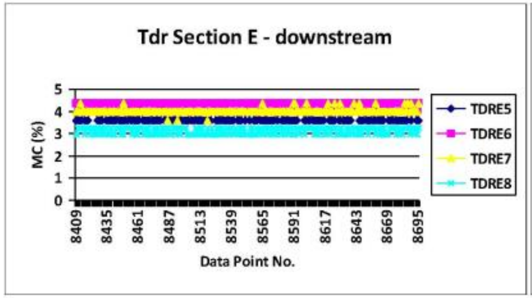
1 24/02/2010 3/03/2010 8 DA Notes: 1st Prelim Test

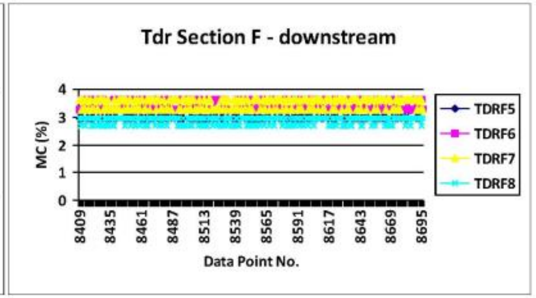




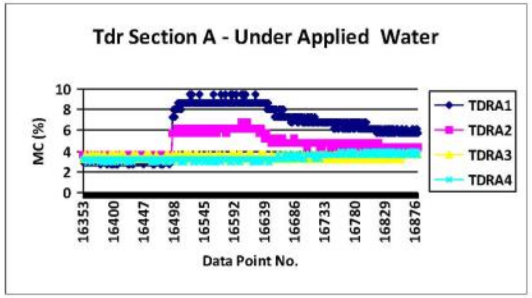


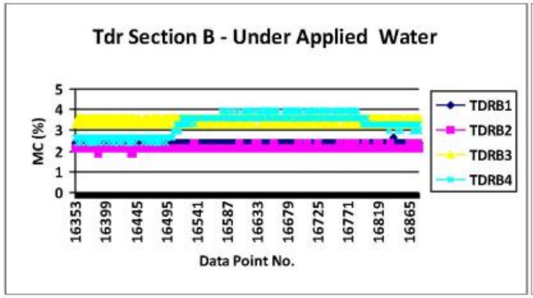


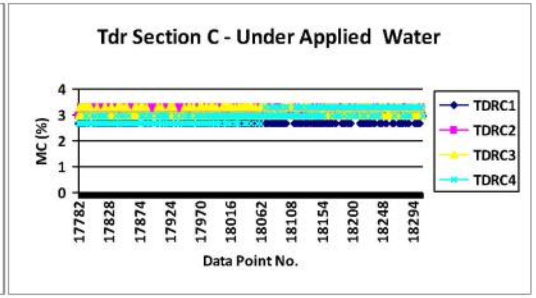


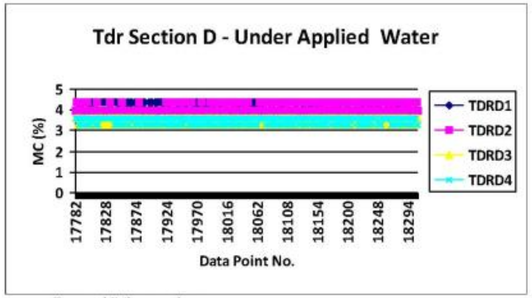


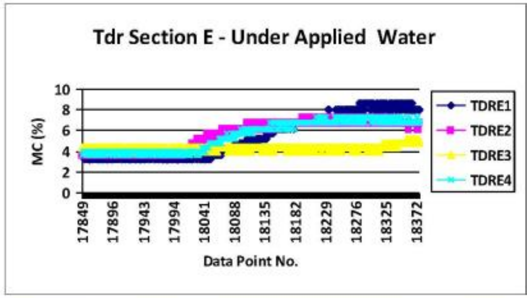
2 30/03/2010 12 DA Notes: 2nd Prelim Test

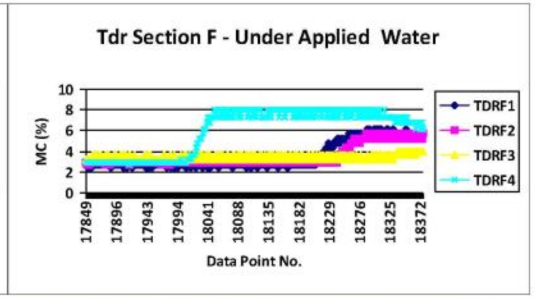












0 Tests and Failures 1 subreport

Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
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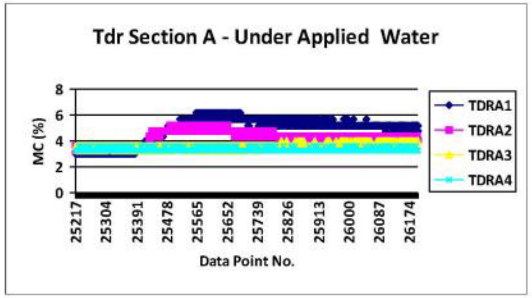
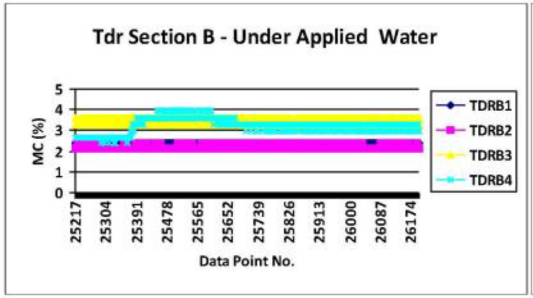
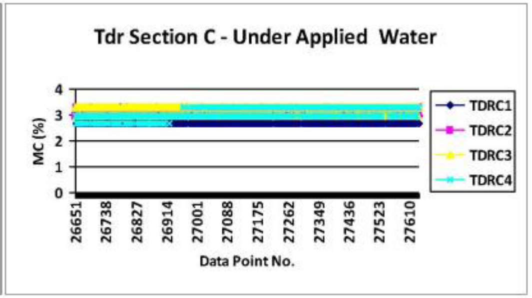
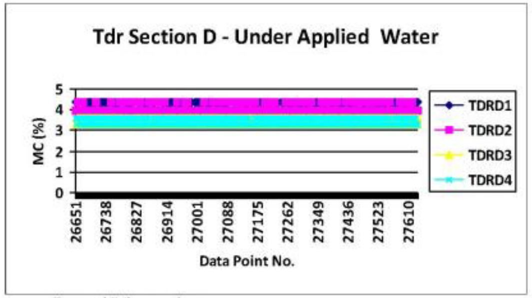
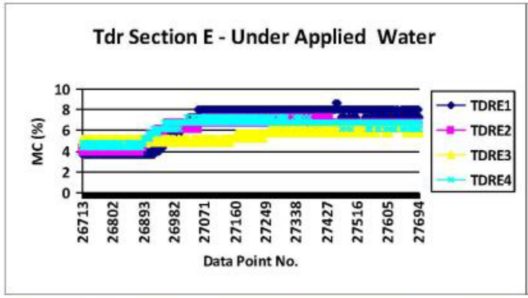
3 29/04/2010 9 DA Notes: 1st Static

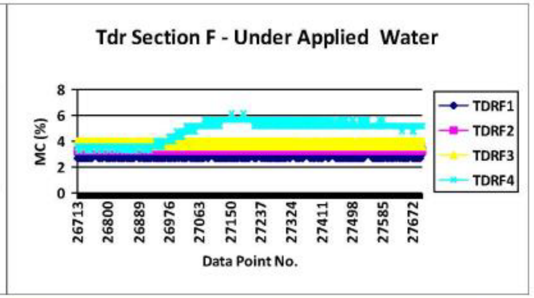












0 Tests and Failures 1 subreport

Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
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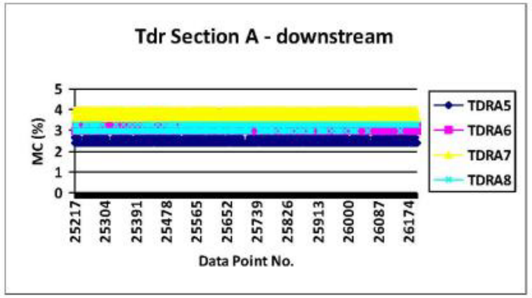
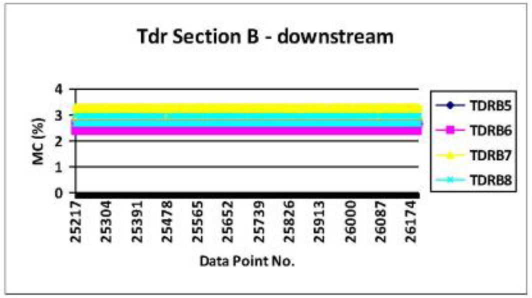
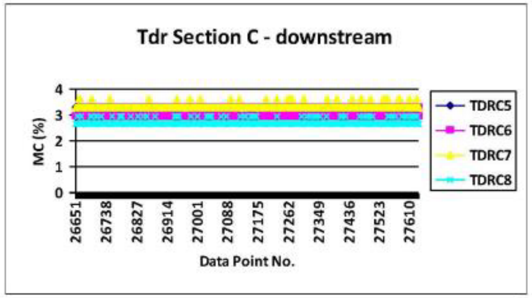
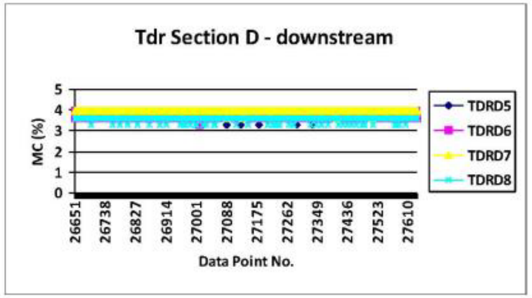
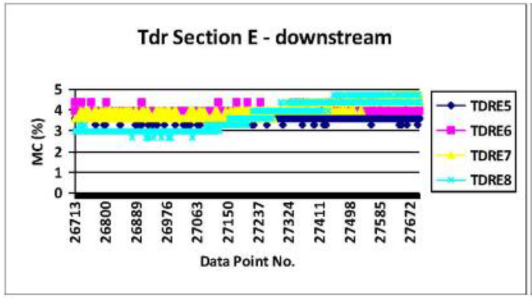
3 29/04/2010 9 DA Notes: 1st Static

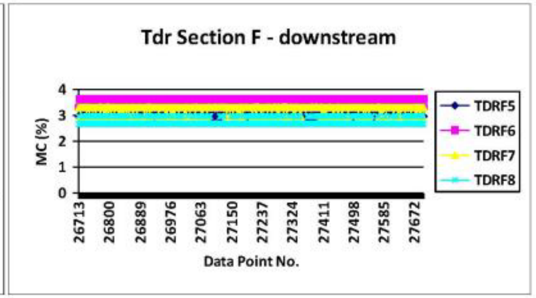




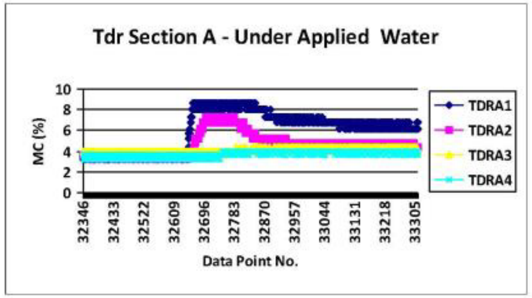


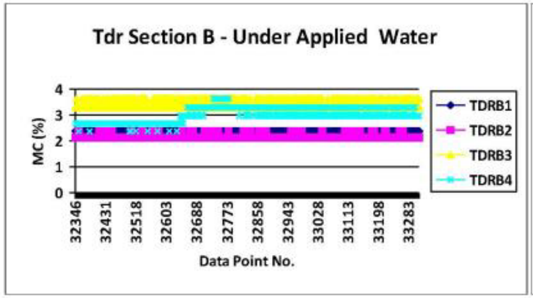


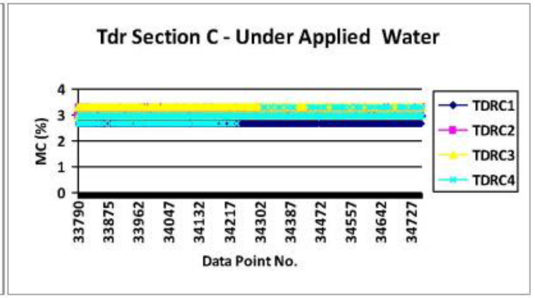


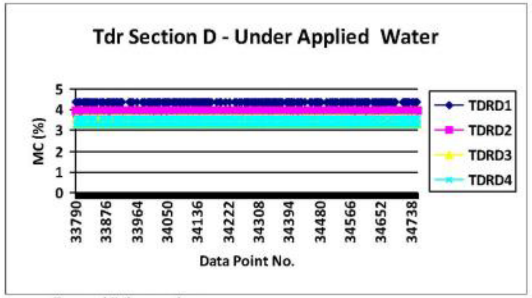


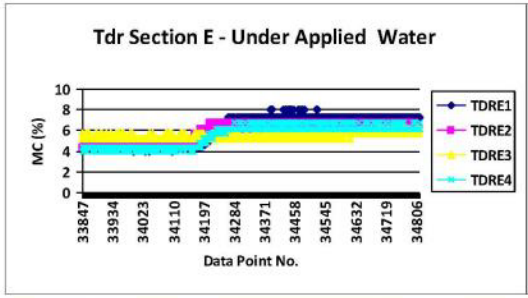
4 19/05/2010 9 DA Notes: 2nd Static

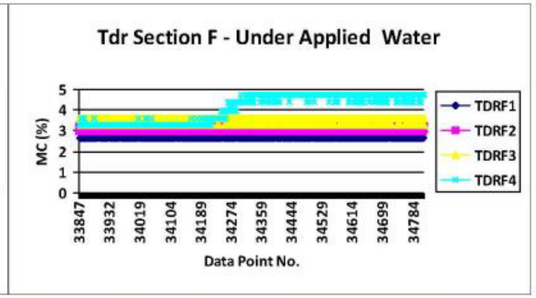








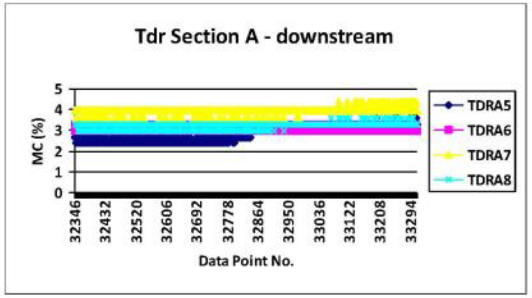


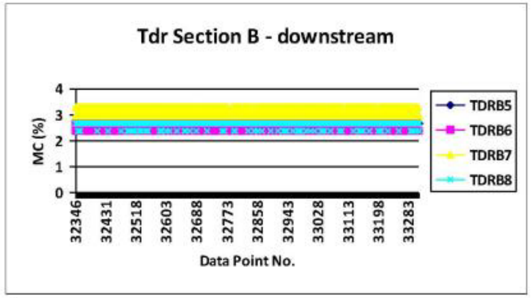


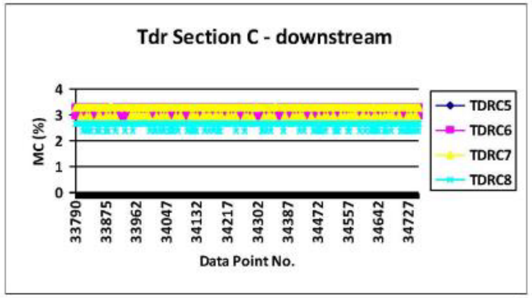
o Tests and Failures 1 subreport

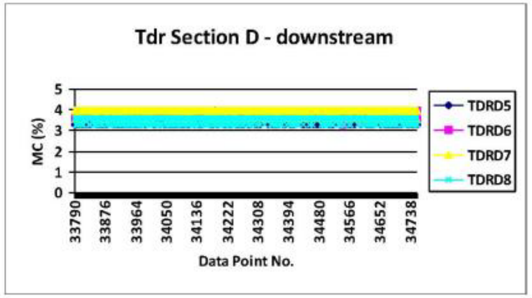
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
4	19/05/2010	9	2nd Static								

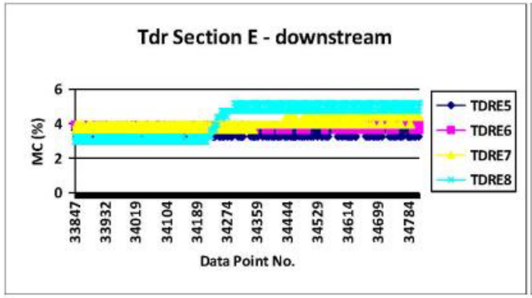
4 19/05/2010 9 DA Notes: 2nd Static

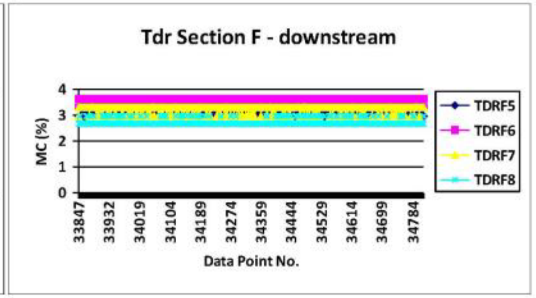




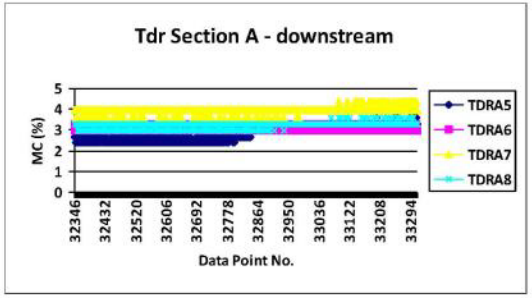


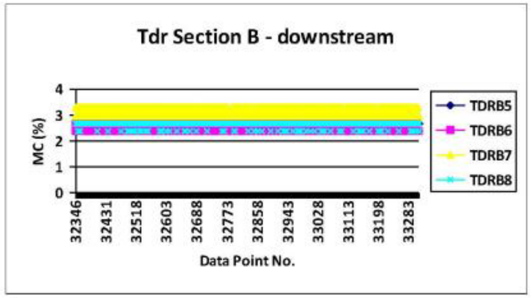


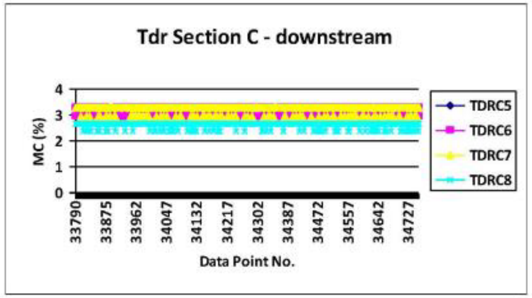


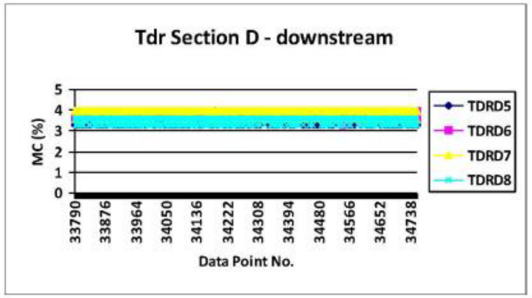


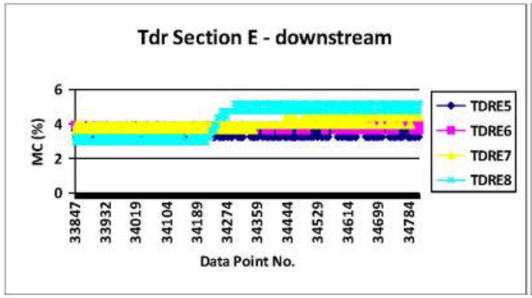
4 19/05/2010 9 DA Notes: 2nd Static

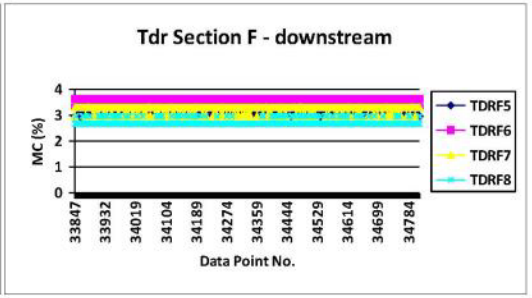




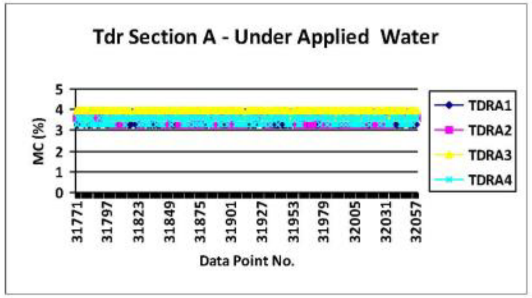


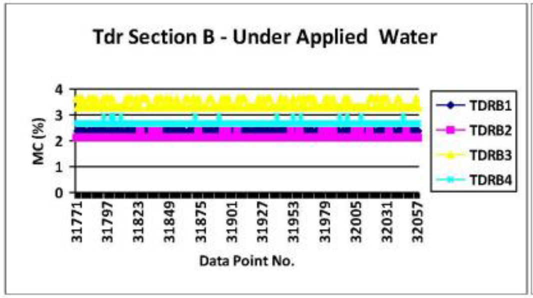


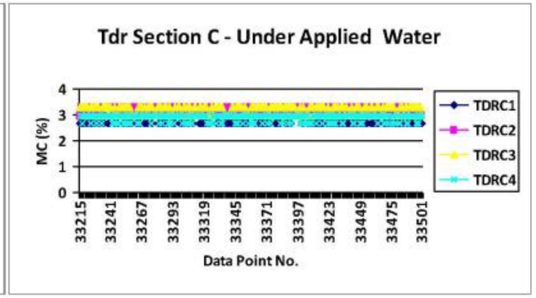


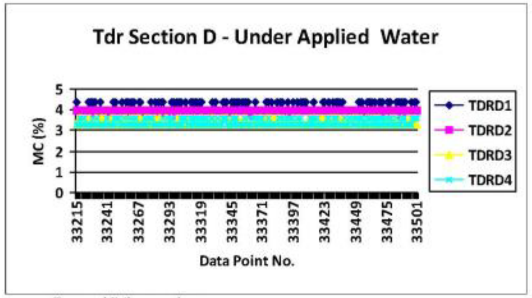


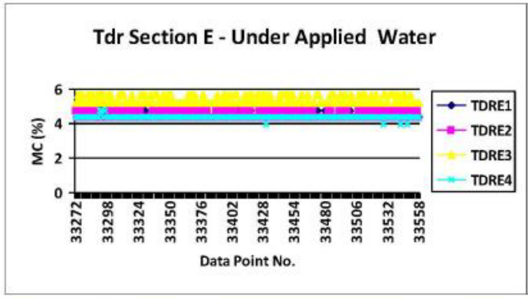
5	17/05/2010	9	DA Notes:	3rd Static

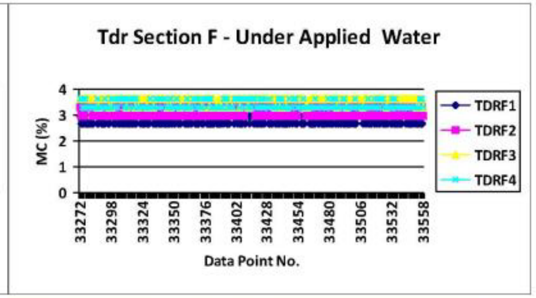








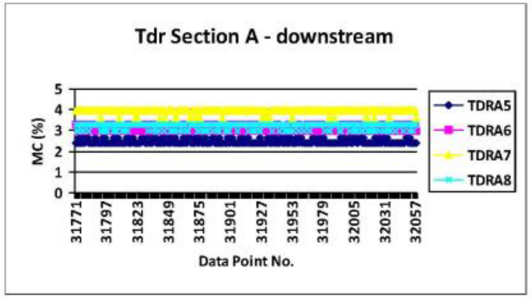


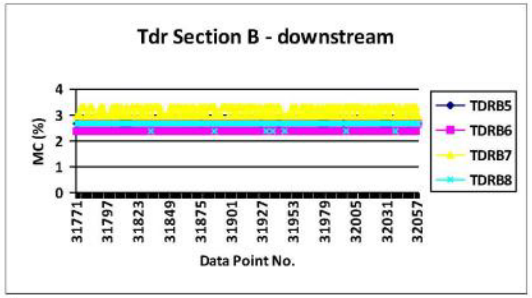


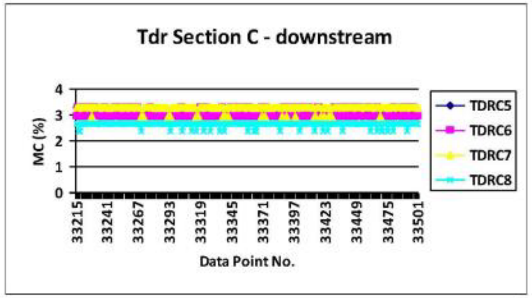
o Tests and Failures 1 subreport

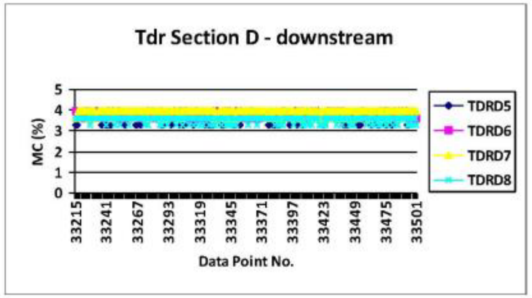
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
5	17/05/2010	9	3rd Static								

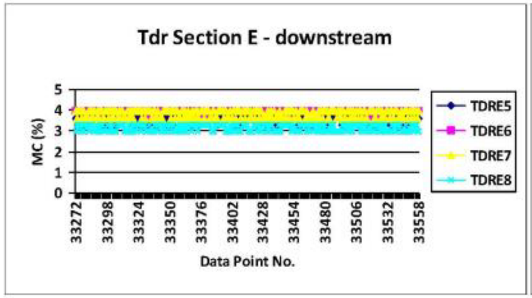
5 17/05/2010 9 DA Notes: 3rd Static

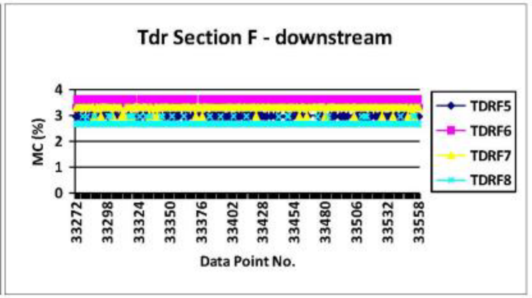




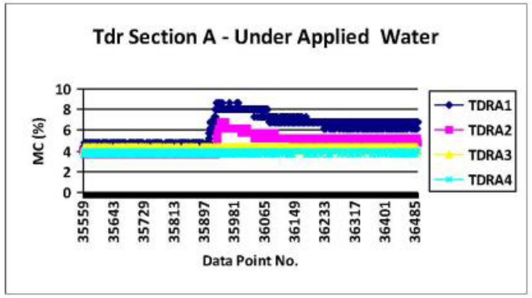


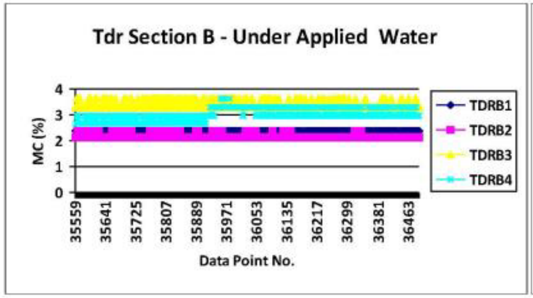


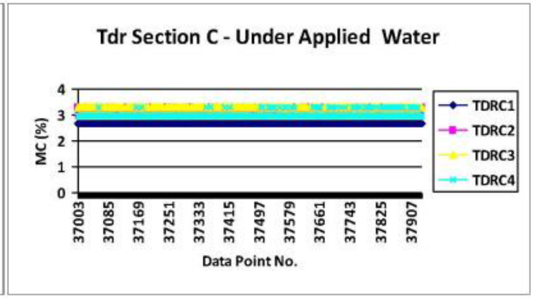


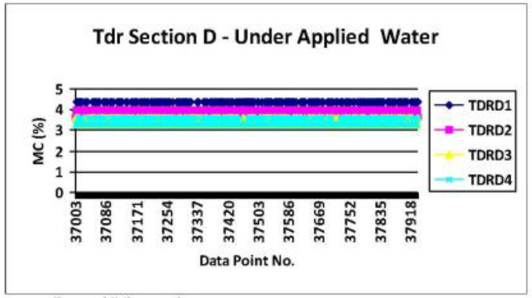


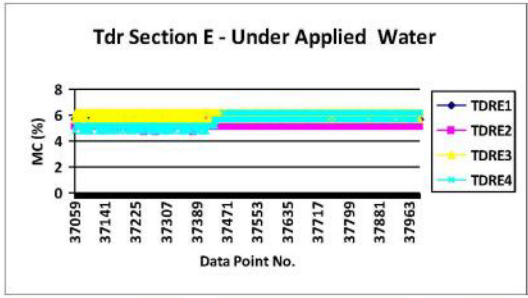
6 26/05/2010 9 DA Notes: 1st Dynamic

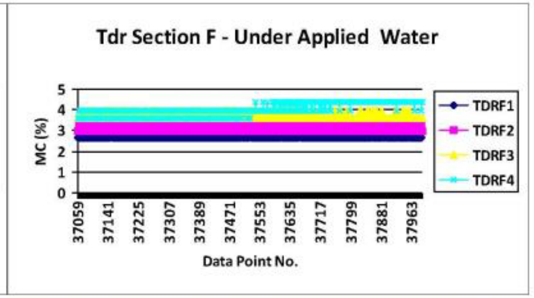








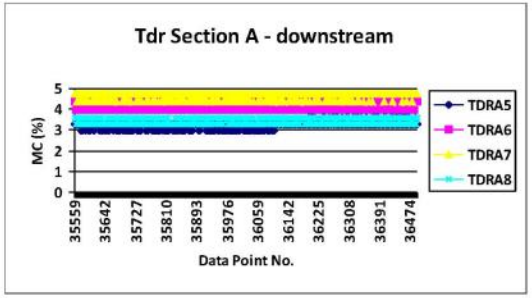


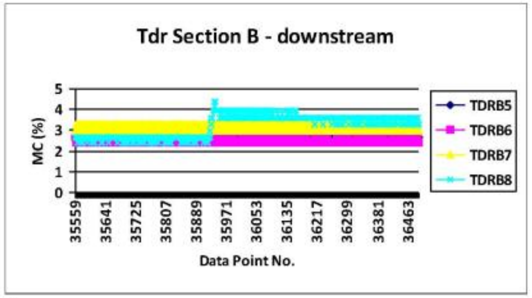


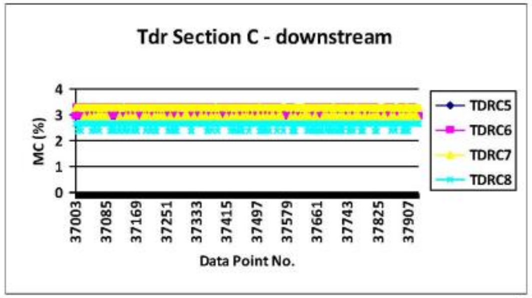
0 Tests and Failures 1 subreport

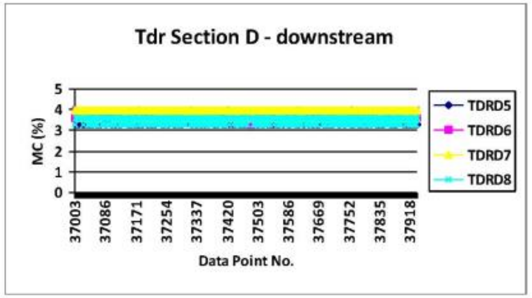
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
6	26/05/2010	9	1st Dynamic	A-un-primed least sensitive (UP	########	1186	Unprimed	3/5 Two Coat First Coat	M/4 AP40	0	6

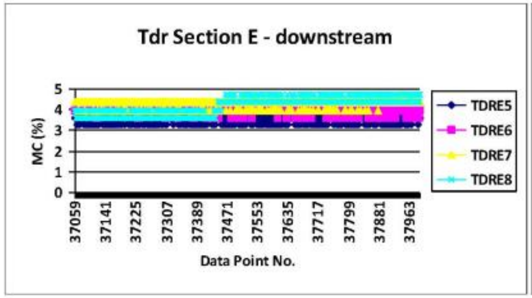
6 26/05/2010 9 DA Notes: 1st Dynamic

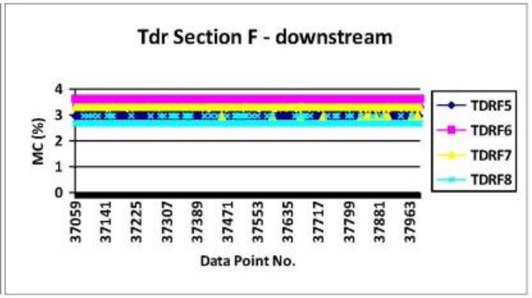




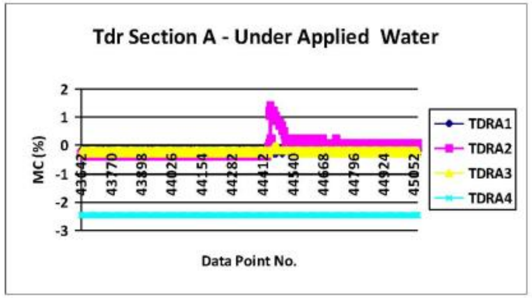


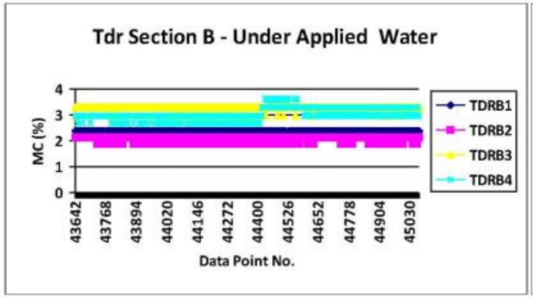


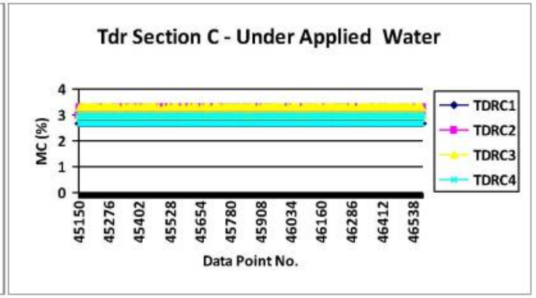


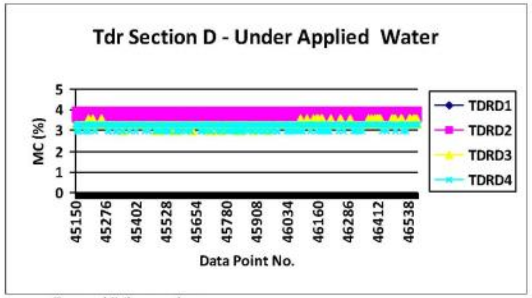


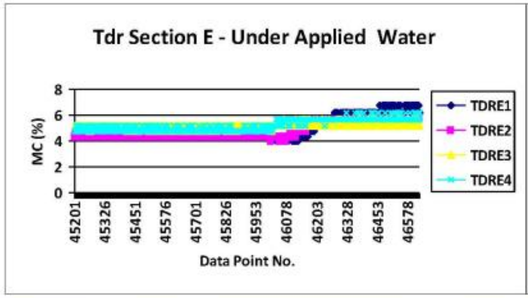
7 17/06/2010 9 DA Notes: 2nd Dynamic

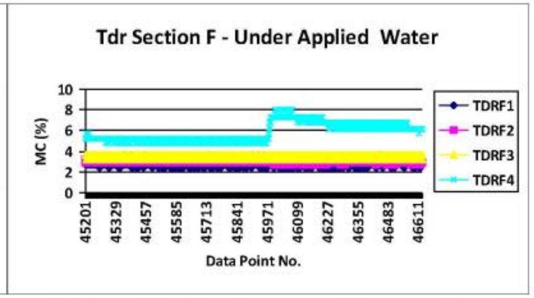








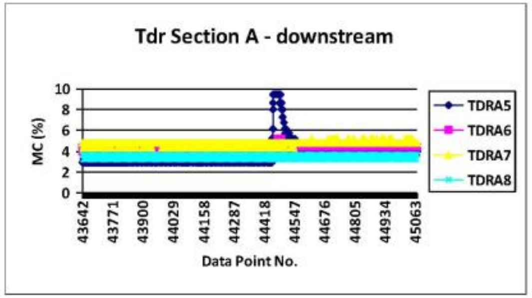


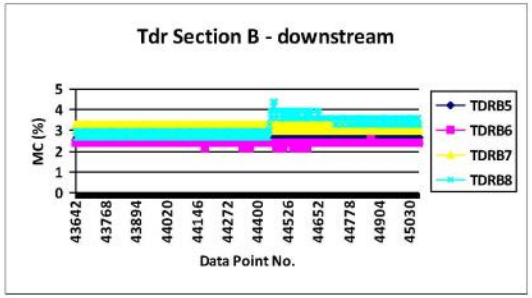


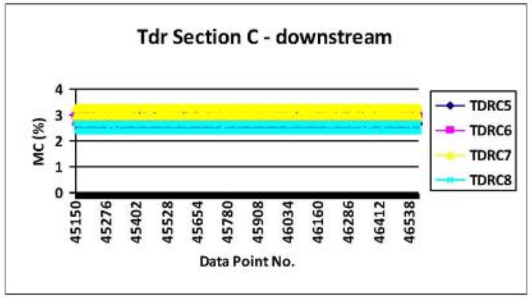
0 Tests and Failures 1 subreport

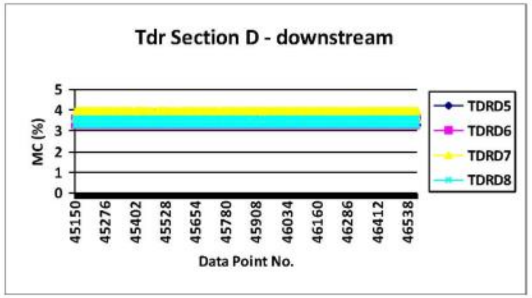
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
7	17/06/2010	9	2nd Dynamic	E=un-primed most sensitive (UP	#########	1401	Unprimed	3/5 Two Coat First Coat	Fines Added AP40	37	43
7	17/06/2010	9	2nd Dynamic	A=un-primed least sensitive (UP	#########	1401	Unprimed	3/5 Two Coat First Coat	M/4 AP40	6	9

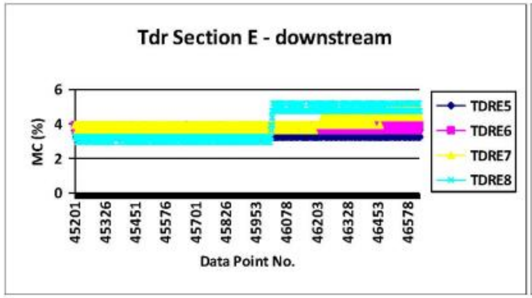
7 17/06/2010 9 DA Notes: 2nd Dynamic

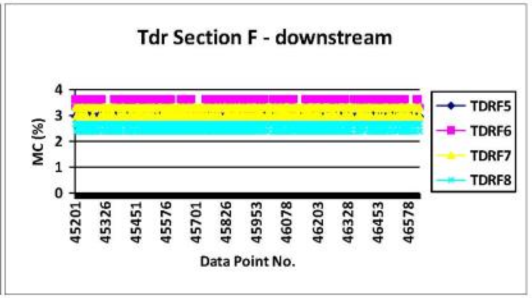




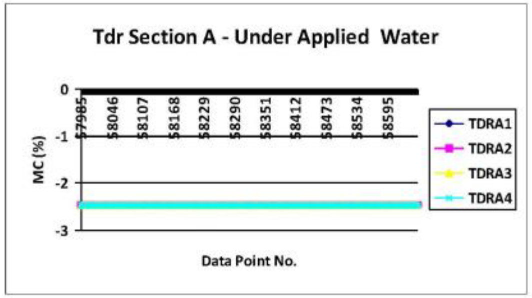


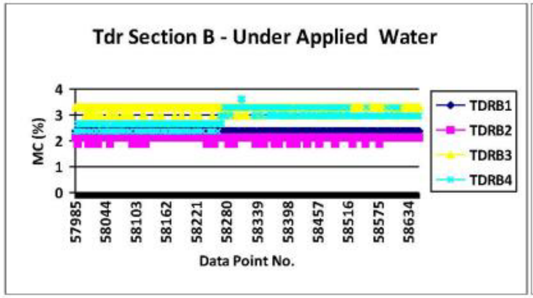


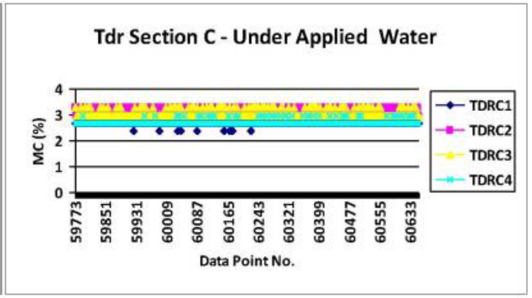


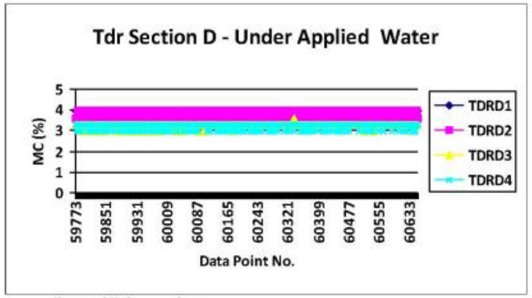


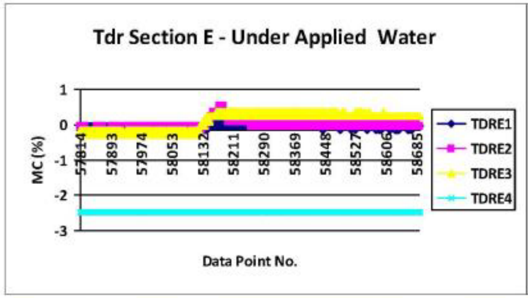
8 12/07/2010 9 DA Notes: 3rd Dynamic

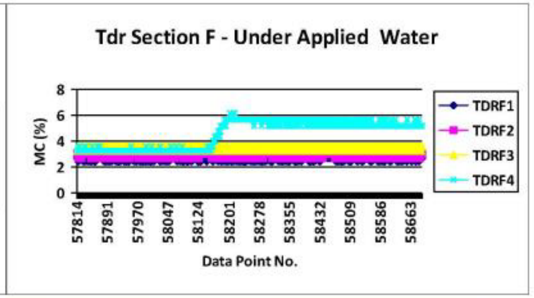








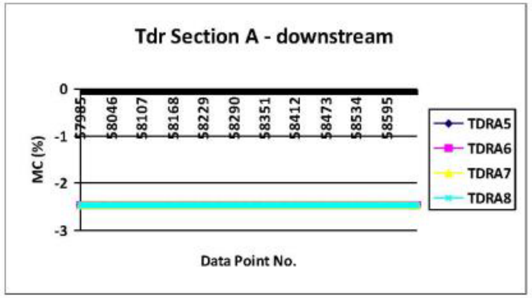


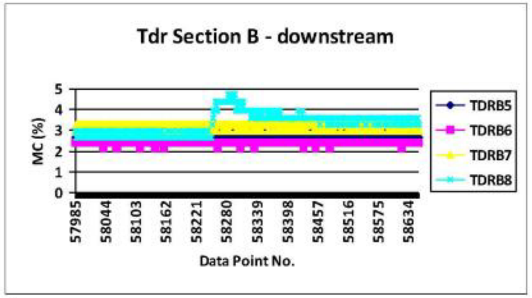


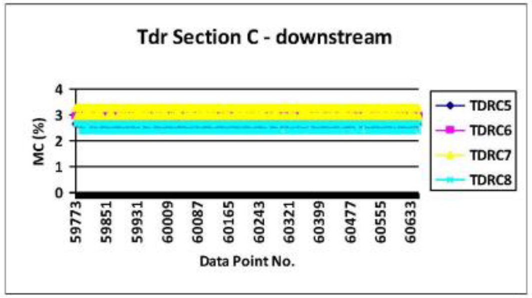
o Tests and Failures 1 subreport

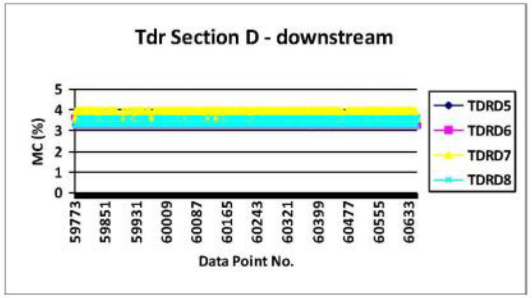
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
8	12/07/2010	9	3rd Dynamic	F=un-primed medium sensitive (	#########	1975	Unprimed	3/5 Two Coat First Coat	Dense Graded AP20	47	57
8	12/07/2010	9	3rd Dynamic	E=un-primed most sensitive (UP	#########	1975	Unprimed	3/5 Two Coat First Coat	Fines Added AP40	43	47

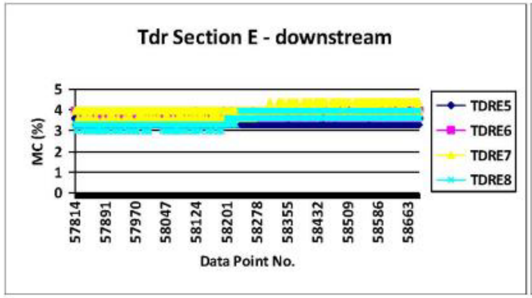
8 12/07/2010 9 DA Notes: 3rd Dynamic

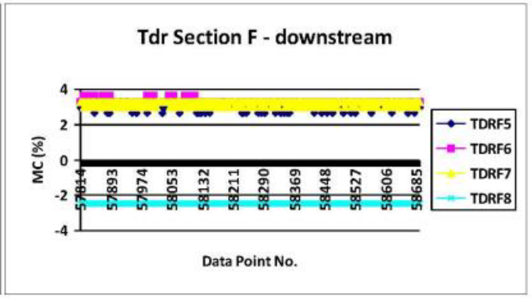




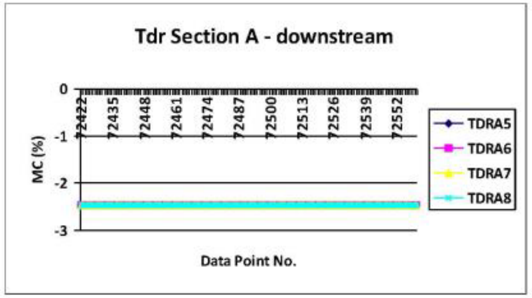


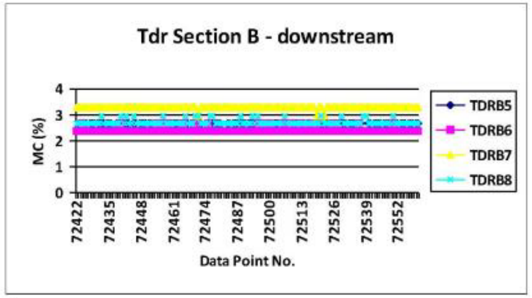


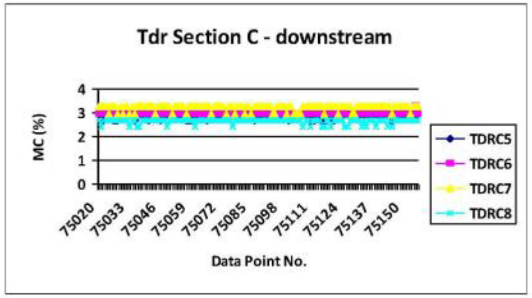


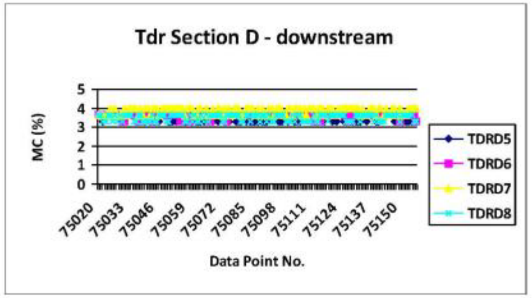


9 26/08/2010 12 DA Notes: 4th Static





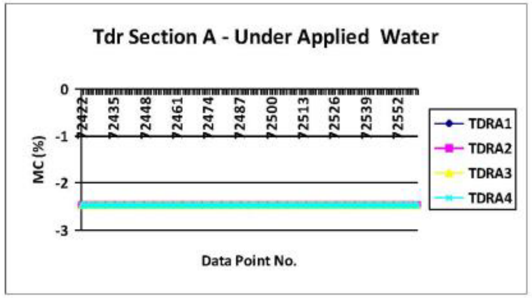


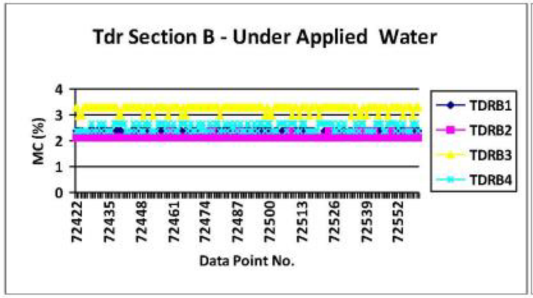


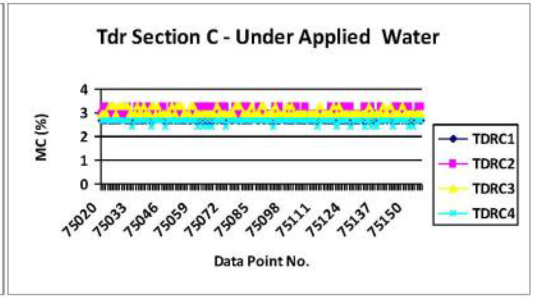
Tdr Section E - downstream

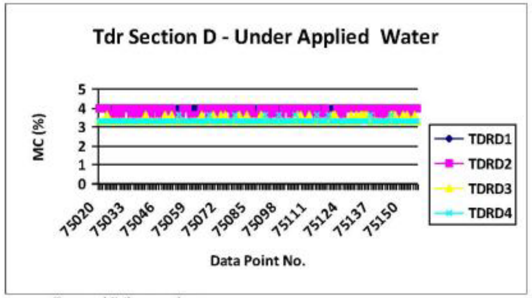
Tdr Section F - downstream

9 26/08/2010 12 DA Notes: 4th Static









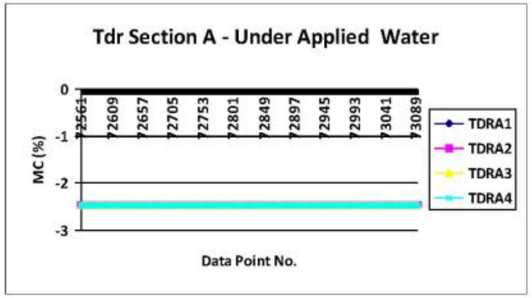
Tdr Section E - Under Applied Water

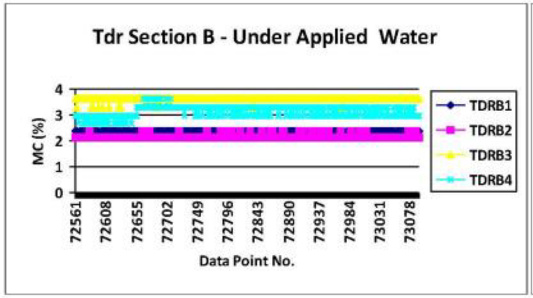
Tdr Section F - Under Applied Water

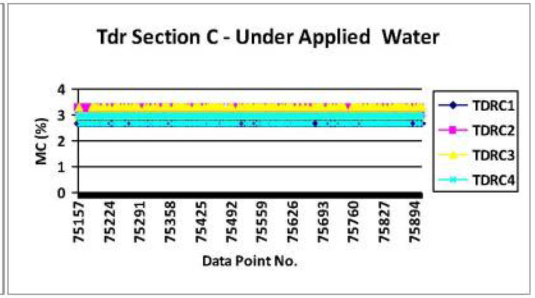
o Tests and Failures 1 subreport

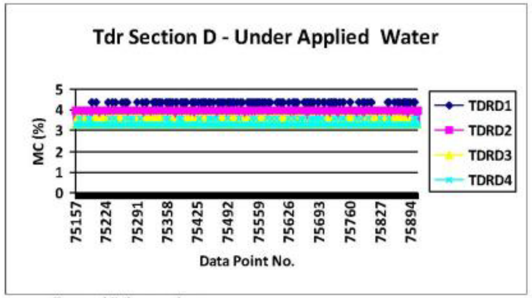
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
9	26/08/2010	12	4th Static								

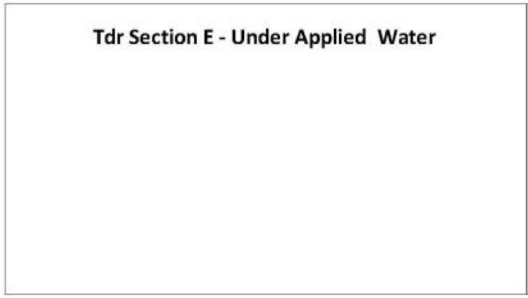
10 30/08/2010 12 DA Notes: 4th Dynamic

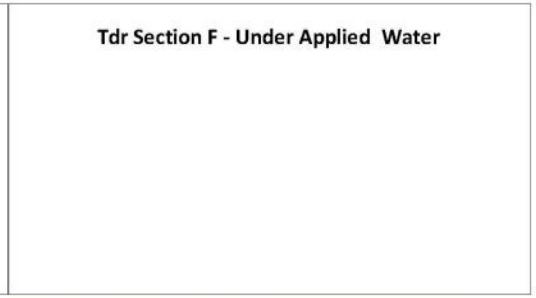








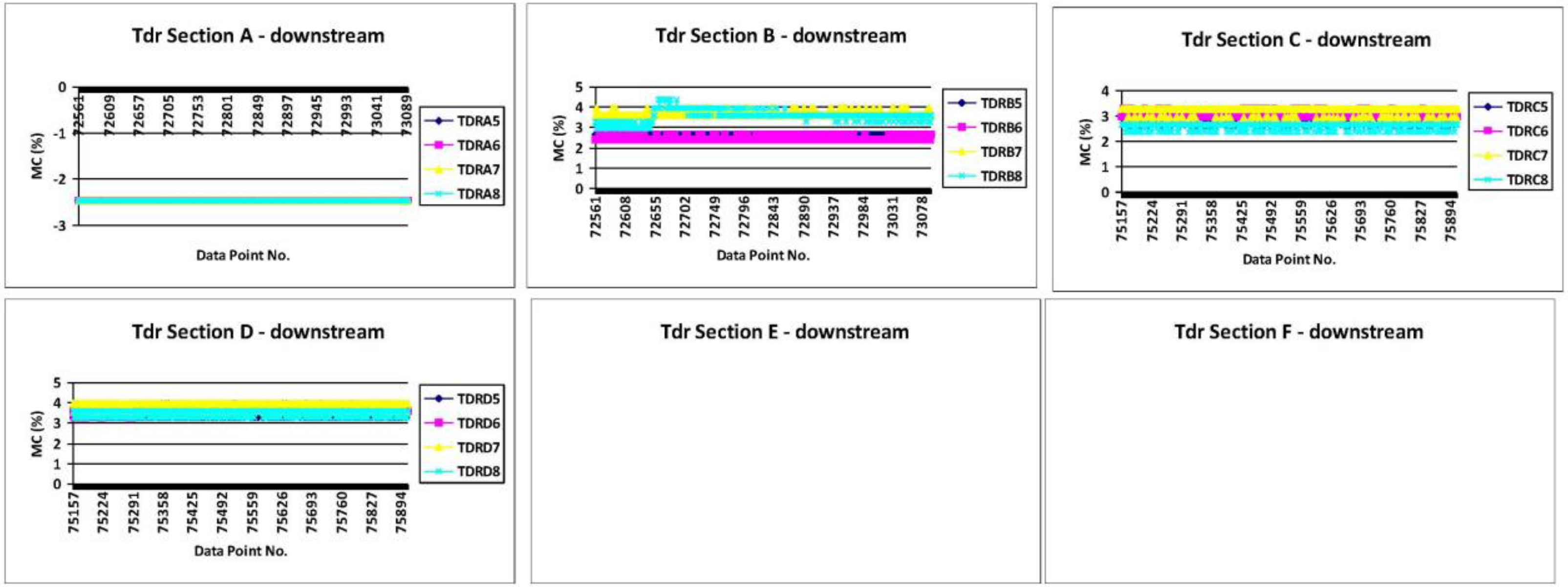




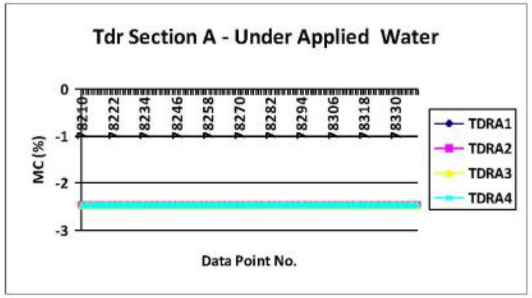
o Tests and Failures 1 subreport

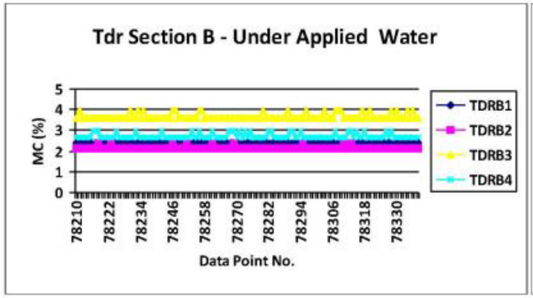
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
10	30/08/2010	12	4th Dynamic	B-primed least sensitive (P-L)	#########	2244	Primed	3/5 Two Coat First Coat	M/4 AP40	9	12

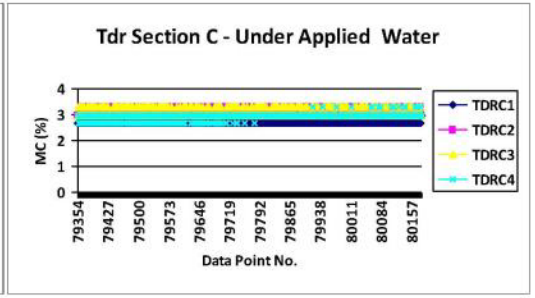
10 30/08/2010 12 DA Notes: 4th Dynamic

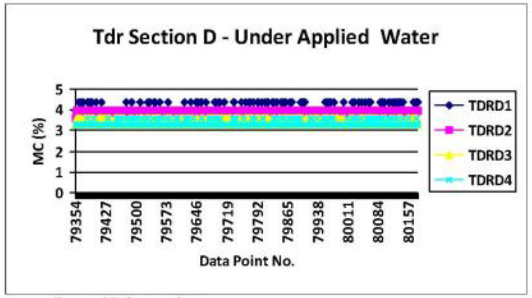


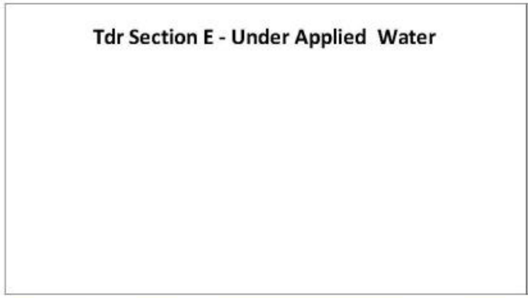
11 16/09/2010 18 DA Notes: 5 Static

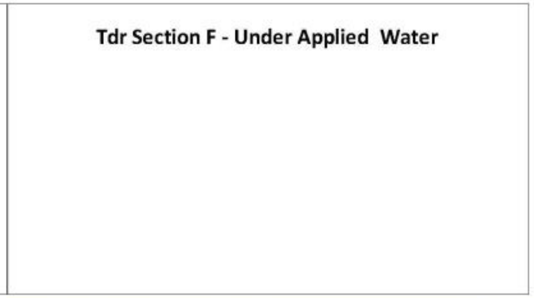








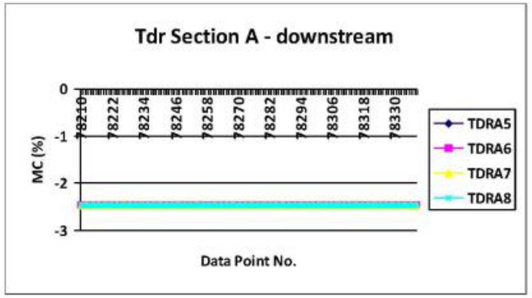


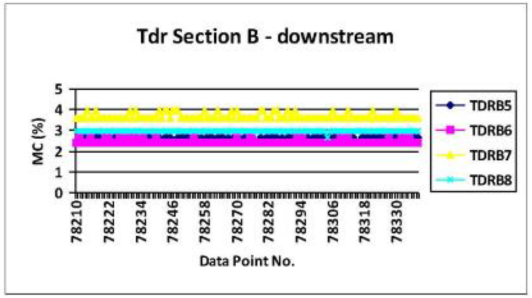


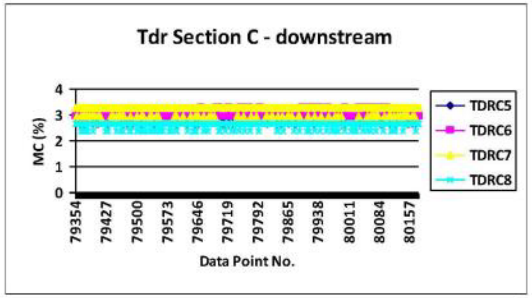
0 Tests and Failures 1 subreport

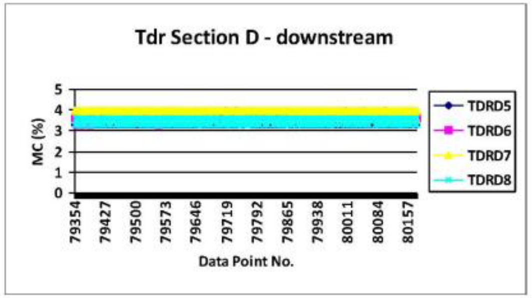
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
11	16/09/2010	18	5 Static								

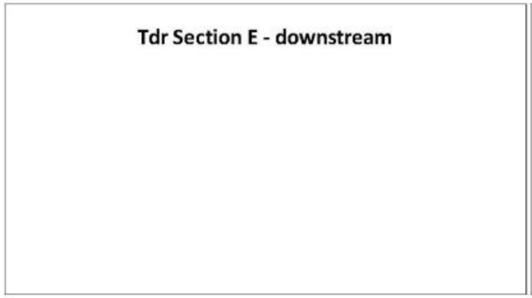
11 16/09/2010 18 DA Notes: 5 Static

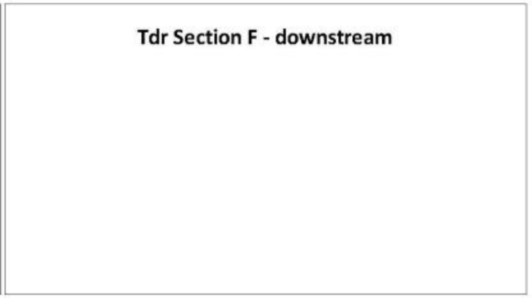




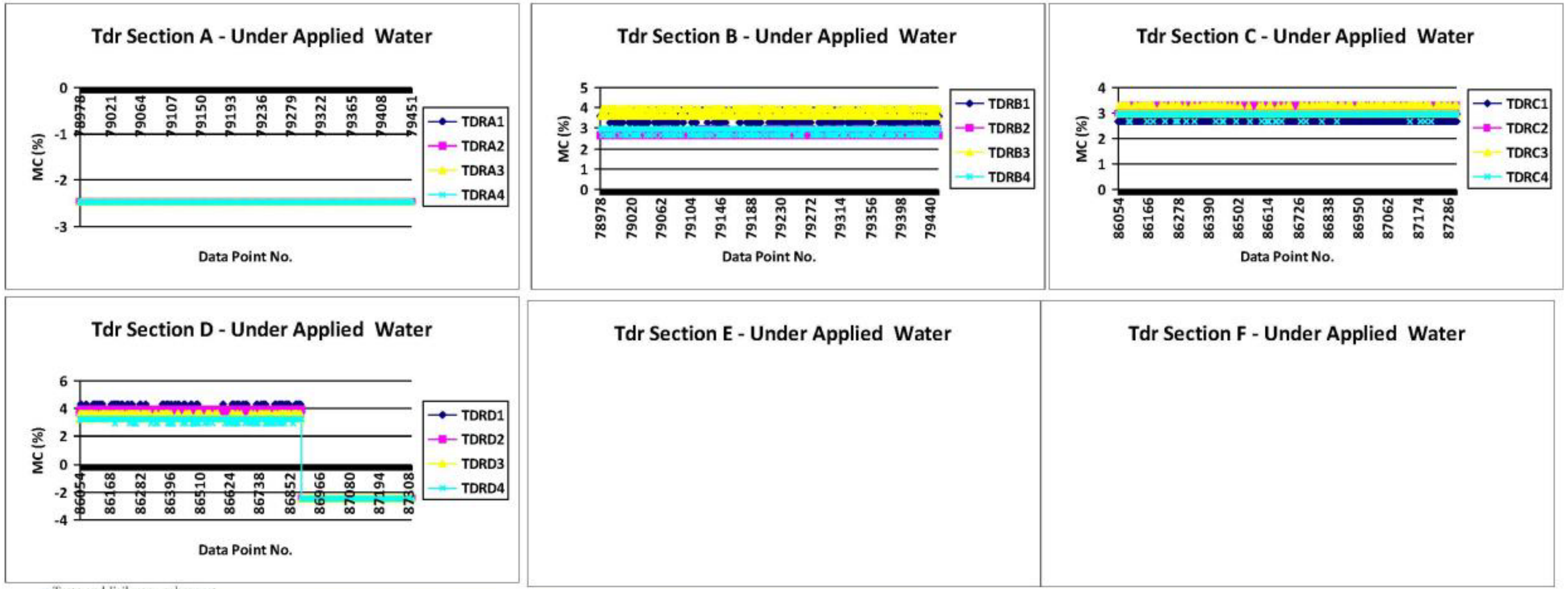








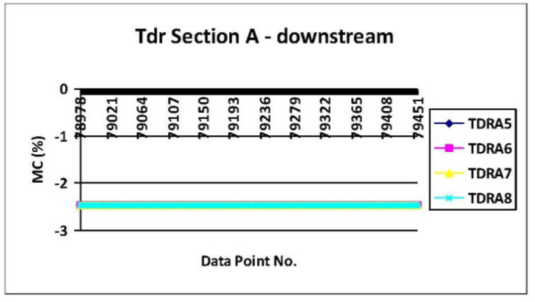
12 22/09/2010 18 DA Notes: 5th Dynamic

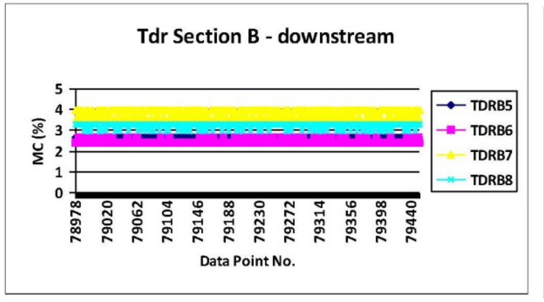


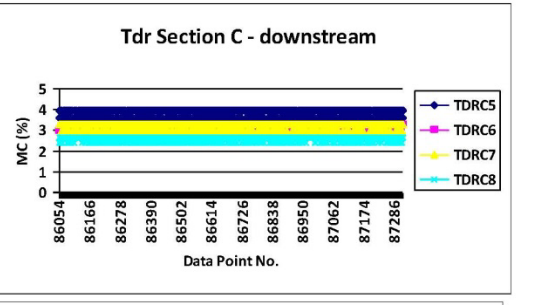
0 Tests and Failures 1 subreport

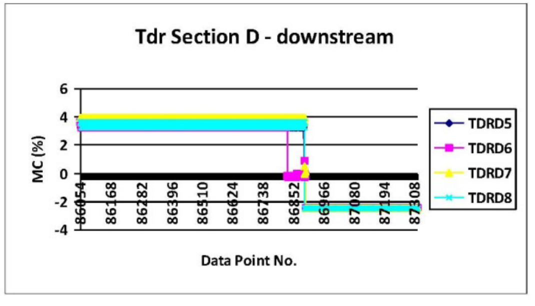
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
12	22/09/2010	18	5th Dynamic	D-primed most sensitive (P-H)	#########	3501	Primed	3/5 Two Coat First Coat	Fines Added AP40	29	37
12	22/09/2010	18	5th Dynamic	B-primed least sensitive (P-L)	#########	3501	Primed	3/5 Two Coat First Coat	M/4 AP40	12	19

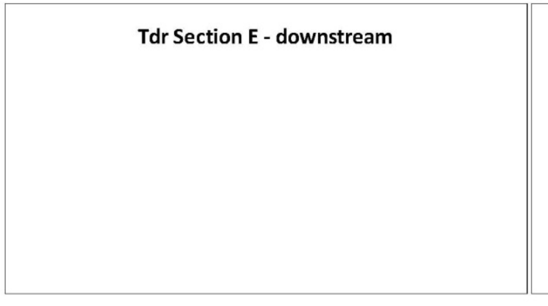
12 22/09/2010 18 DA Notes: 5th Dynamic

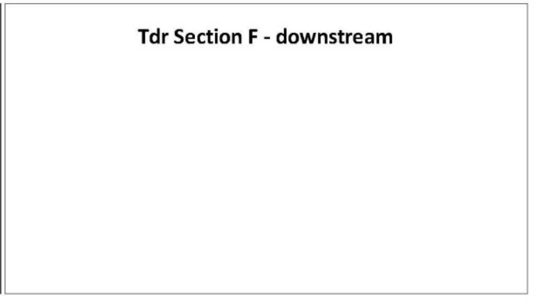










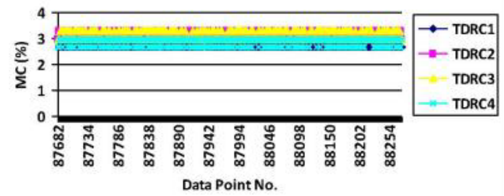


13 5/10/2010 18 DA Notes: 6th Dynamic

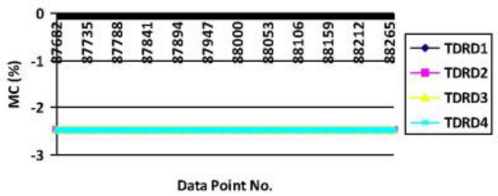
Tdr Section A - Under Applied Water

Tdr Section B - Under Applied Water

Tdr Section C - Under Applied Water



Tdr Section D - Under Applied Water



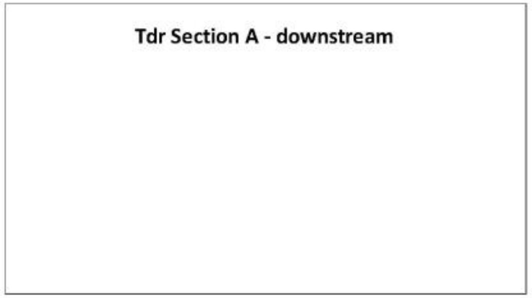
Tdr Section E - Under Applied Water

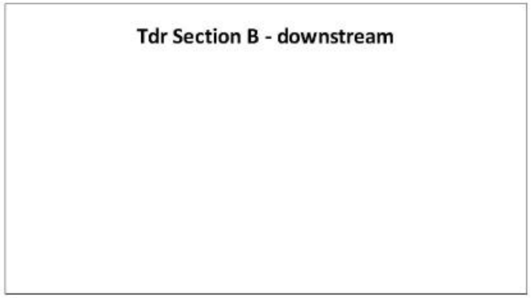
Tdr Section F - Under Applied Water

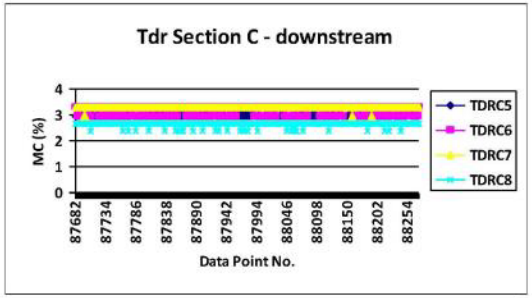
0 Tests and Failures 1 subreport

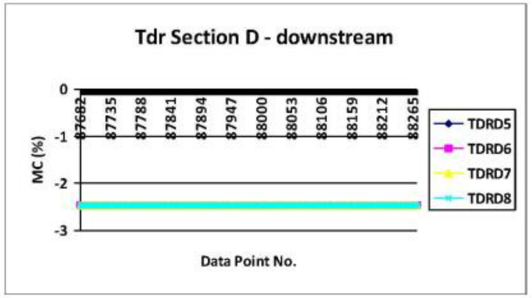
Test No	Test Date	Nozzle dia	DA Notes	Theory	Fail Date	Laps	Primed	Surfacing	Basecourse	Stn start	Stn End
13	5/10/2010	18	6th Dynamic	C-primed medium sensitive (P-	5/10/2010	4917	Primed	3/5 Two Coat First Coat	Dense Graded AP20	19	28

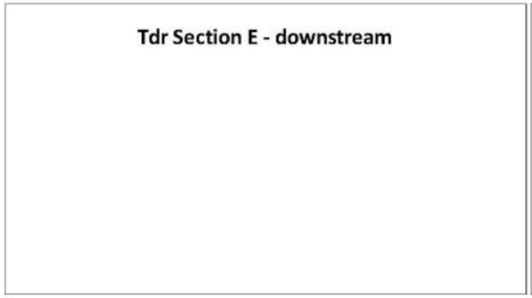
13 5/10/2010 18 DA Notes: 6th Dynamic

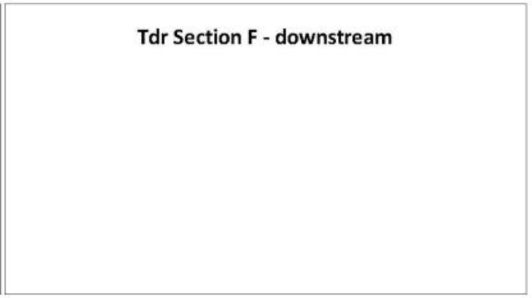




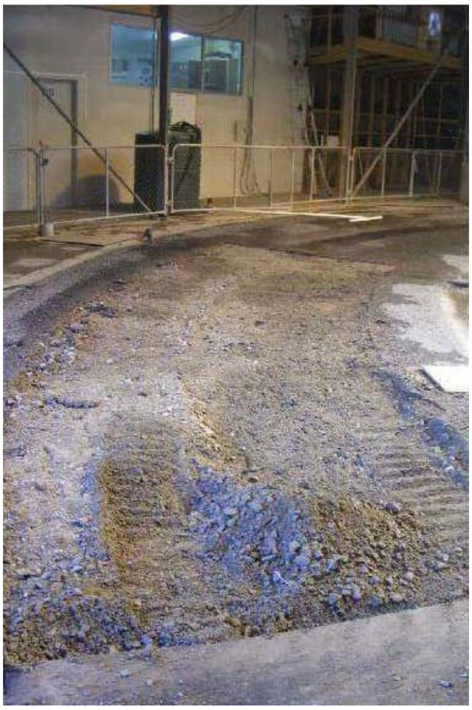


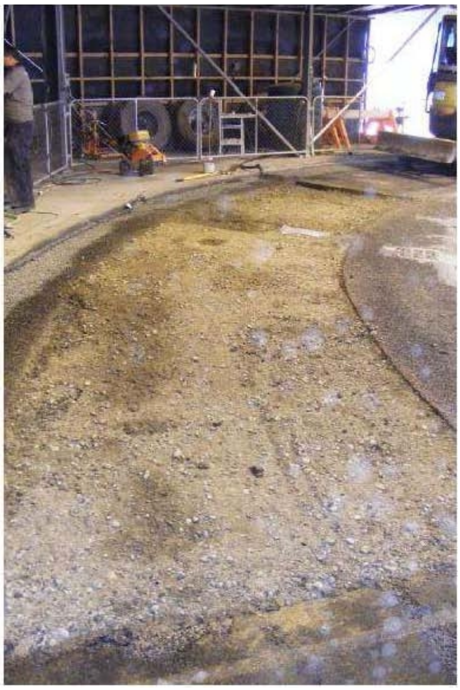






Appendix B: Test 1 failure photos



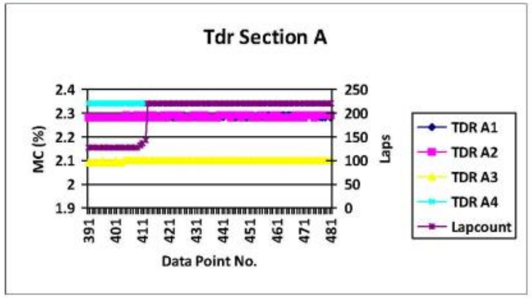


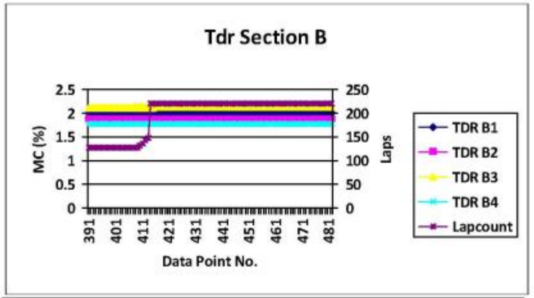
Appendix C: Test 2 TDR results

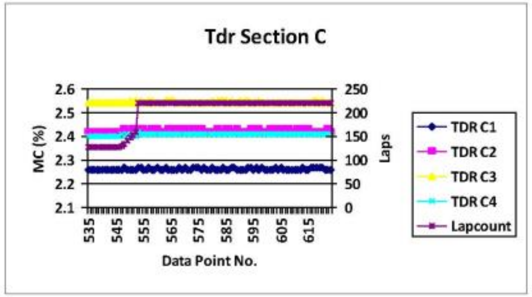
Test Dates 2 - TDR Results Charts

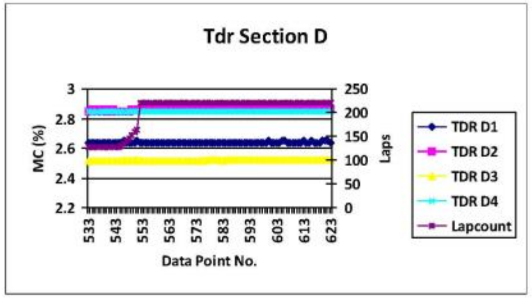
Test No:	1	Nozzle dia:	0	Laps to apply:	100
Speed:	20	DA Notes:	Dynamic		

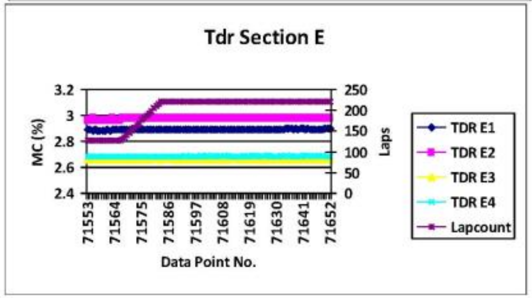
Test Notes: pattern +- 100mm, 127 laps moist running at 190cm using tyre spray. Ran Emus - looked low but is 20kN on a Single. TDR on at Start of loading 11.08am. Stopped test 11.45am. 20 km/hr

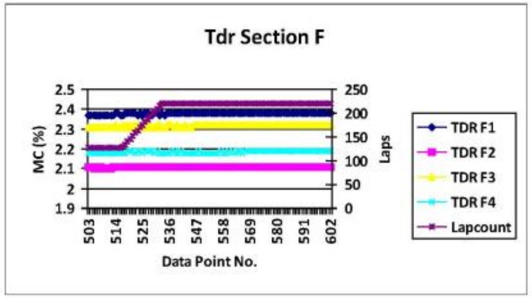










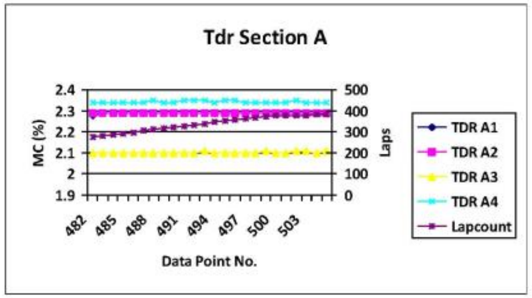


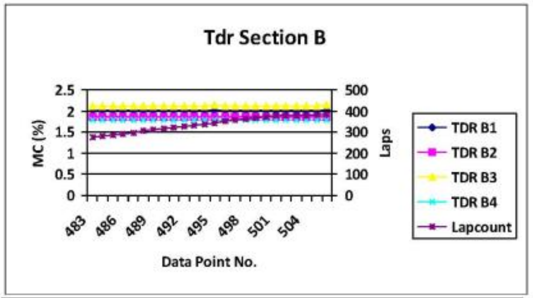
0 Tests and Failures 2 subreport

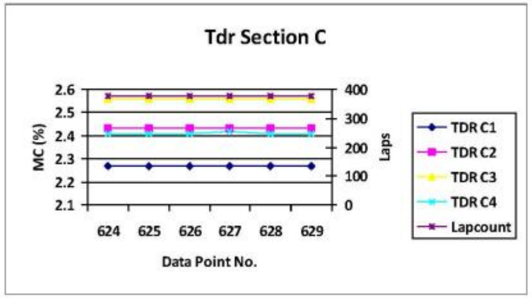
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
1	18/08/2011	100	20	0	Dynamic							

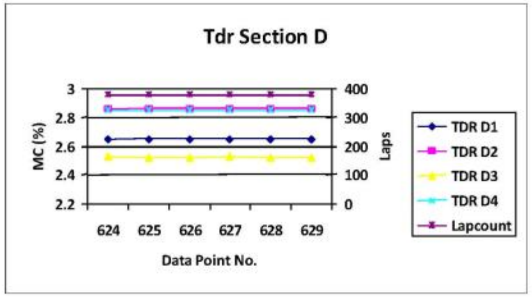
Test No: 2 Nozzle dia: 8 Laps to apply: 100 Test Notes: 100 Laps - Watering at 2,12,21,31,41,50. Top of chips above film. 1-2m spread of water. Nothing observed on TDR over weekend.

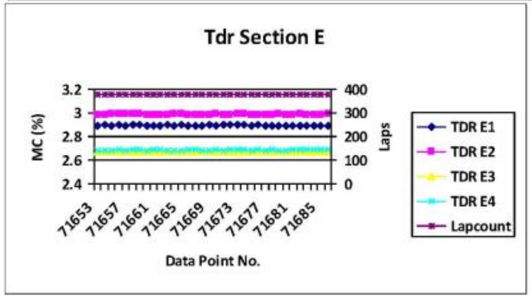
Speed: 20 DA Notes: Dynamic

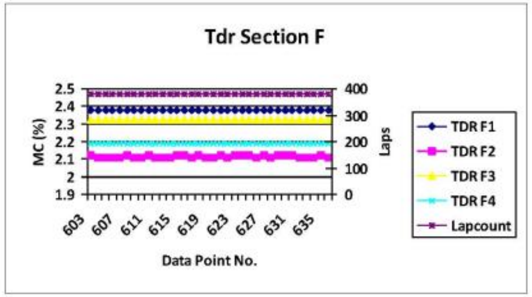








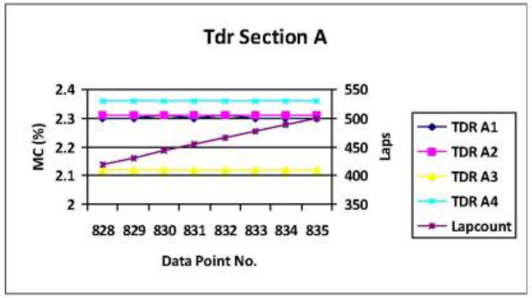


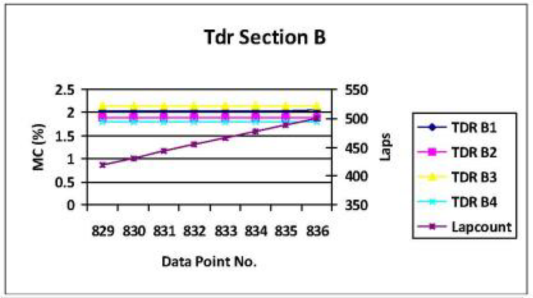


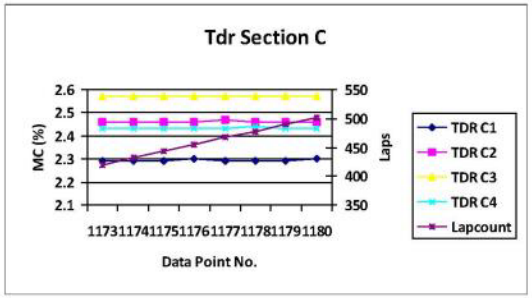
o Tests and Failures 2 subreport

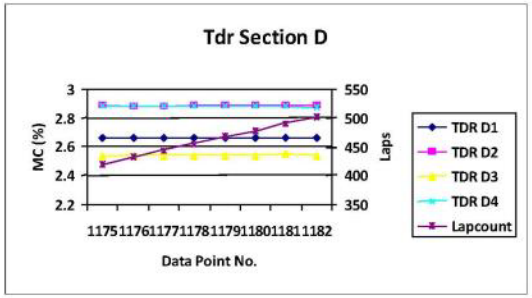
Test No	Test Date	to apply	speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
2	18/08/2011	100	20	8	Dynamic							

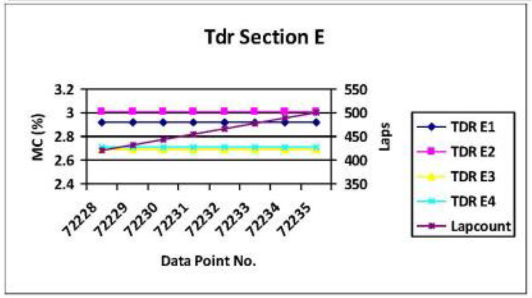
Test No:	3	Nozzle dia:	16	Laps to apply:	100	Test Notes:	Water pumping out of Section C standpipe, nothing on TDR. Note all sections showing sediment in the gutter. 20km/hr 100 laps
Speed:	20	DA Notes:	Dynamic				

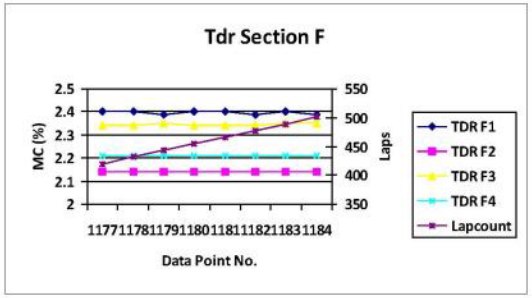










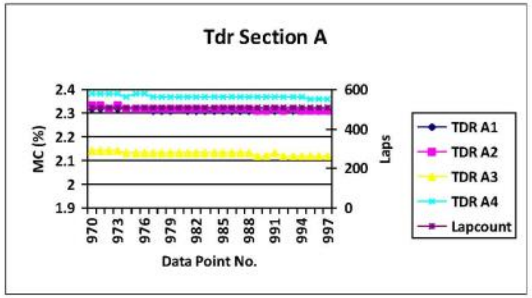


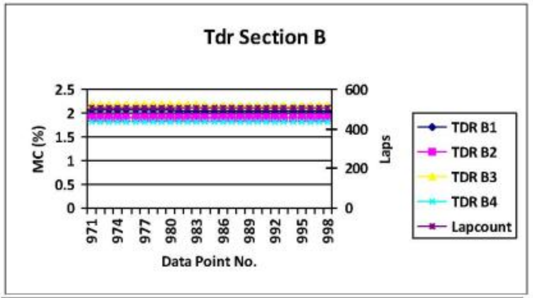
o Tests and Failures 2 subreport

Test No	Test Date	to apply	speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
3	22/08/2011	100	20	16	Dynamic							

Test No: 4 Nozzle dia: 0 Laps to apply: 100 Test Notes: Emu

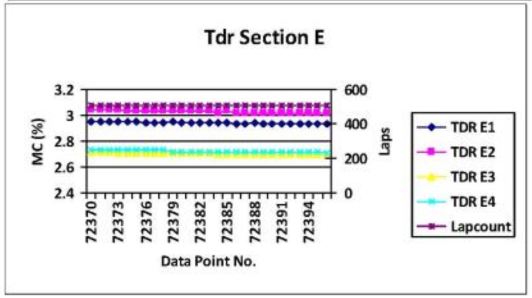
Speed: 20 DA Notes: Moist - Coils

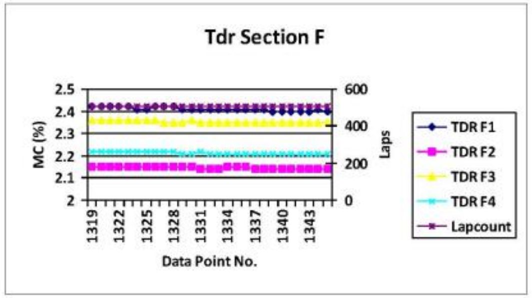




Tdr Section C

Tdr Section D



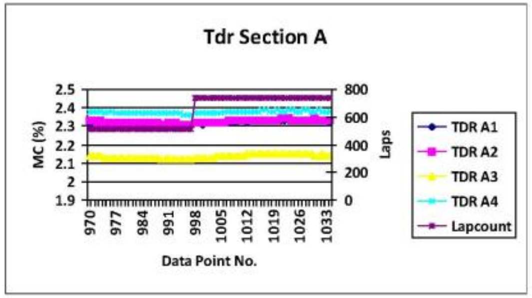


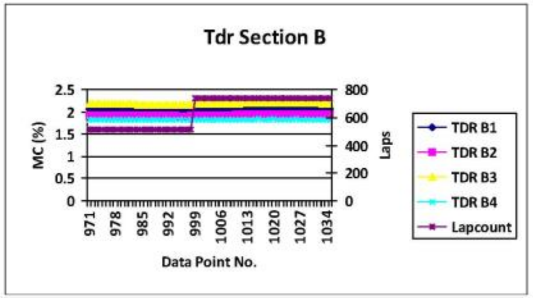
0 Tests and Failures 2 subreport

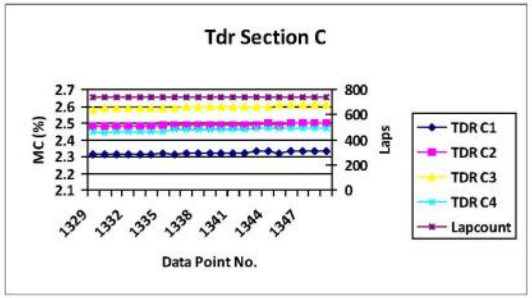
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
4	23/08/2011	100	20	0	Moist - Coils							

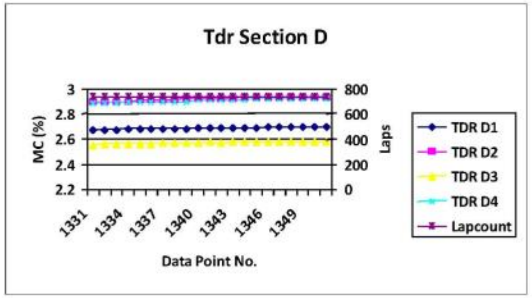
Test No: 5 Nozzle dia: 16 Laps to apply: 100 Test Notes: 27km/hr. Could not make 40 km/hr. Small potholes section A&E on manifold positions. Fixed A with Matrix, Section E still small. Not showing on TDR?

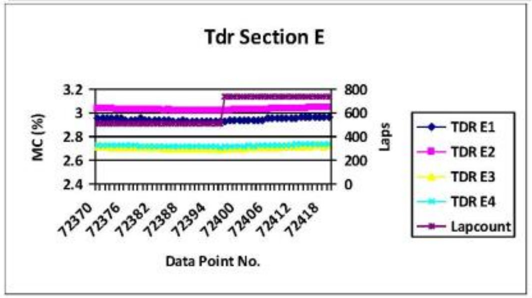
Speed: 27 DA Notes: Dynamic

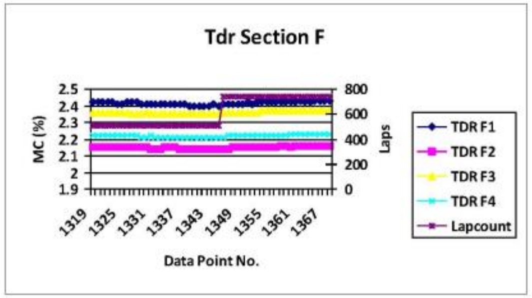










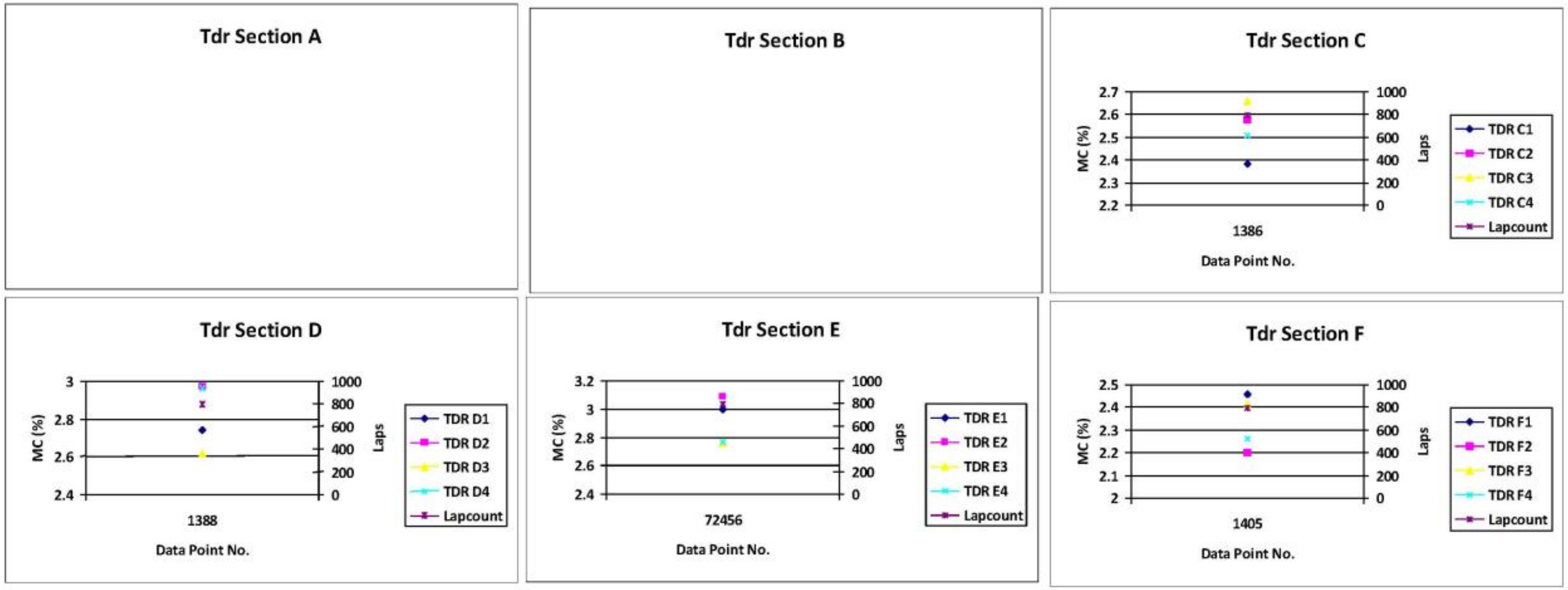


0 Tests and Failures 2 subreport

Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
5	23/08/2011	100	27	16	Dynamic	736	3	4	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat

Test No: 6 Nozzle dia: 0 Laps to apply: 100 Test Notes: Fixing the rig to get 40 km/hr

Speed: 40 DA Notes: Dynamic

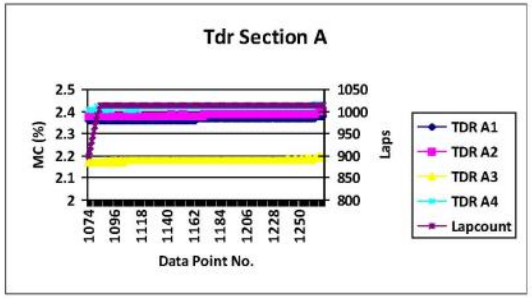


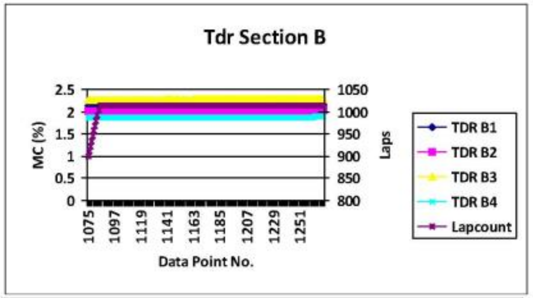
0 Tests and Failures 2 subreport

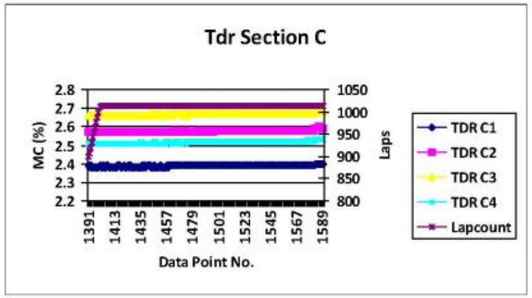
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
6	29/08/2011	100	40	0	Dynamic							

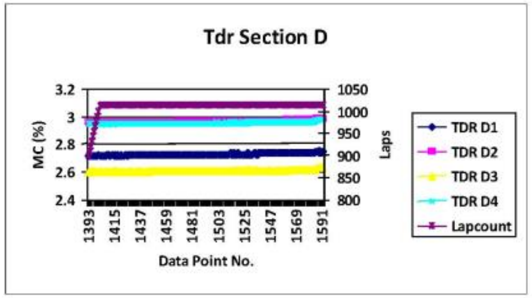
Test No: 7 Nozzle dia: 16 Laps to apply: 100 Test Notes: 100 laps. Running at 40km/hr. start 10.52am. Noticable failure of E at 75 laps.

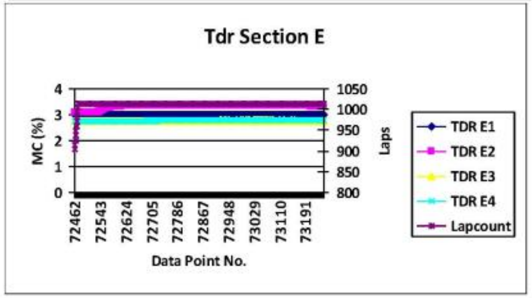
Speed: 40 DA Notes: Dynamic

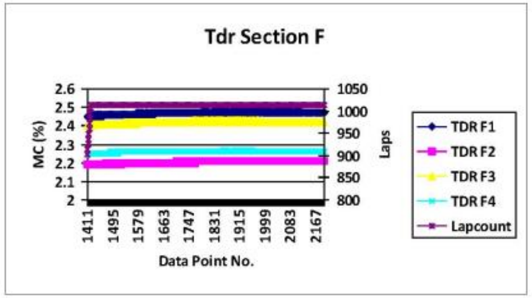












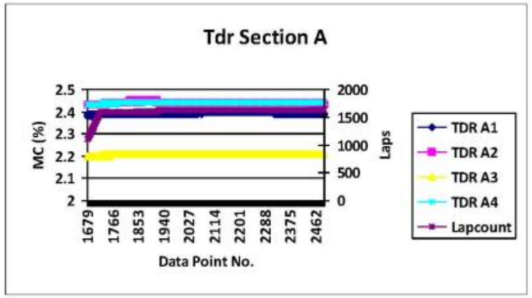
o Tests and Failures 2 subreport

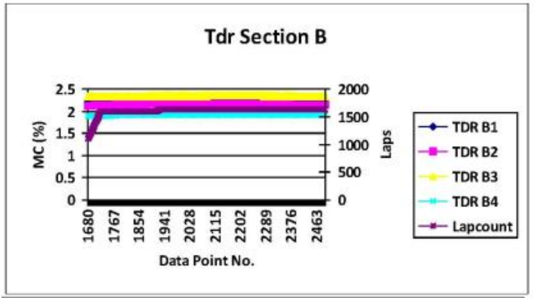
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
7	30/08/2011	100	40	16	Dynamic	1014	41	42	E	E=un-primed most sensitive (UP2-H)	Unprimed	3/5 Racked In First Coat

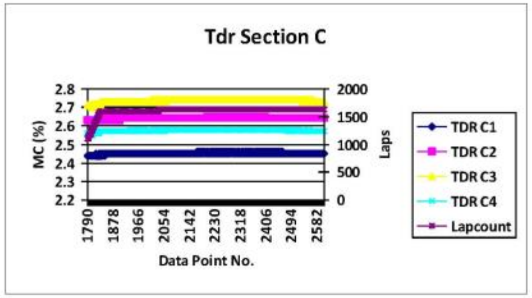
Test No: 8 Nozzle dia: 8 Laps to apply: 500

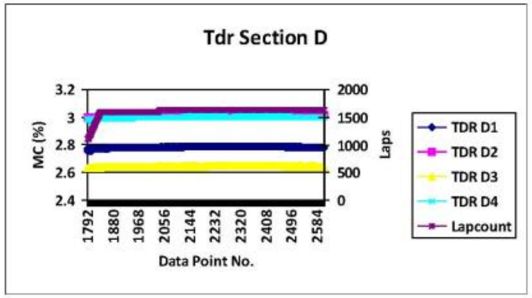
Speed: 40 DA Notes: Dynamic

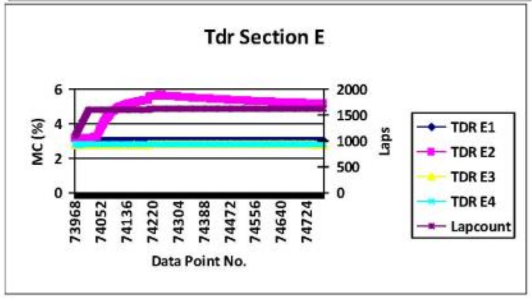
Test Notes: TDR back to normal. 500 laps of 40km/hr on tyre spray only. Noticable increase in TDR by 250 laps but only 0.02%!, could just be temperature. Would only need 1 degC increase. More plucking of the surface. TDR in E took off just downstream of the patch a couple of hours later.

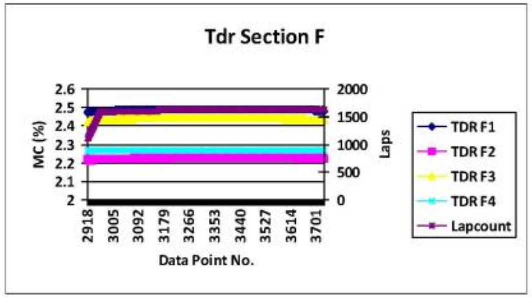










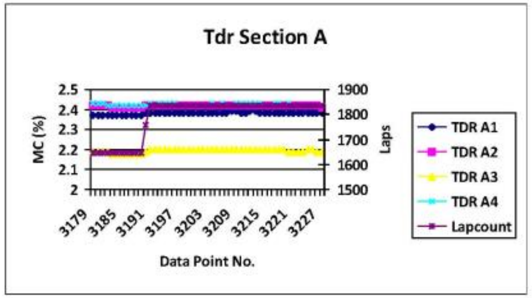


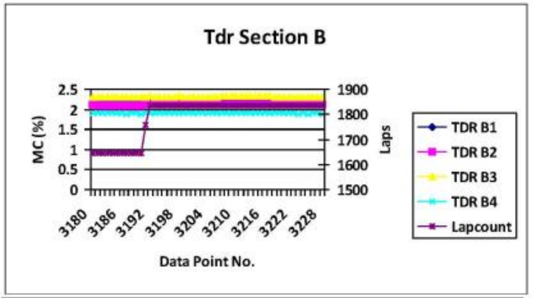
0 Tests and Failures 2 subreport

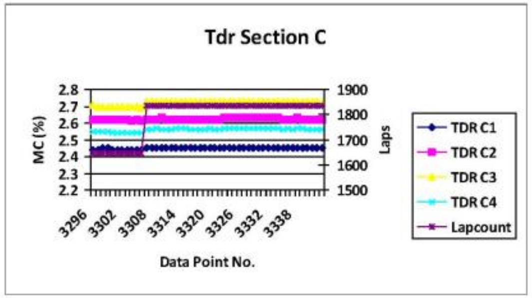
Test No	Test Date	to apply	speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
8	7/09/2011	500	40	8	Dynamic							

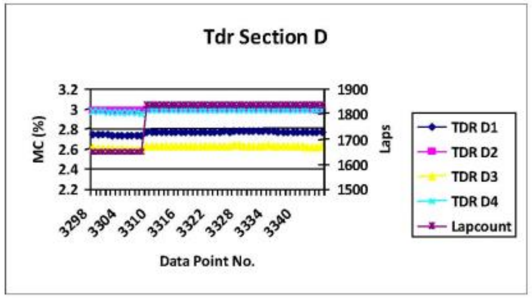
Test No: 9 Nozzle dia: 0 Laps to apply: 300 Test Notes: 100 laps - tyre spray - did emu coils. Chipseal patch repair on section E 14/9. 200 laps at 30 km/hr.

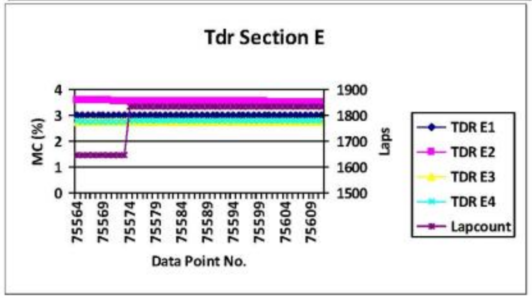
Speed: 20 DA Notes: Moist - coils

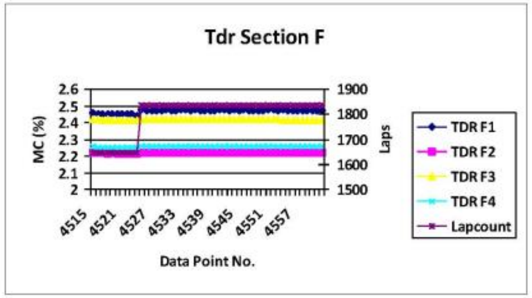










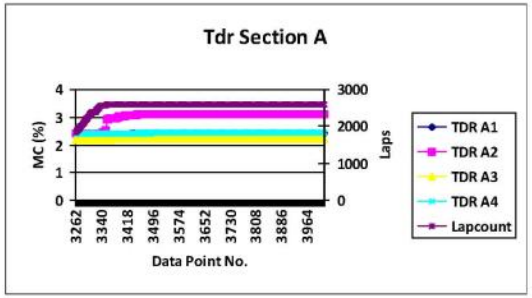


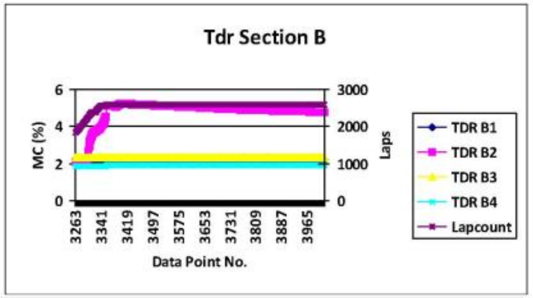
0 Tests and Failures 2 subreport

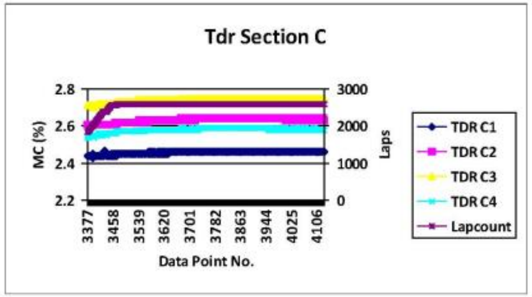
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
9	15/09/2011	300	20	0	Moist - coils							

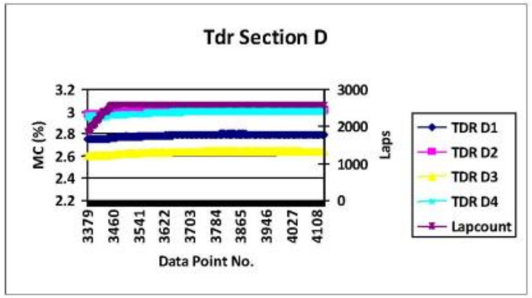
Test No: 10 Nozzle dia: 8 Laps to apply: 500 Test Notes: 40km/hr, 500 Laps. Continued to failure.

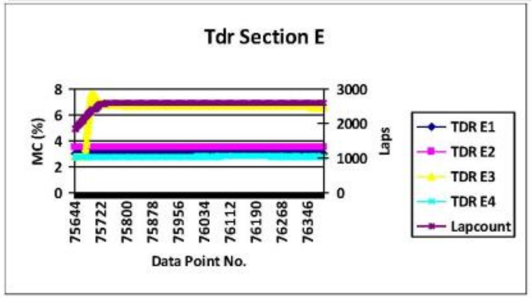
Speed: 40 DA Notes: Dynamic

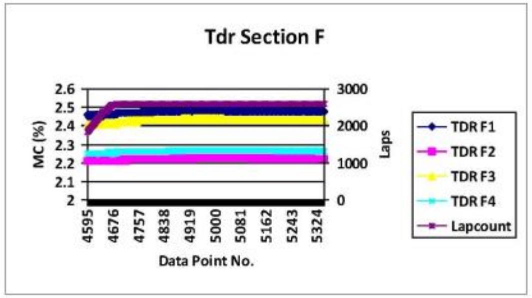








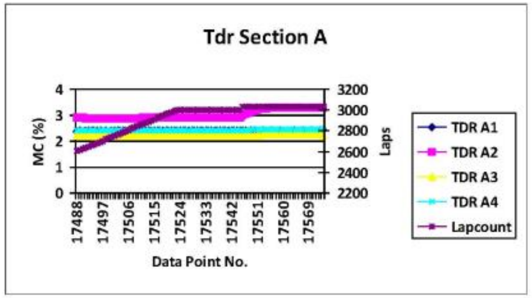


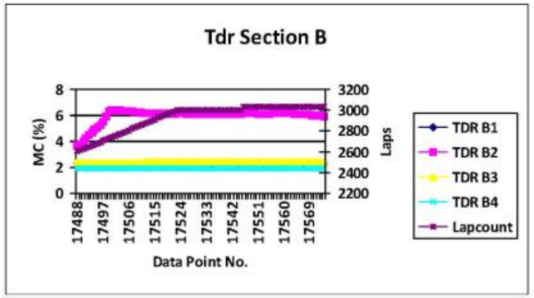


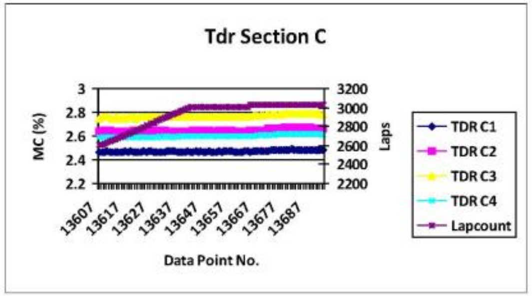
o Tests and Failures 2 subreport

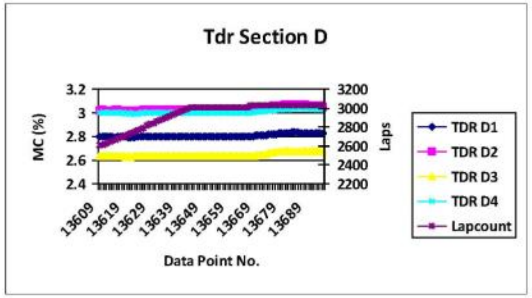
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
10	16/09/2011	500	40	8	Dynamic	2606	42	43	E	E=un-primed most sensitive (UP2-H)	Unprimed	3/5 Racked In First Coat
10	16/09/2011	500	40	8	Dynamic	2606	12	13	B	B=un-primed least sensitive (UP-L)	Unprimed	3/5 Two Coat First Coat

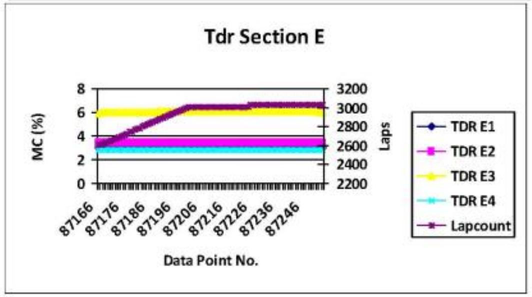
Test No:	11	Nozzle dia:	16	Laps to apply:	500	Test Notes:	stopped at 400 Laps. Heavy water film, TDR in B2 & E2 rising suggesting patch leaking at 90 Laps. Used Ezy street and emulsion on edges of E. B had ezy +100mm of cement stab m/4. 250 laps pothole in E by manifold. 300 Laps rut in B causing surface to fail around patch - deep rut in patch. Tested to 400 laps - stopped to repair E and B. Extra damage done during making repairs due to excavator crossing nib.
Speed:	40	DA Notes:	Dynamic				

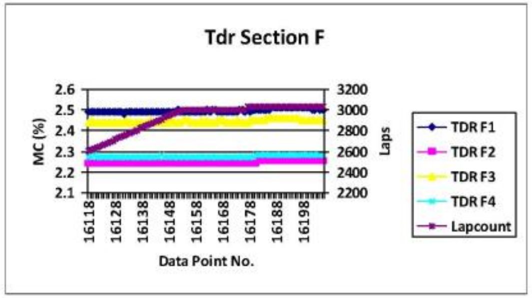










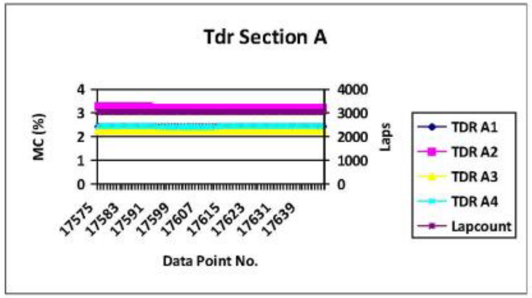


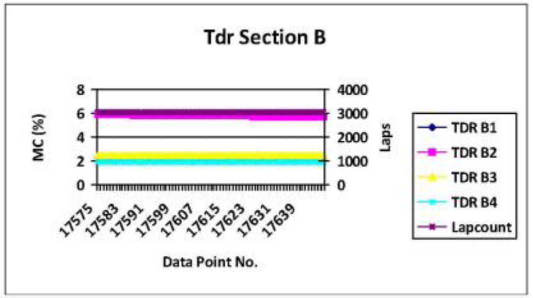
o Tests and Failures 2 subreport

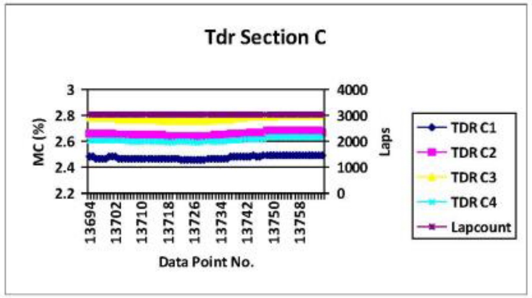
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
11	26/09/2011	500	40	16	Dynamic	3005	12	13	B	B=un-primed least sensitive (UP-L)	Unprimed	3/5 Two Coat First Coat
11	26/09/2011	500	40	16	Dynamic	3005	42	43	E	E=un-primed most sensitive (UP2-H)	Unprimed	3/5 Racked In First Coat

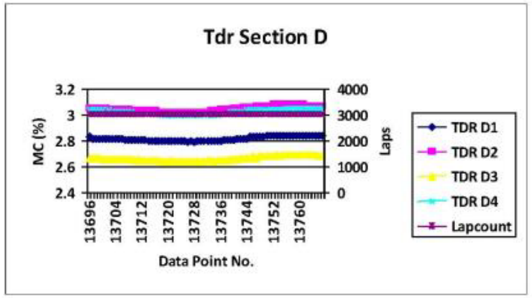
Test No: 11.1 Nozzle dia: Laps to apply: Test Notes:

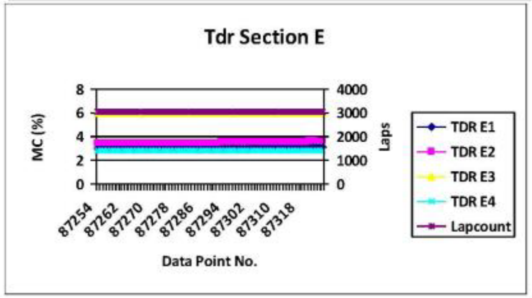
Speed: DA Notes: following day

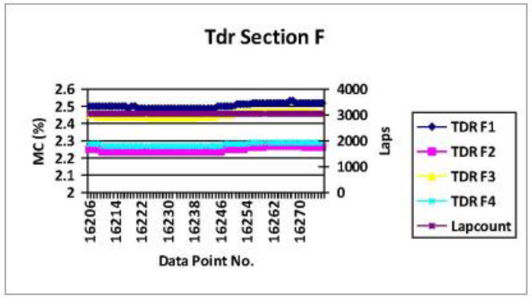










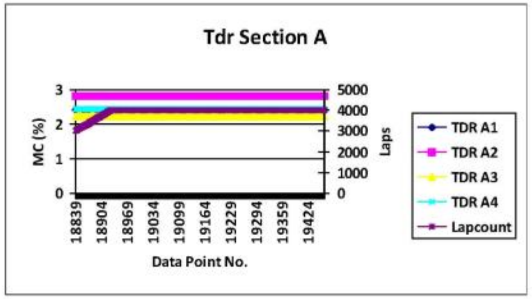


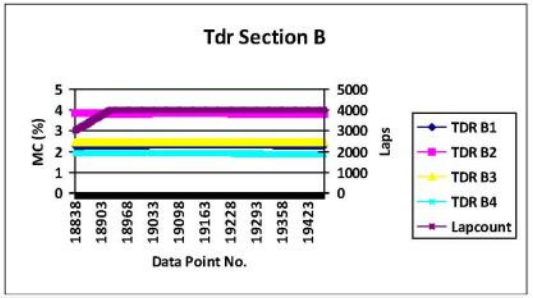
o Tests and Failures 2 subreport

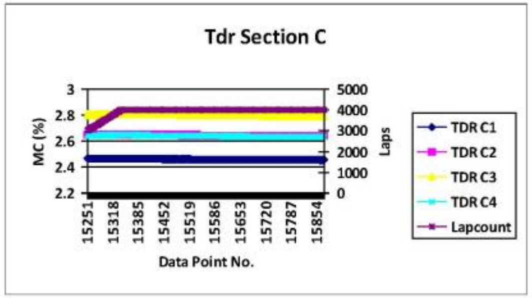
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
11.1	27/09/2011				following day							

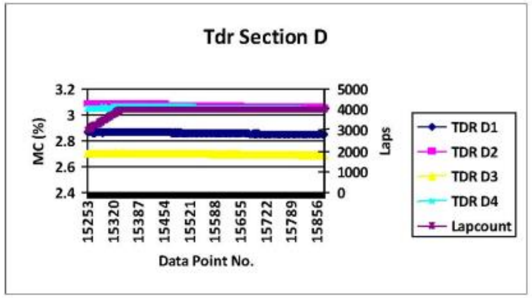
Test No: 12 Nozzle dia: 0 Laps to apply: 1000 Test Notes: 1000 laps wheel spray.

Speed: 40 DA Notes: Dynamic

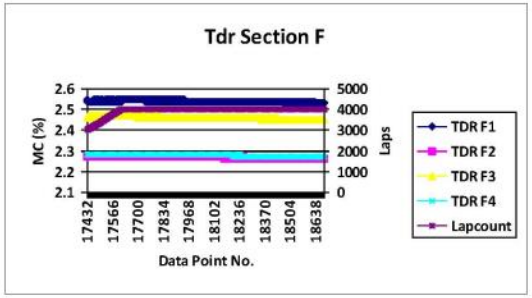








Tdr Section E

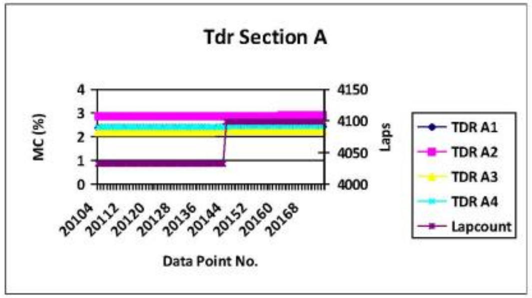


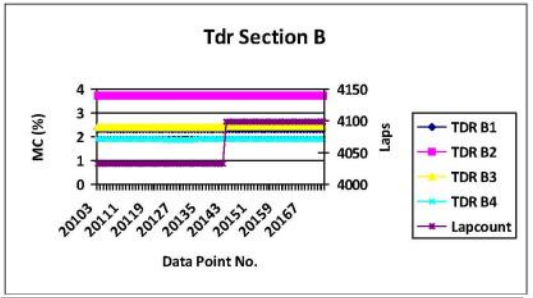
0 Tests and Failures 2 subreport

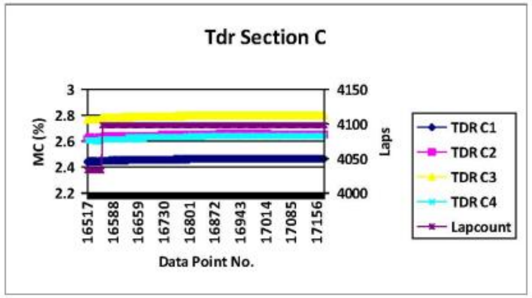
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
12	18/10/2011	1000	40	0	Dynamic							

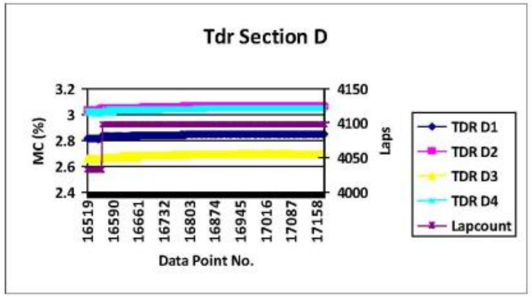
Test No: 13 Nozzle dia: 0 Laps to apply: 100 Test Notes: Coils

Speed: 20 DA Notes: Moist - Coils

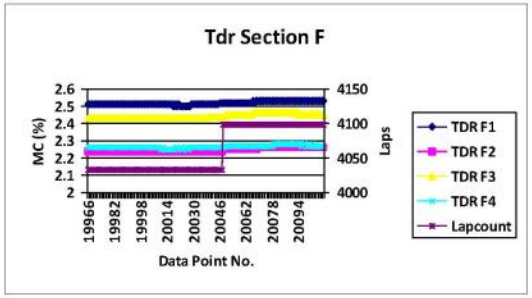








Tdr Section E

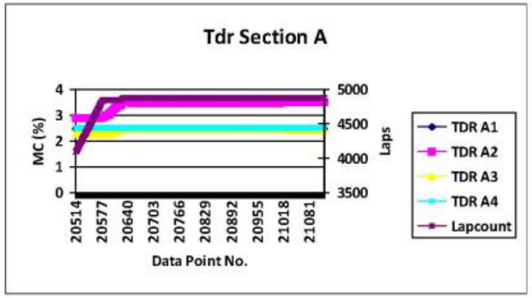


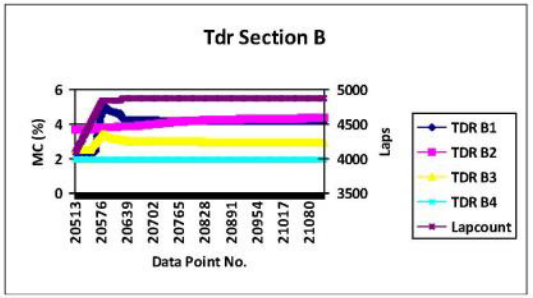
0 Tests and Failures 2 subreport

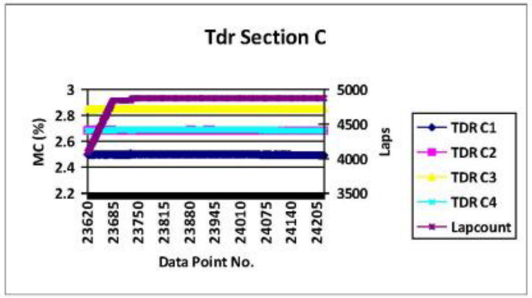
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
13	20/10/2011	100	20	0	Moist - Coils							

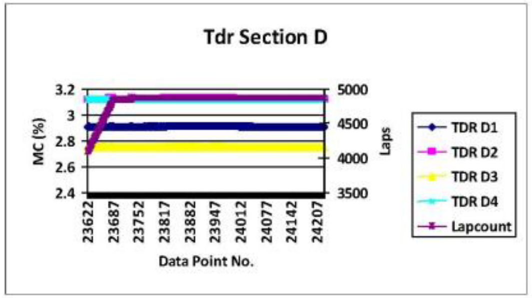
Test No: 14 Nozzle dia: 8 Laps to apply: 1000 Test Notes: Didn't make 1000, shear failure in stn 2.5

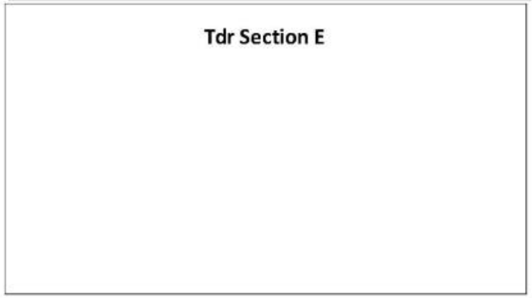
Speed: 40 DA Notes: Dynamic

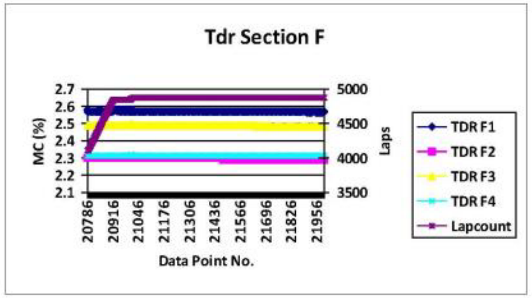










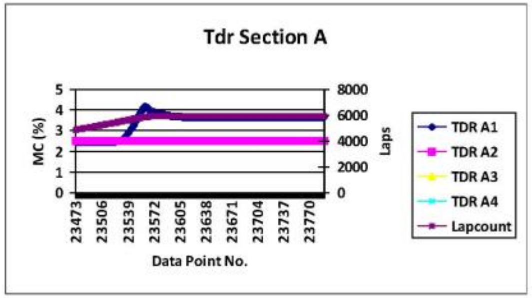


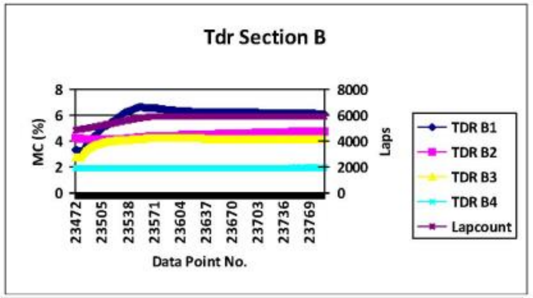
o Tests and Failures 2 subreport

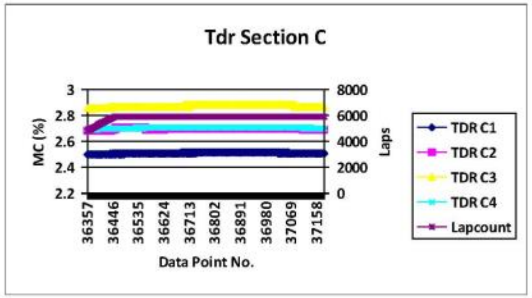
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
14	25/10/2011	1000	40	8	Dynamic	4871	3	4	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat

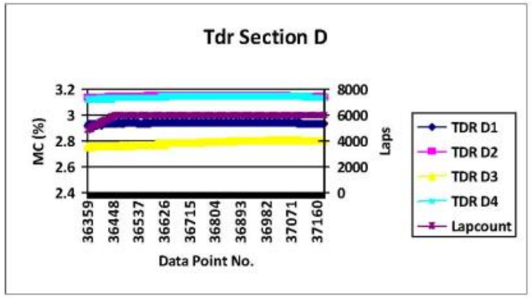
Test No: 15 Nozzle dia: 16 Laps to apply: 1000 Test Notes: almost 1000 laps. A,B,D,F failures, C failed when parked on!!!

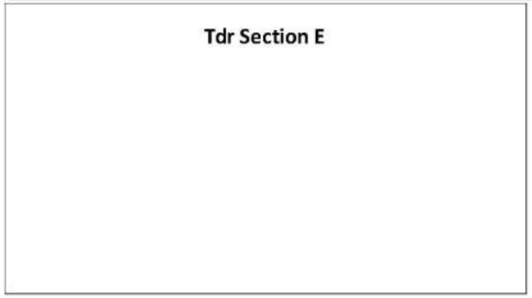
Speed: 40 DA Notes: Dynamic

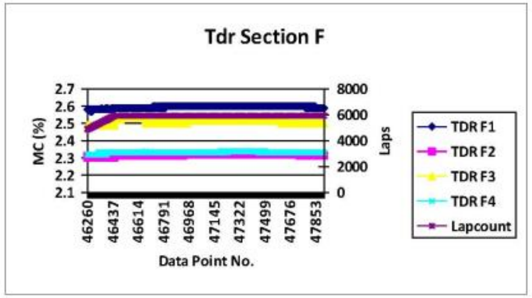










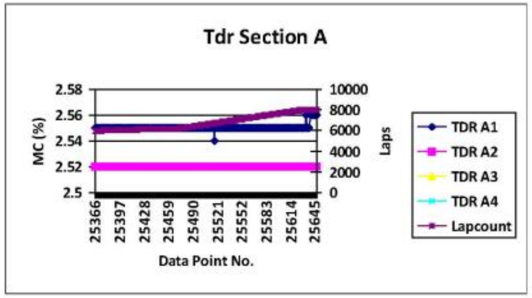


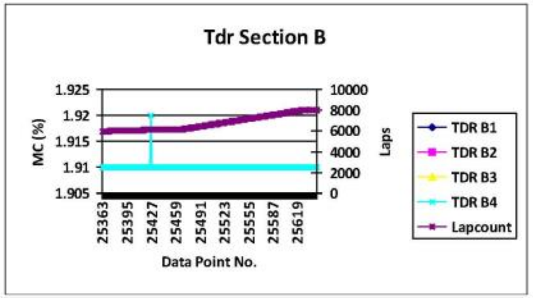
o Tests and Failures 2 subreport

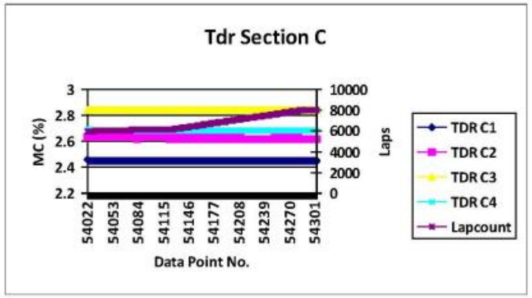
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
15	3/11/2011	1000	40	16	Dynamic	5900	4	5	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat
15	3/11/2011	1000	40	16	Dynamic	5900	49	50	F	F=un-primed medium sensitive (UP2-M)	Unprimed	3/5 Racked In First Coat
15	3/11/2011	1000	40	16	Dynamic	5900	30	31	D	D=un-primed most sensitive (UP-H)	Unprimed	3/5 Two Coat First Coat
15	3/11/2011	1000	40	16	Dynamic	5900	22	23	C	C=un-primed medium sensitive (UP-M)	Unprimed	3/5 Two Coat First Coat
15	3/11/2011	1000	40	16	Dynamic	5900	13	14	B	B=un-primed least sensitive (UP-L)	Unprimed	3/5 Two Coat First Coat
15	3/11/2011	1000	40	16	Dynamic	5900	11	12	B	B=un-primed least sensitive (UP-L)	Unprimed	3/5 Two Coat First Coat
15	3/11/2011	1000	40	16	Dynamic	5900	2	3	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat

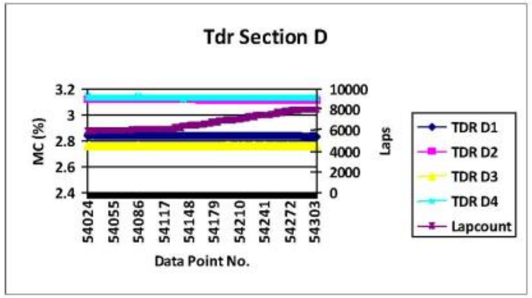
Test No: 16 Nozzle dia: 0 Laps to apply: 2000 Test Notes: Pavement ok

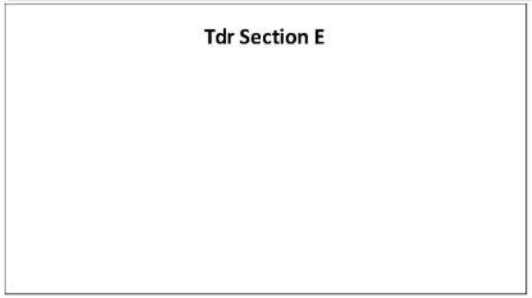
Speed: 40 DA Notes: Dynamic

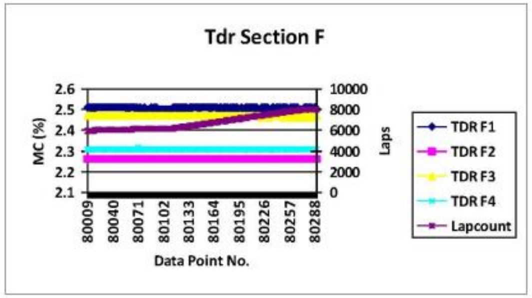










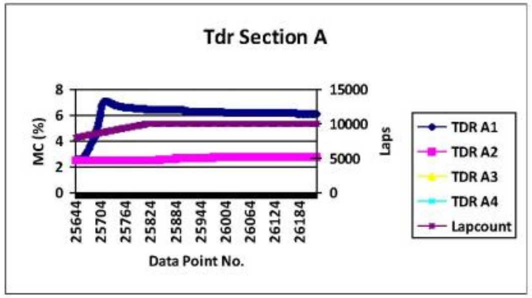


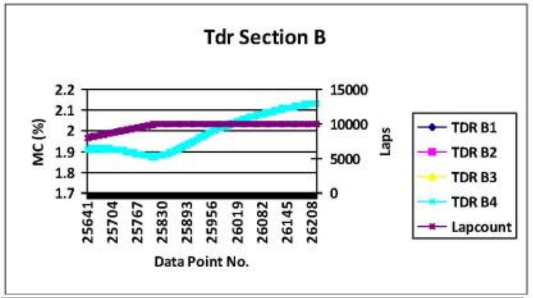
0 Tests and Failures 2 subreport

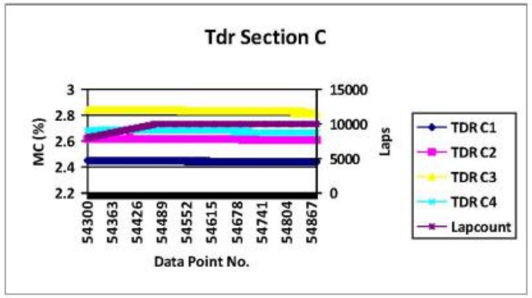
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
16	6/12/2011	2000	40	0	Dynamic							

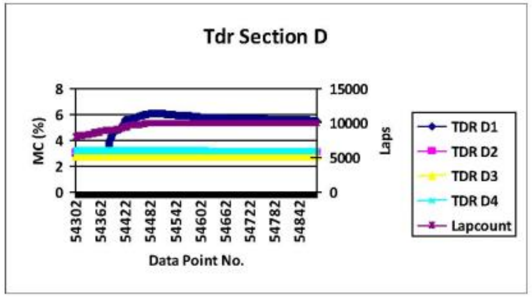
Test No: 17 Nozzle dia: 8 Laps to apply: 2000 Test Notes: Pavement starting to fail

Speed: 40 DA Notes: Dynamic

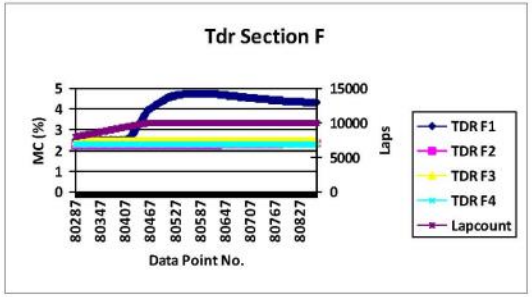








Tdr Section E

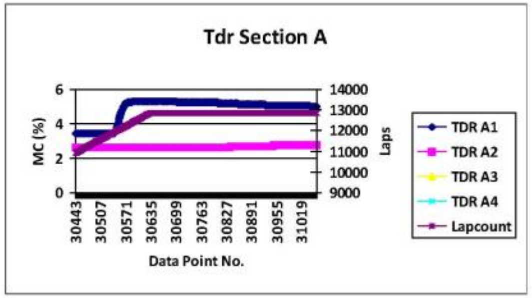


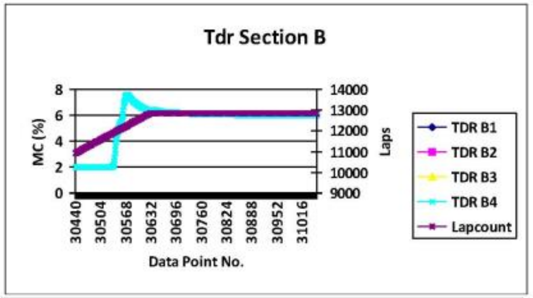
o Tests and Failures 2 subreport

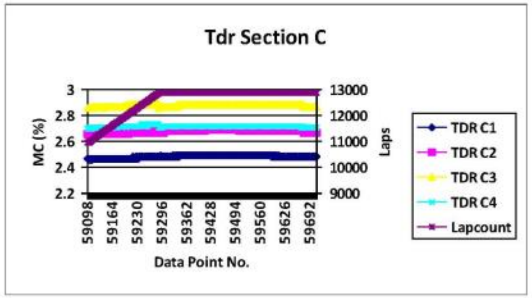
Test No	Test Date	to apply	Speed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
17	6/12/2011	2000	40	8	Dynamic	#####	30	31	D	D-un-primed most sensitive (UP-H)	Unprimed	3/5 Two Coat First Coat
17	6/12/2011	2000	40	8	Dynamic	#####	10	11	B	B-un-primed least sensitive (UP-L)	Unprimed	3/5 Two Coat First Coat
17	6/12/2011	2000	40	8	Dynamic	#####	3	4	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat
17	6/12/2011	2000	40	8	Dynamic	#####	0	1	A	A=un-primed least sensitive (UP2-L)	Unprimed	3/5 Racked In First Coat
17	6/12/2011	2000	40	8	Dynamic	#####	33	34	D	D=un-primed most sensitive (UP-H)	Unprimed	3/5 Two Coat First Coat

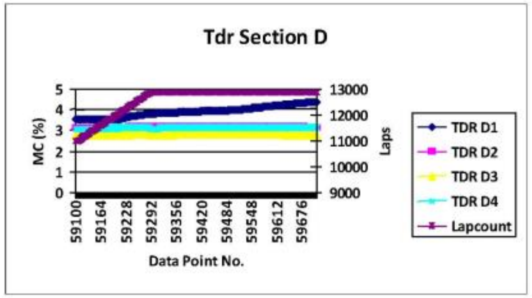
Test No: 18 Nozzle dia: 16 Laps to apply: 2000 Test Notes: Pavement starting to fail - test reduced to 35km/hr due to bounce.

Speed: 40 DA Notes: Dynamic

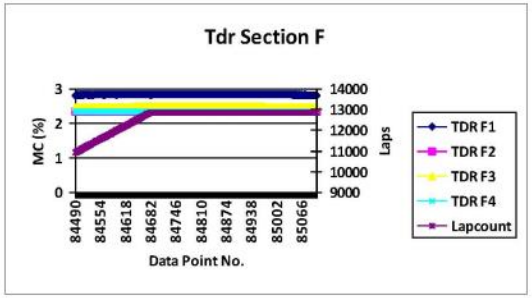








Tdr Section E

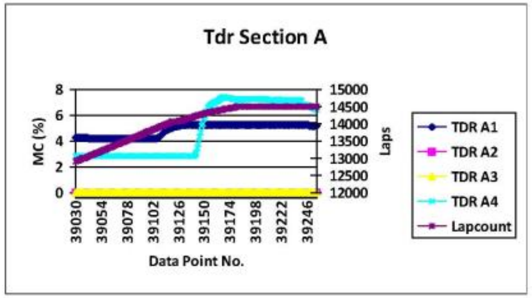


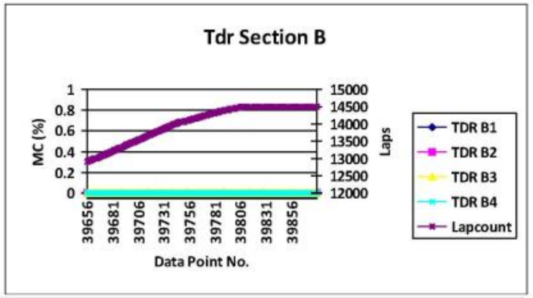
o Tests and Failures 2 subreport

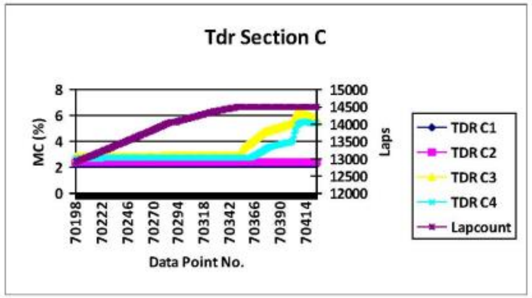
Test No	Test Date	to apply	ipeed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
18	24/01/2012	2000	40	16	Dynamic							

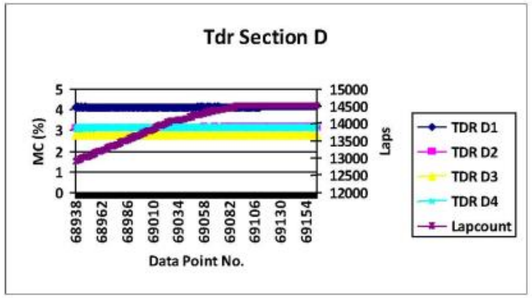
Test No: 19 Nozzle dia: 16 Laps to apply: 2000 Test Notes: Tight shear failure in C. Porosity Evident in AC patches. Depths of AC to be determined.

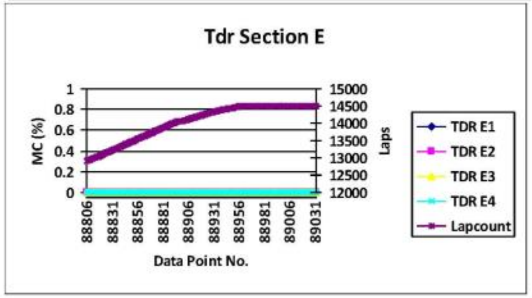
Speed: 40 DA Notes: Dynamic

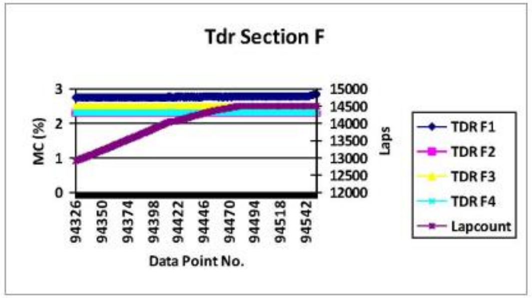












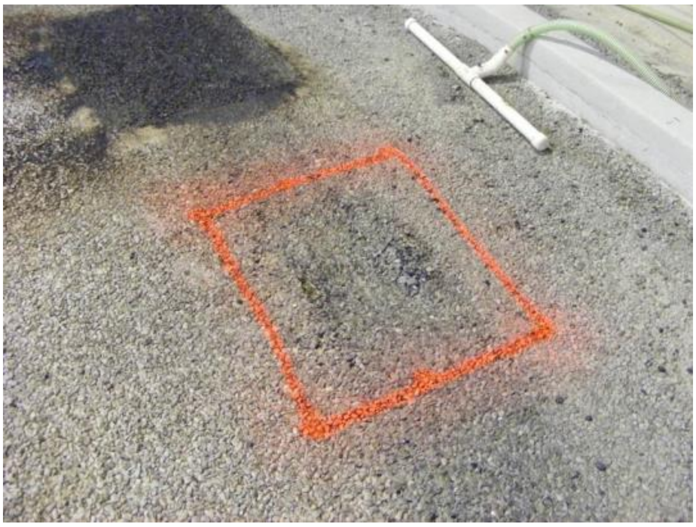
o Tests and Failures 2 subreport

Test No	Test Date	to apply	ipeed	le dia	DA Notes	Laps	Stn start	Stn End	Section	Theory	Primed	Surfacing
19	15/02/2012	2000	40	16	Dynamic							

Appendix D: Water 2 failure photos

30 August 2011

16 September 2011 Stn 42-43

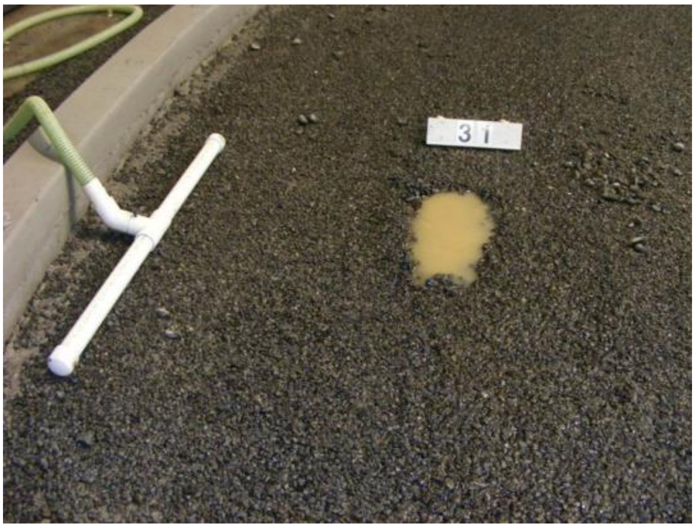


26 September 2011 Stn 12-13

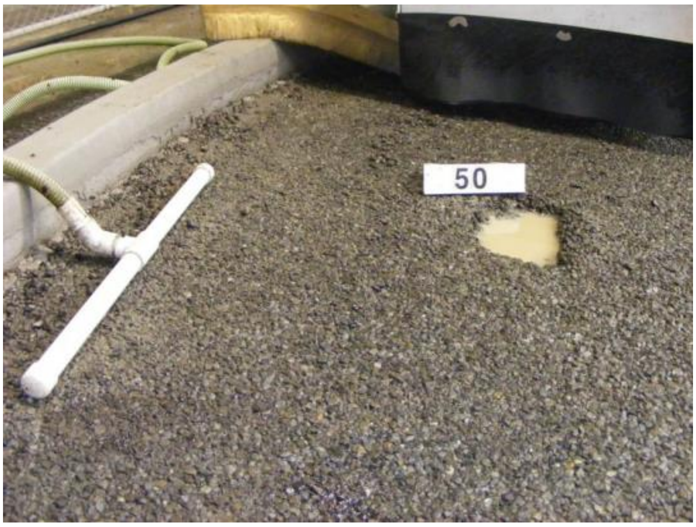
25 October 2011

3 November 2011 repairs

3 November 2011 repairs



3 November 2011 repairs



3 November 2011 repairs

6 December 2011 section A repairs

24 January 2012 section B

24 January 2012 section B top scraped back to dry material

Appendix E: Moisture gauge testing

E1 Suitability of moisture sensors for measuring in-situ moisture content of basecourse material at CAPTIF

E1.1 Introduction

During 2008 some preliminary trials were carried out on various types of moisture sensors to determine their suitability for use in test pavements at the CAPTIF research facility.

E1.1.1 Sensors

Four types of sensors were chosen to evaluate

1 Campbell Scientific CS625. This uses the time domain reflectometry (TDR) method to determine moisture.

2 Decagon Devices ECH2O EC10. This gauge is a capacitance sensor and measures the change in dielectric content with change in moisture.

3 Decagon Devices ECH2O EC5. This is the same as the EC10 but smaller in size.

4 Campbell Scientific 229-L. This uses a heat dissipation method. (Note: This sensor did not arrive in time so was not tested.)

E1.1.2 Installation

The sensors were in the pavement in February. All sensors survived construction.

E1.1.3 Monitoring

The sensors were monitored in the pavement since installation. The TDR sensors proved to be very stable. Minor shifts with pavement temperature change occurred.

The ECH20 sensors showed larger temperature drifts. The ECH20 sensors also exhibited a 'step' shift in their output if the power to the datalogger was switch off. This occurred for Windows updates. The TDR sensors seemed immune to power stop/starts.

Based on these observations, only the TDR sensors were chosen for further evaluation.

E1.1.4 Calibration

Fulton Hogan Ltd supplied AP40 basecourse samples at five moisture contents.

The samples were prepared as follows:-

1 Half the sample was placed in a plastic container and lightly compacted.

2 The TDR sensor was placed on the surface (figure E.1(a)).

3 The remaining material was placed in the container and lightly compacted (figure E.1(b)).

Figure E.1 Calibration of TDR sensor

(a)

(b)

The sensors were monitored for about 24 hours to establish an output for the moisture content.

Note 1: TDR sensors measure volumetric moisture. The calibration samples are made according to gravimetric moisture (mass) methods. Therefore the density of the material after compaction will influence the output of the TDR sensors.

Note 2: Output from the TDR sensors is temperature sensitive and our samples were subject to ambient temperatures.

For the above reasons the calibrations conducted were expected to give a ‘feel’ for the equipment rather than an accurate calibration.

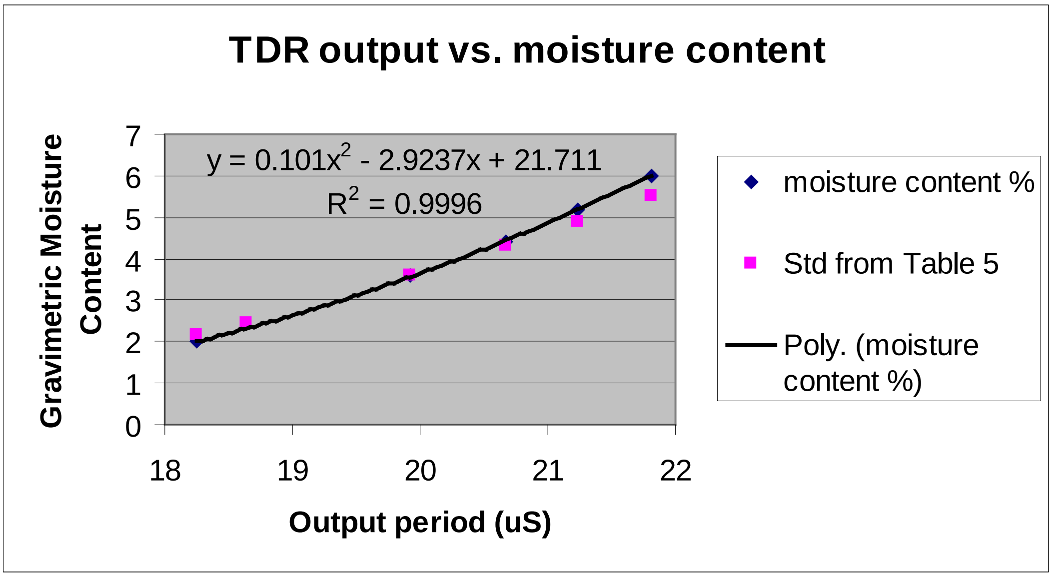
TDR sensors output a square pulse waveform. The period (microsecends) of the waveform is dependent on the moisture content of the sample. The following calibration data was obtained (see table E.1.) Also included (*1) is a comparison with calculated data from calibration coefficients for sandy loam as supplied in the CS615 instruction manual.

Table E.1 TDR output (uS) vs moisture content

uS output	Moisture content %	(*1)	Removed
18.255	2	2.15322625	
18.645		2.46132625	2.8
19.925	3.6	3.57940625	
20.675	4.4	4.31065625	
21.24	5.2	4.89868	
21.805	6	5.51862625	

The data was plotted and graphed (figure E.2). A trendline was added with the equation fitted.

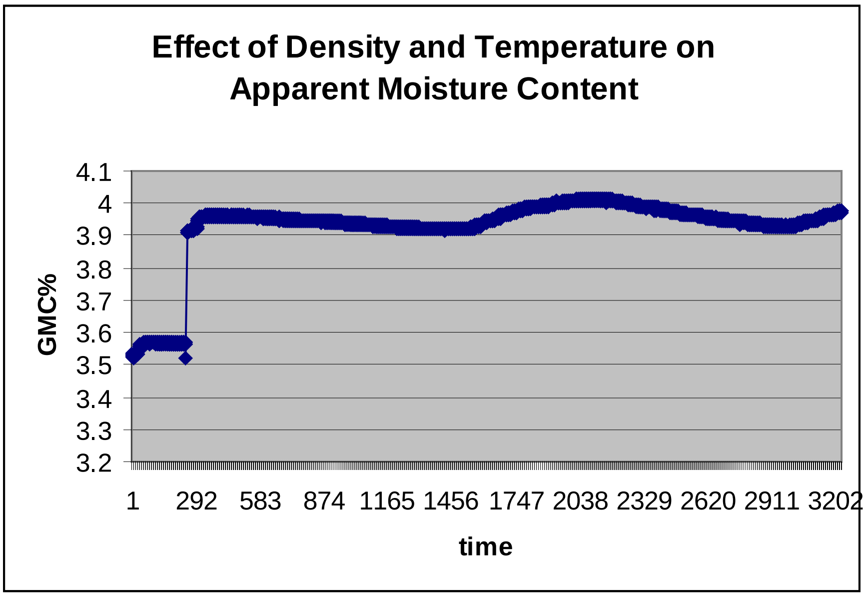
Figure E.2 TDR output vs moisture content



E1.1.4 Density and temperature effects

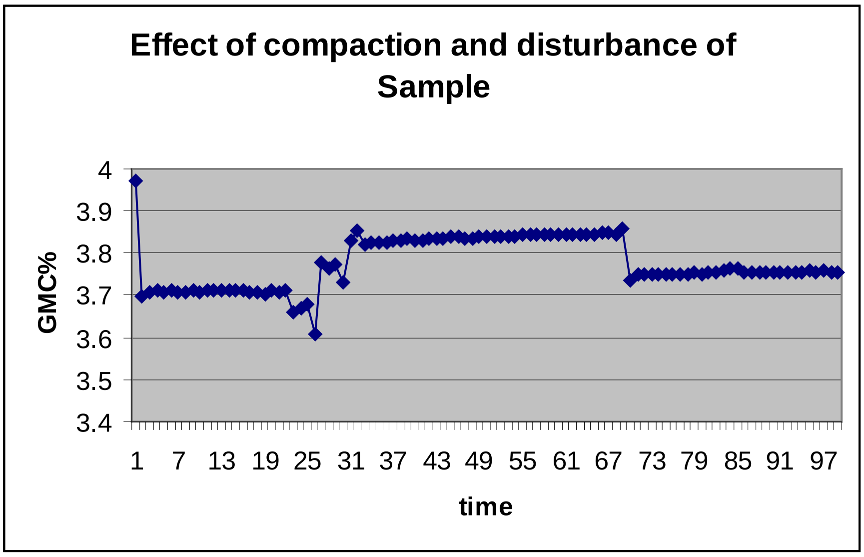
A 3.6% gravimetric moisture content sample was compacted and measured with the TDR gauge. After a short period the sample was re-compacted with a heavier effort. The effect of this is shown in figure E.3. After this compaction the sample was left for 24 hours and the effect of ambient temperature is apparent.

Figure E.3 Effect of density and temperature on apparent moisture content



The sample was picked up and moved. This had the effect of loosening the material and lowering the density. Figure E.4 shows disturbance then re-compaction.

Figure E.4 Effect of compaction and disturbance of sample



The effect of temperature and density can be largely overcome by calibration and compensation. The TDR can be calibrated in samples of equal density (ie with a measured equal compaction effort) and then placed in a temperature controlled environment before the TDR measurement.

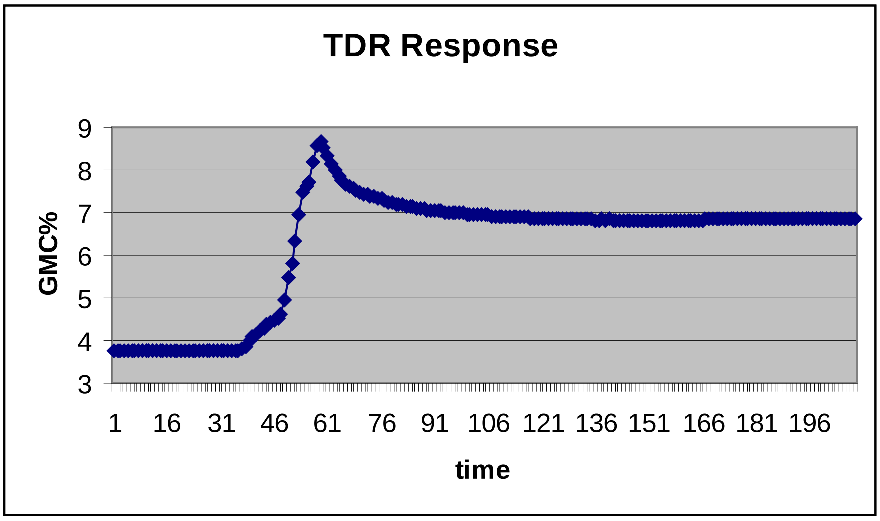
A dummy sensor can be placed in an isolated container in the pavement where it is not subject to moisture change but can be affected by pavement temperature.

The pavement moisture and density can be measured with a nuclear density meter when the gauges are installed so that a baseline offset can be applied to the calibration equation.

E1.1.5 Response

An amount of water was added to the above sample to increase the total water content to about 7%. The water was poured from a container directly on to the surface of the sample. The TDR sensor was recorded at a rate of 1 sample/sec to capture the rapid infiltration of water. As can be seen in figure E.5, a spike of moisture is recorded as the flow passes the sensor. The moisture content then equilibrates through the sample.

Figure E.5 TDR response



E1.1.6 Cost

The TDR sensors are supplied by Scott Technical and cost $385 each.

The equipment needed to read the sensors are PXI 6602 cards and connectors supplied by National Instruments. The cost is about $2,000 per eight channels. These cards plug into our existing PXI chassis.