MOISTURE IN PAVEMENTS: DIRECTIONS FOR NEW ZEALAND RESEARCH

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MOISTURE IN PAVEMENTS : DIRECTIONS FOR NEW ZEALAND RESEARCH

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EXECUTIVE SUMMARY

Introduction

Road pavements are often wet from moisture from the air and from the ground. Knowledge about the source of that moisture, about the amount of moisture, and about its effects on pavements is required by pavement designers. They need the knowledge to carry out realistic modelling of the properties of the materials and layers used for constructing a pavement.

For subgrade layers the pavement design has traditionally been based on the soaked strength of the materials proposed for the construction. This is the most conservative condition. Since the introduction of the AUSTROADS Pavement Design Guide in 1992, the pavement designer has had the ability to design for other than soaked conditions. However to use the AUSTROADS Guide a knowledge of moisture conditions likely to be experienced by a site are needed.

For granular basecourse layers the introduction of the dynamic triaxial test allows the pavement designer to maximise the use of local materials which may not fully comply with Transit New Zealand specifications. Again, in order to fully utilise this test the moisture condition, i.e. degree of saturation likely to be experienced, needs to be known. At present (1998) a conservative condition of complete saturation is assumed.

If a greater understanding of moisture movement in pavements could be obtained, then the conservative saturation conditions (soaked strength) used now for pavement design may not need to be as strict. This would allow greater flexibility in choice of materials, resulting in significant savings in construction costs.

Research

Research into moisture in New Zealand pavements was started in 1979 and led to the instrumentation and monitoring of moisture in two sample pavements. The project recorded in this report was commissioned in 1995 to indicate the future directions that New Zealand research should take to evaluate moisture conditions in pavements.

Research on moisture in pavements is underway in the US by the FHWA (Federal Highways Administration) for the SHRP (Strategic Highway Research Program) and by the Minnesota Department of Transport (MnDOT) for its Mn/ROAD project. Both these projects are researching the long-term effects of seasonal changes of moisture on pavement performance.

Research in Queensland is for prediction of moisture movement in pavements using the simulation program THEWET 1990.

Monitoring techniques that have been used to measure moisture conditions in pavement layers – piezometers, gypsum resistance blocks, Time Domain Reflectometers (TDRs), neutron probe, electric resistivity – are described.

At the same time that moisture contents are recorded, records are taken of the pavement environment, i.e. climate records, subgrade temperatures, pavement properties especially strength. Pavement strength is measured by deflections with different devices.

Recommendations

The conclusion is that fundamental studies should not be commissioned in New Zealand until the results of the SHRP and Mn/ROADS projects become available.

In the meantime while the long-term studies are being developed, research could be carried out as part of pavement operations in New Zealand to give pavement designers basic information on moisture in subgrades and basecourses. Such research during pavement operations is recommended and should:

1. Determine the effects of a range of pavement parameters on the theoretical distribution of moisture in pavements by performing a sensitivity analysis with THEWET software. Use the results to select a minimum of 20 sites for further research.

2. Monitor these sites for a year using the FWD (Falling Weight Deflectometer) to estimate the changes in pavement strength occurring in New Zealand pavements during the seasons. Relate the changes in strength with seasonal changes in moisture in pavements.

ABSTRACT

Research into moisture in pavements in New Zealand started in 1979 and led to the instrumentation and monitoring of moisture in two sample pavements. The project recorded in this report was commissioned in 1995 to indicate the future directions that New Zealand research should take to evaluate moisture conditions in pavements.

Fundamental studies in New Zealand should not be commissioned until the results of long-term projects underway in the US become available. These projects are researching the long-term effects of seasonal changes of moisture on the strength and performance of pavements.

Instead, research during pavement operations is recommended and should:

1. Determine the effects of a range of pavement parameters on the theoretical distribution of moisture in pavements by performing a sensitivity analysis to select suitable sites.
2. Monitor these sites for a year using the FWD (Falling Weight Deflectometer) to estimate the changes in pavement strength occurring in New Zealand pavements during the seasons, and to relate the changes in strength with seasonal changes in moisture in pavements.

1. INTRODUCTION

Road pavements are often wet from moisture from the air, and from the ground. Knowledge about the source of that moisture, about the amount of moisture, and about its effects on pavements is required by pavement designers. They need the knowledge to carry out realistic modelling of the properties of the materials and layers used for constructing a pavement.

For subgrade layers the pavement design has traditionally been based on the soaked strength of the materials proposed for the construction. This is the most conservative condition. Since the introduction of the AUSTROADS Pavement Design Guide in 1992, the pavement designer has had the ability to design for other than soaked conditions. However to use the AUSTROADS Guide a knowledge of moisture conditions likely to be experienced by a site are needed.

For granular basecourse layers the introduction of the dynamic triaxial test allows the pavement designer to maximise the use of local materials which may not fully comply with Transit New Zealand specifications. Again, in order to fully utilise this test the moisture condition, i.e. degree of saturation likely to be experienced, needs to be known. At present (1998) a conservative condition of complete saturation is assumed.

If a greater understanding of moisture movement in pavements could be obtained, then the conservative saturation conditions (soaked strength) used now for pavement design may not need to be as strict. This would allow greater flexibility in choice of materials, resulting in significant savings in construction costs.

The objective of this study was to develop a research strategy for the evaluation of moisture conditions in New Zealand pavements, and of the effects of moisture changes on pavement strength. To do this the results and directions of overseas research were evaluated.

2. PREVIOUS NEW ZEALAND RESEARCH

In 1979 a comprehensive literature review was undertaken (McLarin 1989) which established that moisture in a road subgrade had a significant influence on the subgrade stability and therefore on pavement life.

This review was followed by field evaluation of moisture measurement techniques for determining the subgrade moisture conditions directly. (This was part of National Roads Board Project PD/2, PE/17 Stage 1; Transit New Zealand Research Project PR/17 Stage 2.)

The field work was at one Auckland site and two Wellington sites, instrumented to determine the moisture conditions beneath the road pavements with time. Limited success was achieved at the Auckland site because of instrument failure, and infiltration of water from the road surface caused by disturbance at the time that the instrumentation was installed. In Wellington, the instruments operated successfully over the period of the project.

In the three New Zealand sites, the effect of the change in moisture conditions on the pavement strength was not studied.

Results from the two Wellington sites indicated that the water content, as indicated by soil suction, was higher than expected.

The first site was in a residential street and was considered "wet" (McLarin 1987). Moisture changes showed patterns dominated in winter by ingress of water through the chipseal surface and in summer by "drainage to receding water tables". The moisture movement in the pavement was also affected by the presence of trenches, stormwater drains, manholes and grass verges.

Monitoring was also performed on an elevated section of a four-lane divided highway surfaced with asphaltic concrete and friction course. This site was considered to be "dry" and not affected by underground services and grass verges. Despite very careful installation of instruments, including efforts to reseal the pavement surface, results indicated that the moisture conditions in the subgrade were affected by water leakage from the surface.

3. OVERSEAS RESEARCH

In the course of this project, contact was made with the following researchers:

- Neil Hawks of the Transportation Research Board (TRB), a former Director of the SHRP (Strategic Highways Research Program) program.
- David Newcomb of the School of Civil and Mineral Engineering, University of Minnesota, a principal researcher on the Mn/ROAD project.
- Craig Schrader of the Physical Research Section, Minnesota Department of Transportation (Mn/DOT), a researcher on the Mn/ROAD project.
- Lynne Irwin of Cornell University, Cornell Local Roads Program.
- Aramis Lopez of the Federal Highway Administration (FHWA), Virginia, co-author of the instrumentation installation and data collection guidelines for the SHRP LTPP (Long-Term Pavement Performance) project.

- Keith Wallace of the School of Civil Engineering, Queensland University of Technology, developer of the moisture movement simulation program THEWET.

- Burt Look at the Queensland Department of Transport (DoT), extensive user of TDRs (Time Domain Reflectometers), and considered as the TDR guru at Queensland DoT.

- Steve Zeglin of the CSIRO Environmental Mechanics, Black Mountain, extensive user of TDRs, developer of the system used by Queensland DoT.

- Ian Reeves at the Pavements Business Centre, Queensland DoT, former loan staffer on the SHRP program.

3.1 Strategic Highway Research Program (SHRP)

Research is currently being conducted in the US which, among other things, has focused on the measurement of moisture conditions under roads and the strength of the pavement. The research programme is called the Strategic Highway Research Program (SHRP). It was recognised by the SHRP researchers (Rada et al. 1994) that, as the temperature and moisture content of paved roads changed over the course of a year, the structural characteristics of the pavement layers also changed. SHRP established a seasonal monitoring programme within its long-term pavement performance (LTPP) project. This had, as its main objective, to collect the data required to achieve a fundamental understanding of how variations in temperature and moisture affect pavement response.

Sixty four sites have been identified in this project and instrumented for this purpose. Each site has time-domain reflectometry sensors (TDRs) and thermistor probes to monitor changes in subsurface moisture and temperature; resistivity probes to measure freeze-thaw depth; piezometers to determine the ground-water table; air temperature probes and tipping bucket rain gauges to monitor ambient temperature and precipitation.

At each site deflection basin testing is being undertaken once a month to monitor changes in the structural properties of the pavement.

Of the 64 sites, 75% are on flexible roads and this number is split again between thin (<127 mm) asphaltic concrete surfaces over fine or coarse subgrades, and thick (>127 mm) asphaltic concrete surfaces over fine or coarse subgrades. No sites are on thin chipseal surface roads.

As part of the SHRP LTPP Program, Australia has instrumented nine sites in Queensland, New South Wales and Victoria (ARRB 1994). Six of these sites are on asphaltic concrete on a bound base, and one is asphaltic concrete on a granular base. None are on chipseal.

In 1997, the only reported results available for assessing the success of the LTPP Program were from the instrumentation pilot studies (Rada et al. 1994).

3.2 Mn/ROAD

Also in the USA, the Minnesota Department of Transportation (Mn/DOT) has a full scale pavement instrumentation project called the Minnesota Road Research project (Mn/ROAD) which has been operating for one year (D.Newcomb, pers.comm.). The test facility is running 40 different asphalt, concrete and aggregate pavement sections. Over half of the 4,500 roadway sensors are dedicated to measuring moisture and temperature parameters below the pavement surface.

The structural properties are checked periodically with a falling weight deflectometer (FWD) and a loaded truck. No published results are available for the Mn/ROAD program as at 1997.

4. MONITORING TECHNIQUES

4.1 Introduction

One of the main difficulties in determining moisture conditions in pavements has been associated with developing appropriate instrumentation and installation techniques.

Often direct measurement of moisture content has not been performed, but the effects of moisture changes have been indicated by changes in either soil suction or pavement strength. Some of the techniques used to determine moisture, temperature and climate are described below.

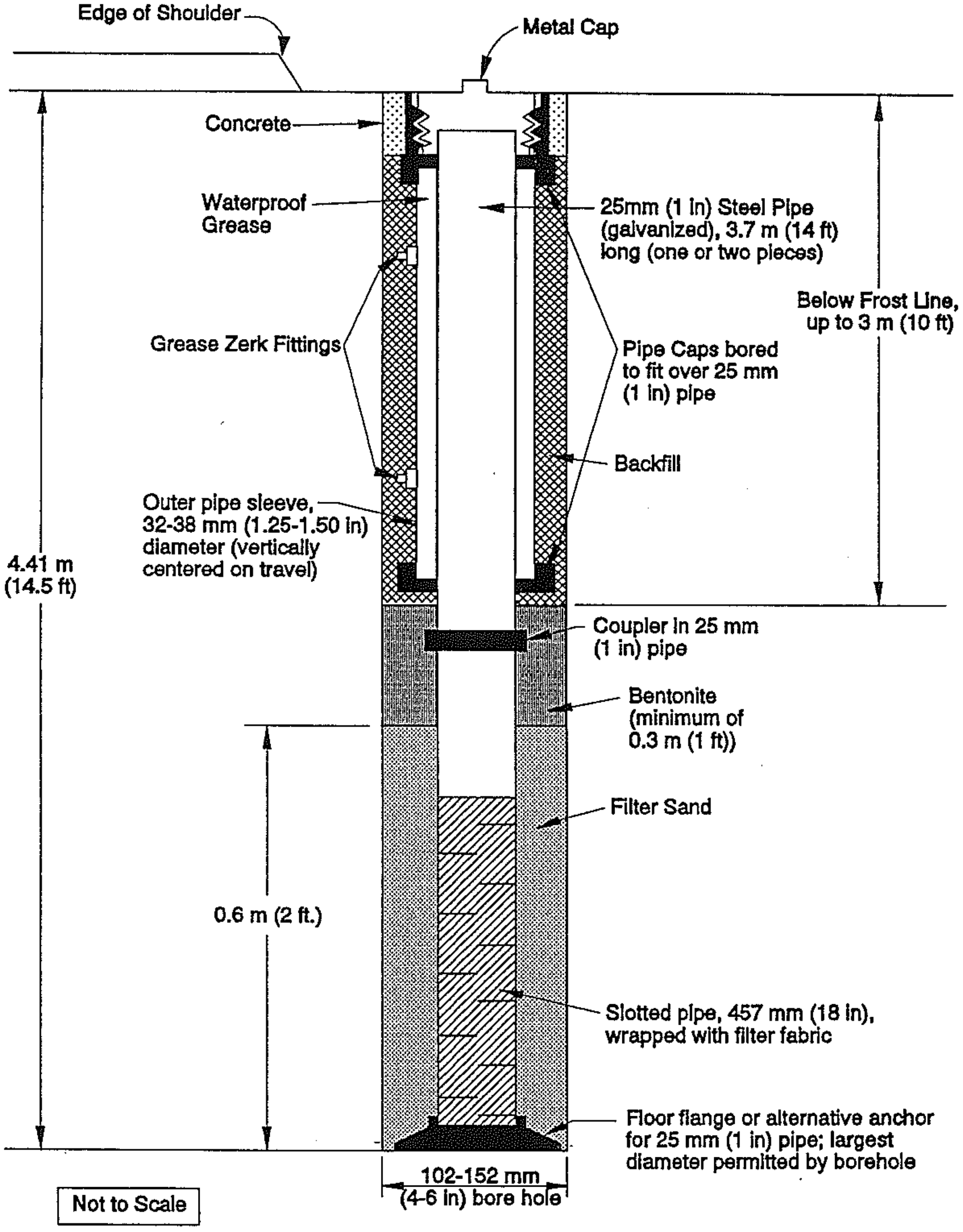
4.2 Techniques for Moisture Measurement

4.2.1 Piezometers

In the New Zealand trials at the "wet" site (McLarin 1987), three types of hydraulic piezometers (tensiometers) had been selected to allow comparison of their performance and ease of use. These piezometers monitor pressure changes in a water-filled tube terminating at the desired depth with a fine pored filter. Such instruments operate at tube pressures up to 80 kPa less than atmospheric pressure.

In the US SHRP Program, the seasonal variation in the ground-water depth is measured by a submersible pressure transducer. Details of the probe are presented in Figure 1.

Figure 1. Observation piezometer for seasonal monitoring program (not to scale).
(from FHWA SHRP Program)



4.2.2 Gypsum Resistance Blocks

The resistance of a gypsum block changes with changing water content of the surrounding material, as they equilibrate to the same suction as their surroundings.

Gypsum resistance blocks had been selected for use in the basecourse in the initial New Zealand trials because they are not limited by water cavitation effects. Based on the experiences at the "wet" site, and because of the expected different subsurface moisture conditions at a "dry" site, namely higher soil suctions, gypsum resistance blocks were selected for the trial (Transit New Zealand 1993). At this dry site, standpipe piezometers were installed beneath the pavement for water-table monitoring. Generally all instrumentation at the "dry" site performed well.

For the Mn/ROAD project in the US, resistance blocks were used as one of three methods for measuring moisture content. The other methods were: time domain reflectometers (TDR), and a neutron probe (D.Newcomb, pers.comm.).

4.2.3 Time Domain Reflectometer (TDR)

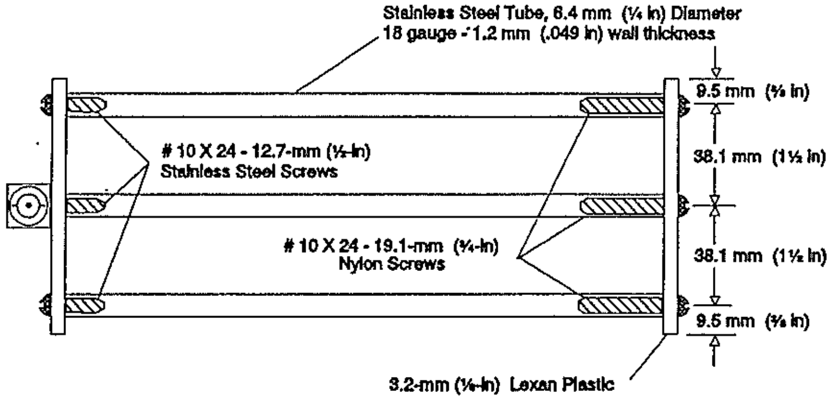
In the Mn/ROAD project, Mn/DoT has found that, as long as the TDR was properly calibrated, it was the most reliable method. In essence, the electrical capacitance of the soil between two parallel steel rods is measured and this is related to the volumetric moisture content. Mn/DOT found that automating the acquisition of TDR data was expensive and so they elected to take manual readings. An important qualifier on the use of TDRs is that with many soils a universal equation relates the measured dielectric to volumetric soil moisture, but on some clay soils a unique calibration needed to be determined (C.Schrader, Mn/DOT, pers.comm.).

In Queensland, S.Zegelin (pers.comm.) noted that the TDRs could give volumetric moisture content to an accuracy of 0.2%. He also noted that, in his experience, the TDRs were most suitable for coarse sandy soils, and that in clay soils the signal is attenuated by the conductivity of the soil. CSIRO has multiplexed up to 16 probes into one TDR system and, if low loss cables are used, these can be up to 50 m in length. Two CSIRO-produced TDRs are being used by Landcare in Havelock North and Christchurch for soil moisture studies. A number of TDR designs are available that are being produced commercially.

Gypsum resistance blocks were paired with the TDRs because they could be read automatically. Because the resistance blocks take a while to come to equilibrium with the surrounding soil, they were used to record changes in soil moisture occurring between the TDR readings.

In the SHRP LTPP Program, the evaluation of moisture measurement devices by Rada et al. (1994) found that the ions in saline or alkaline soils create an effective electrical short across the probe rods of the TDR that makes accurate interpretation of the trace difficult. Details of the probe are reproduced in Figure 2.

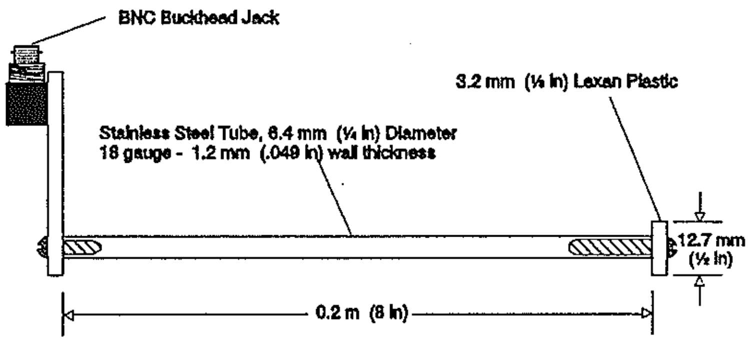
Figure 2. TDR probe for seasonal monitoring program developed by FHWA. (from FHWA SHRP Program)
(Not to scale; 1 in. = 25.4 mm)



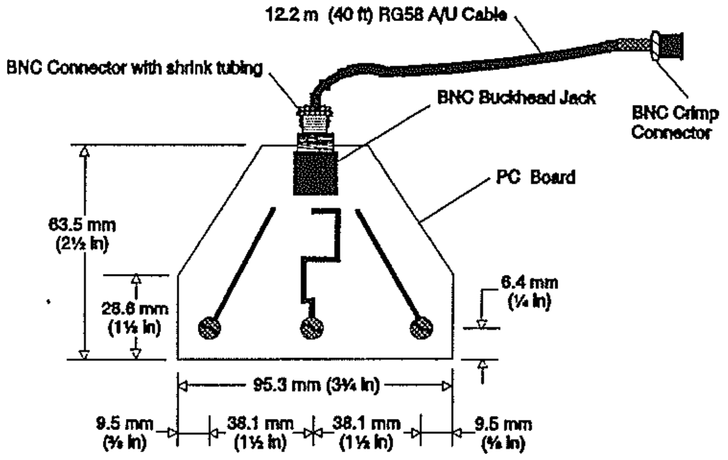
Top View

Specifications for the FHWA Moisture Probe:

The center rod of the FHWA probe is connected to the signal lead of the coax cable. The other rods are connected to the shield of the coax cable. The probe connect directly to a 50 ohm RG58 coax cable. The end view shows the circuit board used to connect the 0.2 m (8-in) stainless steel rods to the coax cable.



Side View



End View (PC Board)

4.2.4 Neutron Probe

In Minnesota the neutron probe is particularly useful because it measures the total moisture content, whether frozen or unfrozen. Since the TDR measures the unfrozen moisture content, the difference between its results and those of the neutron probe gives an estimate of the frozen moisture content.

4.2.5 Electrical Resistivity

In the SHRP Program the freeze-thaw depth is determined using an electrical resistivity probe, developed by the US Army Corp of Engineers' Cold Regions Research and Engineering Laboratory (CRREL). The electrical resistivity of most mineral soils is very high, and virtually all current flow through the soil is carried by free ions in the pore water. Therefore the electrical resistivity of the soil depends primarily on its porosity, the degree of pore water saturation, and the electrical resistivity of the pore water. Since the electrical resistivity of ice is much greater than that of the unfrozen pore water, formation of ice in the pore space causes a net decrease in the effective porosity, and a corresponding increase in apparent or bulk electrical resistivity. Therefore, in addition to determination of freeze-thaw depth, electrical resistivity measurements can indicate changes in moisture content.

4.3 Pavement Temperature Measurements

In the New Zealand trial at the "dry" site (Transit New Zealand 1993), stainless steel-sheathed platinum film resistance thermometers (thermistors) were chosen for temperature measurement in pavements. The sensors were installed in conjunction with the gypsum resistance blocks used for soil moisture measuring.

Because thermistors do not indicate the temperature of the soil or pavement but only their own temperature, they must be packed in close thermal contact with the medium that is being monitored for its temperature.

For the SHRP Program, temperature measurement is being undertaken with thermistors (Rada et al. 1994). They developed a thermistor probe which allows temperatures to be recorded 1" (2.5cm) below the top of the pavement, mid-depth of the pavement, and 1" (2.5cm) from the bottom of the pavement layer. Also, for the first 12" (30cm) depth, thermistors are placed at 3" (8cm) centres and at 6" (15cm) centres below this to a depth of 6 ft (1.83 m). Multiplexing within the probe allows a four-conductor lead cable to be connected to a datalogger.

4.4 Climate Measurements

For the SHRP Program, tipping bucket rain gauges have been installed at each site to monitor precipitation, and air temperature probes for air temperature measurement.

On the Mn/ROAD project two weather stations have been set up to measure ambient temperature, precipitation and relative humidity.

In the 1973 New Zealand studies, meteorological data collected at nearby New Zealand Meteorological Service climate stations were used to indicate site climate conditions.

4.5 Pavement Strength by Deflection Measurements

Many techniques have been evaluated for the determination of pavement deflection and its relationship with the properties, especially strength, of the pavement and subgrade. As strength of a pavement can be affected by changes in moisture, the relationship of changes in deflection and moisture have the potential to be used as an indirect method of determining moisture in a pavement.

Listed below, according to the principle of operation, are the devices referred to in the literature for pavement strength determination:

Static Devices

- Benkelman Beam
- Plate load test (Ioanides 1994)

Dynamic Devices

- Falling weight deflectometer (FWD) (Bentsen et al. 1989)
- Heavy weight deflectometer (Bentsen et al. 1989)
- Colibri (Lepert & Caprioli 1994)
- Clegg impact soil tester (Clegg Hammer) (Clegg 1993)
- Loadman (Roadware Corporation capability sheet, undated)
- Road Rater (Bentsen et al. 1989)
- Dynaflect (Bentsen et al. 1989)

The last two dynamic devices apply a vibration to the road surface.

High Frequency Operation Devices

- Radar (ground penetrating)(GPR) (Van Overmeeren 1994)
- Spectral analysis of surface waves (SASW) (Nazarian & Baker 1992)

4.5.1 Benkelman Beam

The Benkelman Beam test measures the displacement of the pavement surface caused by a dual tyred wheel carrying a load of 4 tonnes. Continuous monitoring of the deflection as the wheel moves off the measurement point provides a deflection bowl shape which is assumed to radiate equally in all directions from the measurement point. A limitation of this system is the accuracy of the recorded deflection at the outer end of the bowl radius. Any small variation in deflection in this area has been found to heavily influence the prediction of the pavement strength properties.

4.5.2 Plate Load Test

The plate load test is conducted on the unprotected subgrade and is therefore a destructive testing method when dealing with existing highways.

4.5.3 Falling Weight Deflectometer (FWD)

The FWD uses a weight that is raised mechanically and dropped onto a wad of rubber cushions and the force is transmitted to the pavement through a steel plate. The force is monitored with a load cell, and the resulting pavement movement is monitored with either velocity transducers or seismometers. A number of FWDs are available which have the same principle of operation. Sophisticated back-calculation procedures have been developed to predict the thicknesses and elastic moduli of up to five soil layers. Uzan (1994) claims that it is difficult to back-calculate the modulus of layers less than 80 mm thick, and also that the layer thicknesses need to be known.

4.5.4 Heavy Weight Deflectometer

The principal of operation of the heavy weight deflectometer is the same as the FWD but the dynamic force is up to twice that applied by an FWD (which is 250 kN).

4.5.5 Colibri

In this system a 1g hammer is used to deliver three blows to the pavement surface in 10 seconds. Accelerometers are used to measure the response of the soil.

4.5.6 Clegg Impact Soil Tester (Clegg Hammer)

The Clegg hammer is normally offered as an alternative to the California Bearing Ratio test (CBR). The apparatus consists of a hammer with a metered handle which is dropped onto the soil surface through a guide tube. The basic principle of the test is that the peak deceleration of the compaction hammer when it is brought to rest is directly related to the resistance offered at the contact resulting from the stiffness and the shearing resistance of the material. The weight of the hammer is generally 4.5 kg and it is dropped from a height of 450 mm. Lighter and heavier hammers are available which drop from 300 mm. The test is generally used for compaction control.

4.5.7 Loadman

The Loadman is described as a portable FWD. A weight is dropped onto a loading plate from 800 mm. The deflection caused by the falling weight is measured by an accelerometer. The measuring result is given as a deflection, the calculated modulus E, the length of loading impulse, and the percentage of the rebound deflection compared to the maximum deflection. The calculated modulus is a single value which is a weighted average of the total pavement modulus. It appears that the instrument is best suited to compaction control on sites where it is difficult to get a larger vehicle-mounted FWD.

4.5.8 Road Rater and Dynaflect

The principal of operation is the same for these two devices as the FWD except that the load is a vibratory load instead of an impulse load.

4.5.9 Ground Penetrating Radar (GPR)

The technique is related to seismic reflection and is based on wave propagation to provide detailed and continuous images of the subsurface. The method depends on contrasts in physical properties in the subsurface. The physical property that determines the reflection of electro-magnetic waves is the dielectric constant or permittivity, ϵ. The propagation velocity of radar waves also depends directly on this property. The GPR transmits short pulses of electro-magnetic energy into the ground using a transmitting antenna attached to the radar unit. The pulses are reflected back to a receiving antenna. The arrival time and amplitude are related to the location and nature of dielectric discontinuities in the underlying materials. The reflected pulses are captured and displayed as a radar waveform from which the properties and thicknesses of the layers within the underlying materials can be deduced.

4.5.10 Spectral Analysis of Surface Waves (SASW)

This method is used to determine shear modulus profiles of pavement sections. Pneumatic sources are used to apply the input frequencies to the pavement, and geophones and accelerometers are the receivers. A sophisticated computer algorithm uses the signals from several receiver spacings to determine a representative dispersion curve in an automated fashion. Finally the elastic modulus for the different layers is determined from the dispersion curve. A recently developed automated inversion process is utilised to determine the stiffness profile of the pavement section. Young's modulus profile is interpreted from the dispersion curve data.

4.6 Recommendation on Pavement Deflection Measuring Device for New Zealand

Currently in New Zealand an FWD is under trial (Transit New Zealand Research Project PR3-0171), and in the SHRP LTPP Program the FWD is used for the pavement strength determinations. Trials of SASW equipment at Opus Central Laboratories underway in 1997 show that this method of pavement strength determination has considerable promise. The other documented systems are unable to provide the same degree of detail, and it is considered that these should not be pursued.

5. PAVEMENT DEFLECTION DATA ANALYSIS

In the SHRP Program the FWD has been standardised for the non-destructive determination of pavement strength (National Research Council 1993a). Having obtained the field data, sophisticated processing is required to derive subsurface layer thicknesses and corresponding elastic moduli. SHRP assessed six software programs found in a literature review to determine the most appropriate for the SHRP data (National Research Council 1993b, c). A program called MODULUS was found to do quite a good job of matching the measured deflection basin, to be fairly independent of the user, and to produce results that were generally "reasonable", and it was selected for the back-analysis.

6. MOISTURE MOVEMENT PREDICTION

Predicting moisture movement in pavements is an important tool for pavement designers. It is being researched at the Queensland University of Technology and Keith Wallace has loaned a copy of the pavements version of the computer software called THEWET (Wallace 1991) for evaluation.

THEWET 1990 is a suite of micro-computer programs which simulate the wetting-up and drainage of earth structures. The first of these programs, WETEDGE, is used to prepare data describing the pavement cross-section, pavement materials, initial moisture conditions, and road shoulder surface climate for analysis of infiltration, redistribution and drainage of water in pavements over a specified period of time. THEWET performs the analysis, stepping through the time period, analysing and displaying the changing moisture conditions within the pavement. The final conditions from one run can be used as initial conditions for a subsequent run, and in this way shoulder climate changes can be modelled. REPLAY presents the results of the analysis on screen, giving an animated display of the wetting and drainage of the pavement cross-section over the period of the analysis.

The analysis is carried out on a half-road width from the centreline to the bottom edge of the verge slope. The analysis region includes the seal (2 m), shoulder (1.8 m) and verge (1.2 m) up to a total maximum width of 5 m, with up to three seal and three shoulder underlayers down to a maximum depth of 580 mm. (The maximum depths to the bottom of the top two underlayers are 315 mm and 500 mm.) A uniform subgrade from the bottom of the layers down to a depth of 800 mm is also part of the region to be analysed.

A number of parameters must be input by the operator. They include the width of seal, width of unsealed shoulder, the table drain depth, the verge slope, and the crossfall of all layers under the seal and under the shoulder/verge. The positions and sizes of impermeable membranes, internal drains and vertical cracks may be specified. Material properties are input next, followed by the moisture environment which includes initial saturation levels, rainfall or evaporation intensities, and ponding details.

The program was trialled using some hypothetical sets of parameters. Analysis on a modern personal computer is convenient, taking about 5 minutes to analyse a two-day duration of moisture flow. The analysis results appear reliable but their relevance in any given situation will, of course, depend on the quality of the input information and any inherent limitations of the governing moisture movement model. The input data that have the most uncertainty for the user almost always relate to the material properties. To specify appropriate values in a particular case, the user must also be aware of the way in which material property variations are handled in the model.

In the wetting and drying of granular materials, the controlling material properties are the suction–water content and the permeability–water content relationships. Typically both of these are highly non-linear and are not easily determined for individual soils.

In addition, the suction–water content relationship exhibits hysteresis (i.e. the wetting and drying curves are not coincident). Also, the permeability value is often dependent on the direction of flow (particularly if the direction is horizontal rather than vertical), and the relationship is very sensitive to quite minor changes in the material. Barely perceptible changes in its texture or structure can change the permeability tenfold or more.

The material property model employed in THEWET allows complete specification of a layer through seven material property parameters. This simplification has been achieved by postulating a "wet state" and a "dry state" with power law functions describing the variation of suction and permeability between these states. (Hysteresis is ignored, although Wallace points out that, to some extent, allowance for this effect can be made by specifying drainage or a wetting critical suction values depending on the expected dominant flow mode in the case being analysed.)

The seven parameters comprise:

- *wet state properties*
    - vertical permeability,
    - horizontal to vertical permeability ratio,
    - suction head,
    - water content;
- *dry state property*
    - water content;
- *power law indices*
    - suction–water content index,
    - vertical permeability–water content index.

The dry state permeabilities or suction head do not need to be specified as the model assumes they are zero and infinite respectively. This assumption highlights that the model is not suitable for situations approaching the dry state, and Wallace advises that the model is most suited to relatively wet conditions corresponding to suctions from saturation up to heads of about 10 m.

The wet and dry states are not fundamental properties of the materials, but rather are concept states suited to this particular model. The wet state water content is called the "resaturated" value and corresponds to the water content "at 3-5% air voids" typical of the degree of air entrapment in the voids during infiltration processes. The dry state water content is defined as the value "beyond which water does not have a significant effect on moisture characteristics closer to saturation". Compared to the usual uncertainty associated with specifying the wet state permeabilities, the analysis is not sensitive to either of these wet or dry water contents. It is also not sensitive to the values selected for the power law indices. Wallace recommends generally accepting the default values provided for these four parameters, and focusing on the realistic specification of the wet state suction head and permeabilities for each pavement layer and the subgrade.

The approach recommended is to back-calculate wet state permeability and suction head values from a field or laboratory flow process which most closely simulates the conditions that are to be analysed. For existing road shoulders, this means field infiltration tests with observation of the vertical and lateral extent of infiltration. For pavement materials to be used in new roads, this means vertical and horizontal laboratory infiltration tests on specimens which have been preconditioned as they will be in the field. If drainage is the prime consideration then laboratory drainage tests are more relevant. As pointed out above, the wet state suction head to be used needs to be tailored to the dominant flow process under consideration (infiltration or drainage), or set to some intermediate value to sensibly model mixed flow processes. Wallace states that infiltration test results (field or laboratory) "will suggest values of a few hundred mm".

The values controlling water retention during drainage will usually be much greater and of the order of those that can be estimated (as detailed by Wallace) from the 10% size of the material. It is worth noting that once the moisture retention suction head exceeds the thickness of a "drainage layer" by a small amount, corresponding to the crossfall of that layer, gravity drainage will be ineffective in the layer and the main method of moisture removal will be by suction gradients arising from evaporation at the shoulder surface.

Wallace observes, in his discussion of the influence of material properties, that "any engineer who has attempted to predict the rate of consolidation of foundation soils will appreciate the difficulties of prediction of performance involving the parameter permeability". Unsaturated moisture flow is complicated further by the role of moisture suction and by the dramatic effect of desaturation on permeability.

This suggests that the most useful role for analyses of moisture movement in pavements is in comparative studies of how changing one or two key features of a design will affect the relative pattern of moisture movement. In this way experienced engineers will be able to make better judgements between feasible alternatives.

7. APPLICABILITY OF OVERSEAS RESEARCH TO NEW ZEALAND PAVEMENTS

7.1 Pavement Construction

As noted in Section 3.1 of this report, test sections in the SHRP or Mn/ROADS studies do not include a thin chipseal over basecourse. Therefore, the flexible pavement sections referred to in the SHRP reports are likely to be less flexible than typical roads in New Zealand which are generally chipseals.

However, the principles, methodology and instrumentation used in these studies will be of direct benefit to New Zealand, and also the findings will be applicable to structural asphaltic concrete that is used for high traffic volume roads.

7.2 Influence of Climate

The results of the US research on the influence of climate on moisture movement in subgrades will be adapted to New Zealand conditions.

The range of climate conditions covered in the SHRP studies is greater than experienced in New Zealand, although this does not detract from the worth of the SHRP results. While the US researchers are interested in the effects of freezing and thawing on the pavement strength, this problem is localised in New Zealand.

8. RESEARCH STRATEGY

To obtain a better understanding of the mechanism and effect of moisture movement in pavements, the following research strategy is recommended.

8.1 Fundamental Long-term Research

The research being undertaken in the SHRP long-term monitoring program and the Mn/ROADS project has the potential to provide a more fundamental understanding of moisture movement in pavements. It is recommended that New Zealand await the results of this research and then determine its applicability to New Zealand conditions even though the full results may not be available for another five years.

8.2 Immediate Research

Two areas of research warrant immediate implementation in New Zealand because the results can be used by pavement designers for pavement operations while the long-term fundamental research is being performed in the US.

- **Sensitivity Analysis using THEWET software**

Perform a sensitivity analysis using THEWET software to determine the effects of parameters such as permeability of basecourses and sub-bases, shoulder width, construction in cut or fill conditions, etc., on the theoretical distribution of moisture in the pavements.

Although recognising that full validation of THEWET has not been performed yet, the program has potential to help identify the most important factors affecting moisture in pavements, and their interactions.

This research would alert the pavement designer to the site conditions that need to be taken into account if moisture conditions other than those of saturation were to be assumed in the pavement design.

The results of this analysis would also be used to select a minimum of 20 sites for the second area of research.

- **Monitoring seasonal moisture changes and pavement strengths**

Monitor a selection of a minimum of 20 sites, covering the range of seasonal moisture conditions expected over a year, for changes in pavement strength using an FWD.

At present the variation in pavement strength that may occur because of seasonal changes in moisture conditions in the pavement layers is not known. This knowledge is needed when analysing existing pavements for rehabilitation treatment because pavement properties determined in different seasons may give different pavement strengths.

For example, determination of pavement properties made during dry weather for example may result in over-estimates of pavement strength, so that thinner than optimum overlay thicknesses may be constructed.

However the FWD, which is easy to use and gives consistent measurements, is becoming more common for analysing pavement strength by pavement deflections. These FWD deflections can be used to monitor changes in pavement strength.

Therefore pavement strength at a minimum of 20 sites should be monitored for a year using an FWD. The sites would be selected using the results of the sensitivity analysis and would cover a range of moisture conditions that are expected to occur in New Zealand roads. The changes in strength could then be related to changes in seasonal moisture conditions.

- *Summary*

Results from these two areas of research would help verify the predictions of THEWET software. They also assist the pavement designer when adjusting results of strength analysis by FWD, to ensure that the design is the most appropriate for the moisture conditions likely to be experienced by the pavements to be constructed or rehabilitated.

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