THE USE OF FWD TESTING AS A QUALITY CONTROL TOOL DURING CONSTRUCTION

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ABSTRACT

Falling Weight Deflectometer (FWD) testing has proven to be an effective tool for Pavement Engineers to characterise the in situ behaviour of existing pavement layers and subgrade materials. The most common use of FWD results both locally and internationally include overlay thickness calculations, the identification of uniform pavement sections and estimation of pavement layer stiffness's.

A number of state road authorities in Australia have also identified the benefits of deflection testing during construction. There is however a general absence of evaluation criteria for FWD deflections at the top of foundation layers in Australia.

This paper presents the potential benefits of FWD testing on top of the foundation layers during construction, as well as practical considerations and limitations based on the experiences gained during the duplication of a section of the Centenary Highway near Brisbane. Recommendations regarding potential evaluation criteria for FWD testing on top of foundation layers as a quality control tool during construction are also included in the paper.

INTRODUCTION

Falling Weight Deflectometer (FWD) testing is widely accepted within the industry for pavement investigations during the planning and design phases of maintenance, rehabilitation and new construction projects. FWD testing has been and continues to be specified during pavement construction at the top of foundation layers (working platform in Queensland) underneath heavy duty pavements in South East Queensland. There is however currently a lack of local guidance on appropriate methodologies for analysis of the FWD data and no acceptance criteria have been developed to date.

It is proposed that an acceptable methodology can be developed based on the concept of Foundation Surface Modulus (FSM). The primary consideration in the development of the methodology is to provide an analysis technique which will be quick and straight-forward, without the need for complex analysis during construction, but is also consistent with the technical basis of the design and design parameters.

This paper describes the current Department of Transport and Main Roads (DTMR) pavement design system and specification requirements to provide context for the proposed methodology. The proposed methodology is also presented and applied to a local case study. A discussion on the potential issues with FWD testing during construction is presented and recommendations are given on a potential way forward based on the findings of the research and case study.

QUEENSLAND DEPARTMENT OF TRANSPORT AND MAIN ROADS HEAVY DUTY PAVEMENT DESIGN SYSTEM

Heavy Duty Pavement Configurations

The Queensland Department of Transport and Main Roads (DTMR) recommends the use of High Intensity Low Intervention (HILI) pavement configurations for roads that are expected to carry more than a 1 000 Equivalent Standard Axles (ESA's) per day in the design lane at the time of opening (DMR, 2009). A HILI pavement may comprise of any one of the following pavement types:

- Plain, jointed reinforced or continuously reinforced concrete;
- Flexible composite (comprising of an asphalt base over a lean mix concrete subbase);
- Deep strength asphalt (comprising of an asphalt base over a cement stabilised subbase); or
- Full depth asphalt (comprising of an asphalt base without a subbase).

Furthermore, HILI pavement configurations require a working platform below the lowest pavement layer to:

- Provide protection to the underlying subgrade materials;
- Provide a sound platform for construction of the overlying pavement layers; and
- Provide access for the construction vehicles.

The working platform should also meet the following minimum requirements in order for it to function as part of the subgrade during the service life of the pavement (DMR, 2009):

- Comprise of a granular material (min. CBR 45 %) stabilised with a minimum of 2 % cement or cementitious blend;
- Have a minimum UCS of 1 MPa and a maximum UCS of 2 MPa after 7 days curing;
- Have a maximum Weighted Plasticity Index of 1 200 for the untreated material;
- Be placed and maintained at a degree of saturation of not greater than 75 %;
- At least 150 mm (compacted) thickness; and
- Be primed and sealed.

The use of a working platform under heavy duty pavements is common within other road authorities in Australia albeit under different names, such as RTA's Select Material Zone (SMZ) and Vicroad's Type A Selected Material.

PSTS101

The requirements for the working platform underneath HILI pavements are also included in the Project Specific Technical Standard 101 (PSTS101) that are currently being used on most of the major DTMR road infrastructure projects throughout South East Queensland. PSTS101 specifies that FWD testing be undertaken during construction on top of the working platform layer. The wording in both PSTS101 and the DTMR Pavement Design Manual would suggest that the intention of FWD testing during construction is to confirm that the design parameters adopted for the subgrade and working platform is applicable and that the quality of the working platform is adequate to provide long term support to the overlying pavement layers and protection to the underlying subgrade materials. Indications are thar testing during the pre-construction phases of the project may also not always be sufficient to characterise the subgrade materials. FWD testing therefore allows the contract administrator the additional benefit of ensuring that the design assumptions made previously are applicable to the sections of road under construction.

Clause 4.4 of PSTS101 specifies that the contractor should undertake the following tests and analysis in order for the working platform to contribute towards the pavement design:

- A review of the Contractor's pavement design and all quality records including the original test results;
- FWD deflection testing and analysis every 250 m in each wheel path of the final pavement. The FWD testing is to be used to identify general stiffness and any need for further investigation in a particular location;
- Sampling and testing of materials as relevant for all the Technical Standard properties for that material type at least every 500m and at locations of lowest strength as identified by FWD analysis and assessment for compliance with the relevant specified requirements;
- In situ CBR determined from dynamic cone penetrometer (DCP) testing and assessment for compliance with the requirement for a minimum CBR of 15.

The specification does however not include any guidance on deflection conformance criteria; neither does it provide guidance regarding analysis procedures acceptable to the contract administrator. Essentially, the responsibility lies with the contractor to demonstrate compliance with the specification. There is therefore a need to include a standardised analysis procedure in the specification in order to reduce the risk of inappropriate interpretation of the specification during construction.

RECOMMENDED ANALYSIS APPROACH

Background

Some road authorities in Australia and elsewhere have identified the benefit of deflection testing during construction to ensure adequate structural integrity of the pavement layers and subgrade. Traditionally, deflection testing during construction comprised of a proof roll on the prepared subgrade or pavement layer with a loaded construction vehicle (typically a water truck). The visually observed deflections were assessed against allowable standards (typically no visual deflection is allowed). Even though the proof roll has been a valuable tool in the past, it has been the cause of many disagreements on site as to what constitutes acceptable movement. The test itself is subjective and depends on the quality of the observer's eyesight, position of observer, level of experience, type of material and moisture content, vehicle load and axle configuration. Inappropriate interpretation could also potentially lead to overly conservative subgrade treatments (Colenbrander et al, 2007).

More sophisticated deflection testing techniques are also used both locally and internationally to evaluate the structural behaviour of pavements. Traditionally, deflections have been measured with the Benkelman Beam in Australia and in more recent times with the FWD device. Deflection analysis can generally be divided into two categories: analysis of deflection bowl parameters (typically maximum deflection and curvature) to determine pavement life or performance; and backcalculation of the stiffness of pavement layers and subgrade materials from measured deflection bowls (Rohde et al).

The backcalculation procedure used to estimate the in situ stiffness of pavement layers requires specialised software and a high level of expertise that are not necessarily available during construction. Furthermore, the non-uniqueness of backcalculation solutions could potentially create contractual issues when used to measure compliance against a specification and hence the authors do not consider this to be a practical analysis procedure during construction. As such, the authors consider the Foundation Surface Modulus (FSM) concept that relies on a single bowl parameter i.e. maximum deflection to evaluate the structural integrity of the foundation layers during construction to be more appropriate.

Foundation Surface Modulus

The Foundation Surface Modulus (FSM) can be defined as the Stiffness Modulus based on a known applied load at the top of the foundation, or in this case the working platform (IAN 73/06, 2009). It is important to note that the FSM is a composite value that comprises of the contribution of all of the underlying layers. This concept has been adopted by the Highways Agency in the United Kingdom and is used in their foundation design system and construction specifications. The authors recommend that a similar approach be adopted in Queensland to evaluate the FWD results and integrity of the foundation layers during construction. The FSM is a function of the applied stress, load radius, measured maximum deflection and poison’s ratio of the subgrade materials and can be calculated from the following equation (IAN 73/06, 2009):

$$E = \frac{2 \times (1 - \upsilon^2) \times R \times P}{D} \qquad (Equation\ 1)$$

E = Foundation Surface Modulus (MPa)

υ = Poisson’s Ratio (typically 0.35 – 0.45)

R = Load Plate Radius (150 mm for standard FWD load)

P = Contact Pressure (567 kPa for standard 40 kN FWD load)

D = Deflection under the centre of the plate (in microns).

The theoretical foundation model shown in Figure 1 was recommended by Chaddock and Roberts (2006) and adopted by the authors for the case study discussed below. The theoretical FSM is determined at the top of the foundation layer (working platform in Queensland) by applying a 40 kN load (similar to FWD load) and determining the maximum deflection underneath the centre of the load through a linear elastic analysis. Most pavement design procedures assume an infinitely deep, uniform subgrade. This assumption is not necessarily correct and typically results in higher predicted deflections compared to observed deflections in practice. As such, the theoretical model includes a stiff layer at a depth of 1.5 m below the surface of the subgrade to overcome this assumption and allow for a more accurate prediction of foundation deflections. It is also important to note that the layer stiffness values used in the theoretical design model is based on the expected long term performance of the foundation layers (Chaddock et al, 2006).

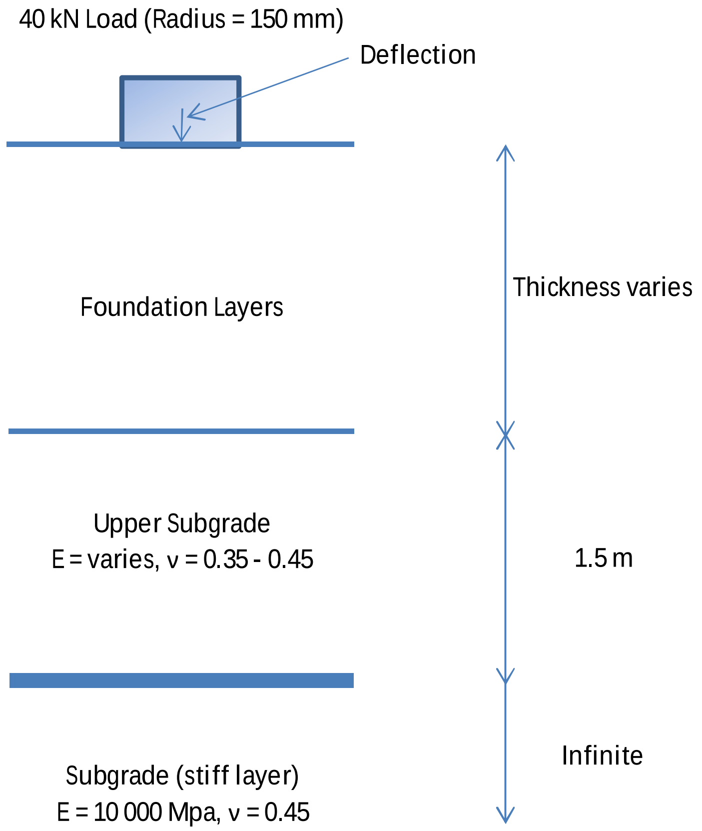

Figure 1: Recommended Theoretical Foundation Model

The theoretical maximum deflection determined can then be used to determine the theoretical long term in-service foundation surface modulus of the pavement. The theoretical deflection and modulus values should be adjusted to allow for field conditions i.e. the confinement effect of the pavement over unbound foundation materials and potential strength gain and/or deterioration of bound foundation materials. Interim Advice Note 73/06 (IAN 73/06, 2009) recommends the following adjustment factors for foundation materials:

- 0.8 for unbound materials (i.e. target construction value equals 0.8 x theoretical value). The FSM required for construction is lower than the theoretical in-service long term stiffness to allow for the fact that testing during construction is done at the partially confined state and does not include the effect of the overlying pavement layers;
- 1.5 for fast-setting cement bound materials (i.e. target construction value equals 1.5 x theoretical value). Fast-setting materials are defined as materials that achieve more

than 50 % of their specified compressive strength at 28 days curing. The FSM required for construction is higher than the theoretical in-service long term stiffness to allow for deterioration of the bound materials in-service; and

- 0.75 for slow setting materials (i.e. target construction value equals 0.75 x theoretical value). Slow-setting materials are defined as materials that achieve less than 50 % of their specified compressive strength at 28 days curing. The FSM required for construction is lower than the theoretical in-service long term stiffness to allow for additional strength gain after construction testing has occurred.

It is important to note that these factors are based on research in the United Kingdom and may not necessarily be applicable to Australian conditions and materials. However, in the absence of locally developed factors, the authors consider the prudent use of these factors in the interim until local factors have been developed appropriate. These factors are likely to depend on the quality of the material prior to stabilisation, the amount and type of stabilising agent used, construction techniques and specifications, age when tested, overlying pavement structure and environmental conditions.

The strength gain of cement stabilised working platforms is considered a significant variable in the assessment. Stabilising agents typically being used in Queensland include:

- GP or GB cement; or
- Cementitious blends of Portland cement with fly ash, blast furnace slag or hydrated lime.

Strength development of the working platform, particularly in the first seven (7) days, can vary significantly based on:

- The stabilising agent used to modify or stabilise the material; and
- The percentage of stabilising agent used.

For the purpose of development and presentation of the methodology, it is assumed that FWD testing is undertaken at 7 days when the UCS is typically approximately 75% of the 28 day UCS. However, it is recommended that individual relationships are developed for each specific material source, stabilising agent type and percentage of stabilising agent. The adjustment factors presented in this paper can then be further refined based on the time of testing.

The deflections or FSM measured during construction can then be compared to the adjusted deflections or FSM determined from the theoretical foundation model. Areas where the field deflections are higher than the target values indicate potential structurally inadequate foundation layers and should be further investigated.

The project specific target deflection values can easily be included in the Annexure to PSTS101 by the design engineer prior to construction and used as assessment criteria during construction.

CASE STUDY – DARRA TO SPRINGFIELD TRANSPORT CORRIDOR

Background

The recommended analysis approach can best be illustrated with a case study. As discussed previously, it is a requirement of DTMR to undertake FWD testing on the working platform underneath HILI pavements prior to placement of the pavement layers. The FWD test results from the Darra to Springfield Transport Corridor (DSTC) project was used to illustrate the benefits of FWD testing during construction. The DSTC project included the upgrade of approximately four (4) km of a section of the Centenary Highway to a four lane motorway, the construction of entry and exit ramps, upgrade of local roads and the construction of a new railway line. The pavement configuration for the new motorway comprised of:

- 45 mm Stone mastic asphalt surfacing with a polymer modified binder;
- 45 mm Dense graded asphalt binder layer with a polymer modified binder;
- 280 – 300 mm Dense graded asphalt base layer with a Class 600 binder;
- 150 mm Granular working platform modified with a cement/slag blend; and
- Various types of subgrade treatments in cut and on fill.

FWD testing was done during construction and the results analysed for each of the work lots. The results of two (2) lots are discussed in this paper. The two (2) sections are located along the north- and southbound carriageways between ch 3 200 m and ch 3 750 m.

In situ CBR tests were done on the subgrade materials as part of the conformance testing for the underlying earthworks lots. The road is in shallow cut through this section and the subgrade comprised of a sandy material with a characteristic CBR of 20. The DTMR pavement design system limits the CBR of subgrade materials to 15 (DMR, 2009). A 150 mm controlled subgrade layer with a CBR of 45 was constructed underneath the working platform layer to allow for potential subgrade swell requirements. The theoretical model adopted to determine the long term in-service surface modulus of the foundation layers is shown in Figure 2. It is important to note that the layer stiffness values used in the theoretical design model is based on the expected long term performance of the layers and were adjusted to conform to the DTMR pavement design system.

The Australian General Mechanistic Design Procedure was used to determine the theoretical deflection at the top of the working platform directly underneath the centre of a 40 kN circular load (Austroads, 2010). The deflection determined for the theoretical foundation model was 1 074 microns, corresponding to a long term in-service surface modulus of 140 MPa (equation 1). The FSM was adjusted by a factor of 1.5 (for fast-setting materials) to achieve a target FSM of 225 MPa (716 microns), allowing for future deterioration of the stabilised working platform layer.

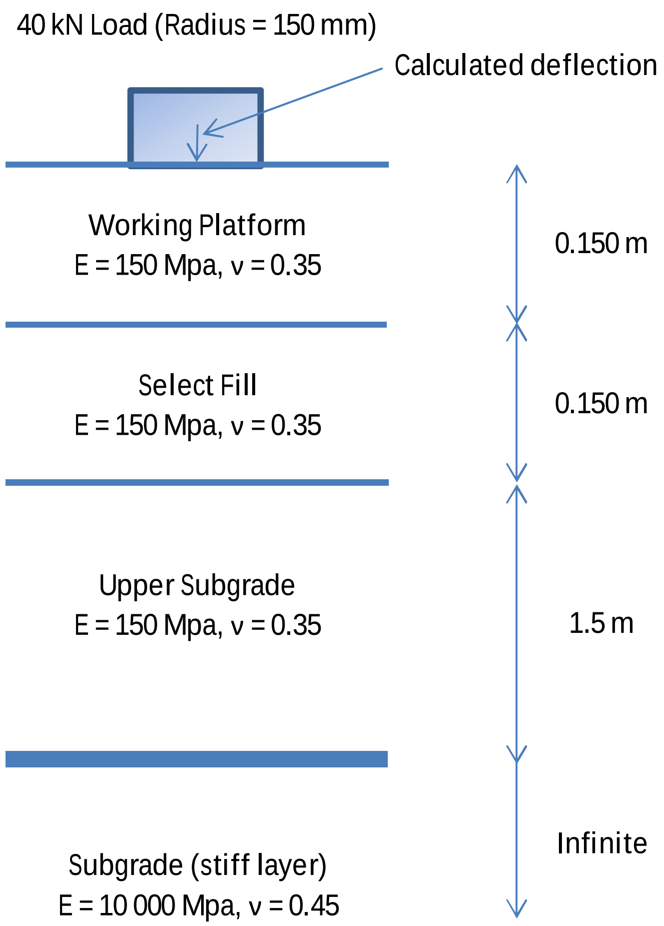

Figure 2: Theoretical Foundation Model Adopted for DSTC Project

The FSM measured at each test location during construction is shown in Figure 3. The FSM of the section between ch 3 300 m and ch 3 650 m along the southbound carriageway varied between 130 MPa and 220 MPa and did not meet the minimum target value.

The section identified in this paper as not conforming to the target FSM values coincided with the original section that was identified during construction for further investigations.

During construction the contractor was requested to undertake the following additional investigations to determine the reason for the high deflection values:

- Backcalculation of the layer stiffness;
- Proof roll with a loaded water truck;
- Dynamic Cone Penetrometer (DCP) tests; and
- Test pits.

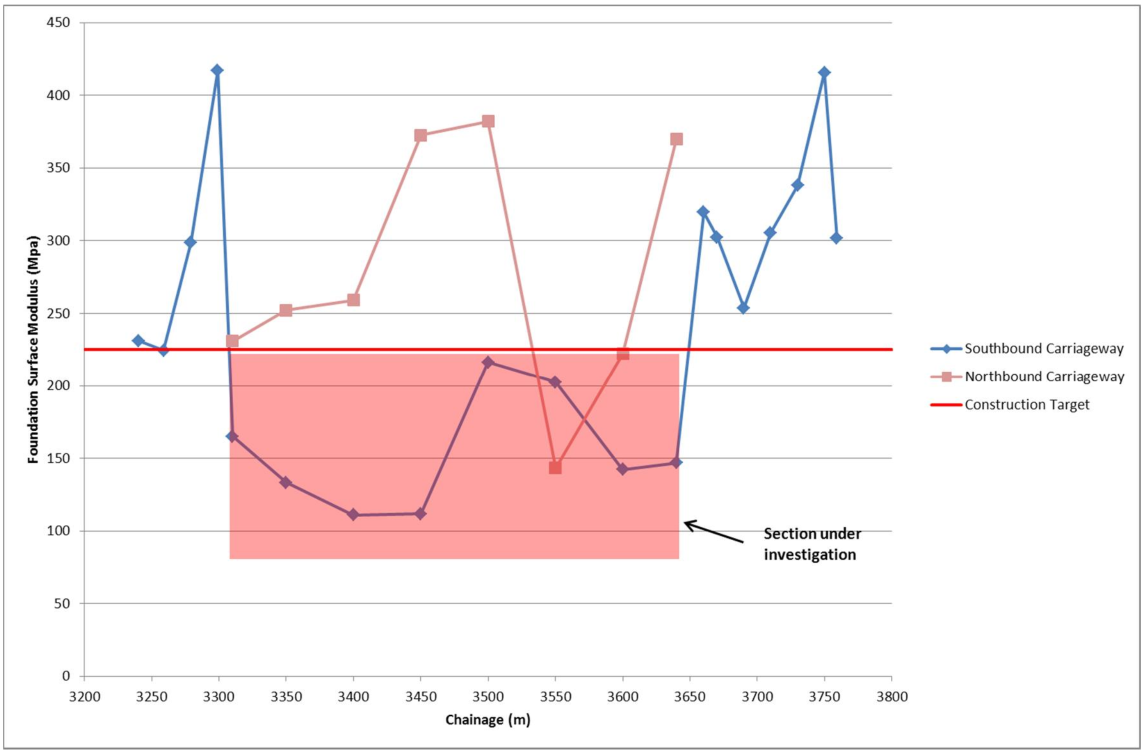

Figure 3: Measured Foundation Surface Modulus

Backcalculation of Layer Stiffness

The layer stiffness of the working platform, select fill and in situ subgrade was backcalculated using the deflection bowls measured with the FWD. The backcalculated stiffness of the working platform along the northbound carriageway varied between 400 MPa and 900 MPa, with a 90th percentile stiffness of 500 MPa. The stiffness of the working platform along the southbound carriageway varied between 250 MPa and 600 MPa, with a 90th percentile stiffness of 300 MPa. These values falls within the expected range for cement modified granular materials shortly after construction.

The 90th percentile backcalculated stiffness of the 150 mm select fill layer along the southbound carriageway was estimated to be approximately 30 MPa, which was considerably less than 160 MPa estimated along the northbound carriageway. This indicated that the higher deflections along the southbound section under investigation could potentially be as a result of a structurally inadequate select fill layer underneath the working platform.

The 90th percentile backcalculated stiffness of the in situ subgrade along the southbound carriageway was estimated to be 50 MPa, which was also considerably less than the 100 MPa estimated for the northbound carriageway. Again, this indicated potential structural concerns within the subgrade underneath the select fill layer.

The analysis of the backcalculated stiffness values indicated that the higher deflections and lower FSM measured along the southbound carriageway were most likely as a result of a structurally inadequate select fill layer and in situ subgrade below the working platform. The lower support that these layers offer to the working platform could also potentially explain the lower stiffness backcalculated for the working platform along the southbound carriageway compared to the northbound carriageway. The cause for the weaker layers below the working platform could not be confirmed through the available construction data (compaction, CBR, grading etc.) and it was decided to do some additional field investigations.

DCP Tests

The contractor was requested to undertake a number of DCP tests along the southbound carriageway. Typical DCP curves are shown in Figure 4. The DCP tests confirmed a weaker zone of approximately 300 mm below the working platform, with a penetration rate of between 12 and 13 mm/blow compared to 4.7 mm/blow measured in the areas with a higher FSM. The weaker zone identified with the DCP tests correlates well with the lower backcalculated stiffness values of the select fill layers and subgrade below the working platform.

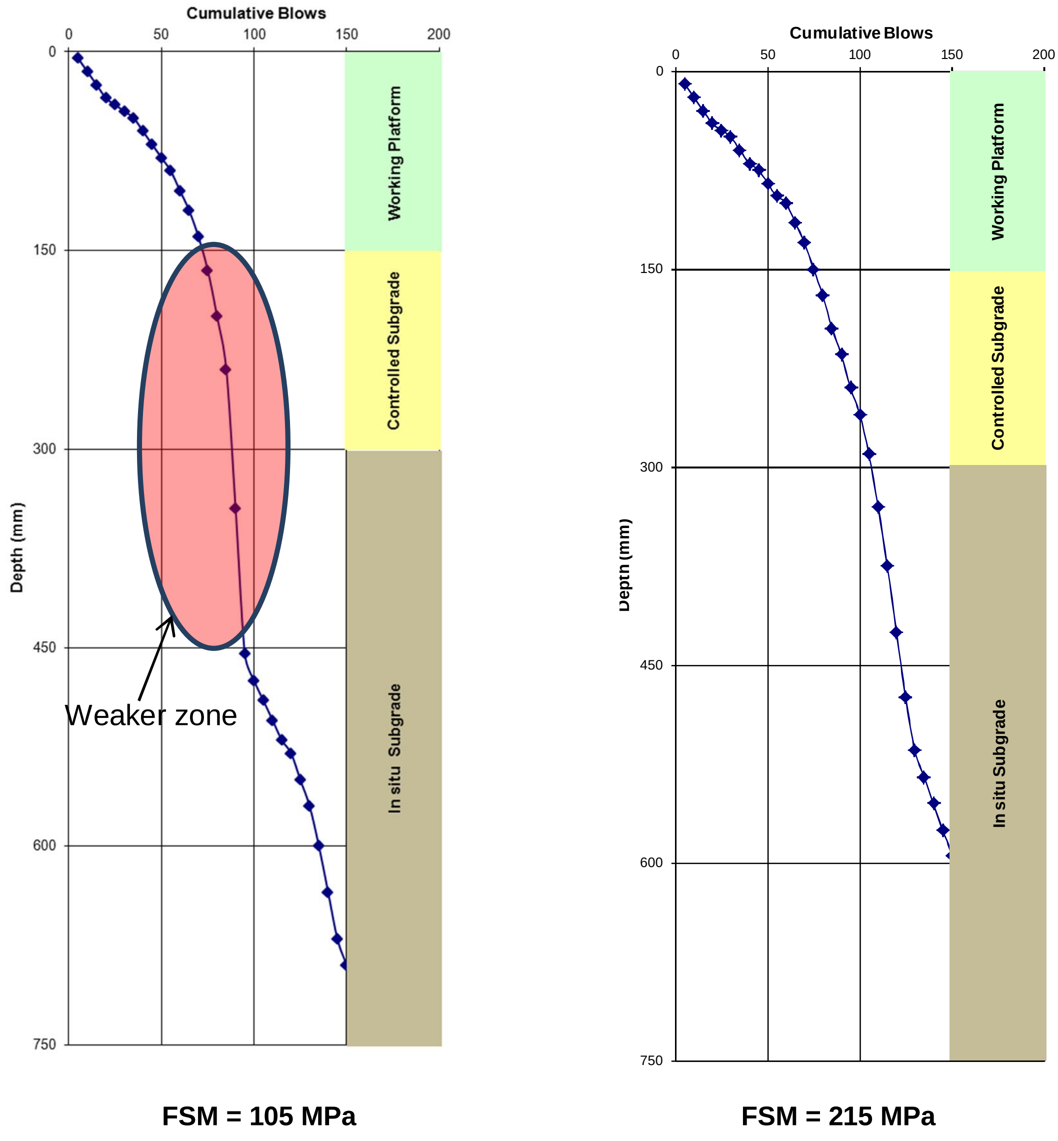

Figure 4: DCP Penetration Rates

Proof Roll

Significant visual deflections were also observed during a proof roll with a loaded water truck, confirming the results of the FWD testing.

Test Pits

A number of test pits were excavated along the poorer section between ch 3 300 m and 3 650 m in an attempt to identify the possible cause for the high deflections and DCP penetration rates. A high in situ moisture content, as can be seen in Figure 5, was observed in the select fill and upper in situ subgrade layers. It was subsequently concluded that the cause of the higher deflections and lower FSM was most likely as a result of an undesirably high moisture content in the materials immediately below the working platform.

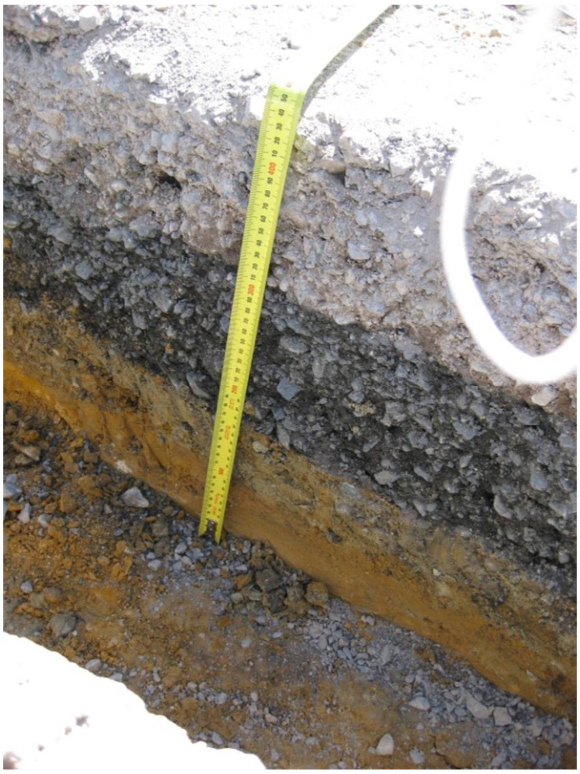

Figure 5: Moisture in subgrade

Remedial Action

The contractor subsequently re-worked sections of the working platform and controlled subgrade layers and installed a subsoil drain adjacent to the new pavement in an attempt to prevent future build-up of moisture in the foundation layers.

PRACTICAL LIMITATIONS AND CONSIDERATIONS BASED ON EXPERIENCE

Availability of Equipment

The availability of FWD equipment varies significantly across Queensland and Australia. The scope of this paper has been confined to HILI pavements which are typically constructed close to major cities where the majority of FWD devices are located.

In order to utilise this methodology, the constructor requires a carefully planned and managed construction program and early engagement of the FWD tester, to coordinate the testing and reporting program with the construction program, is considered to be critical.

Within the current specification (PSTS101), whilst the FWD testing is a specification requirement, there is no conformance criteria associated with the test. It is not desirable to delay construction works to wait for FWD testing and analysis to be carried out, given conformance of the works can still be evidenced with reference to the other specification criteria. This results in that the opportunity to evidence compliance of the pavement with the design intent is lost.

There is some flexibility within the construction program for the FWD testing to be undertaken between the completion of the working platform and start of asphalt construction. The FWD results will vary during this window of time depending on:

- The strength gain characteristics of the cement modified/stabilised materials;
- Moisture content of the materials at the time of testing; and
- Whether the working platform has been sealed at the time of testing.

The strength gain is considered a significant variable in the assessment as discussed previously in this paper, however the seal is not considered significant as long as the tested surface is clean and broomed.

Processing Time and Resources

Typically the short time frames available within the construction program and availability of design resources at this stage of the construction program limits the ability to fully analyse and act on the data collected using this procedure.

In the absence of a suitable criteria and analysis methodology, as described in this paper, the extent of assessment may be limited to:

- A subjective review of variability of the maximum deflections across the construction lot; and/or
- A subjective assessment of the acceptability of the maximum deflections measured.

Further assessment of the data may include:

- Assessment of the homogeneity of the lot, typically by assessment of the Coefficient of Variation of the dataset. This may identify areas where the subgrade conditions are statistically different which may warrant creating sub-lots for further assessment; and/or
- Further testing in the areas where unacceptably high maximum deflections are recorded.

Corrective Actions during Construction

One of the key challenges for the designer is what corrective action to take if the FWD results are found to be unacceptable. The corrective action is typically constrained by:

- Construction program;
- Costs associated with re-work, re-design or rehabilitation; and
- Contractual arrangement between the designer, constructor and road authority.

Typically, if all other conformance testing and specification requirements have been met in the earthworks operations, subgrade preparations and cut floor treatments, it is unlikely that an entire lot will be deemed unacceptable.

The FWD testing will generally only identify specific localised issues which may be associated with unique situations within the formation such as cut/fill transitions, verges and tie-ins or localised moisture that may trigger the need for more detailed investigations.

As such, it is important to note that the FWD testing is required to be analysed in conjunction with the remainder of the conformance testing and construction records and is not a substitute for other tests.

The corrective action would rarely involve increasing the pavement thickness, given other level constraints within the road design due to adjacent drainage and structures which may have already been designed and possibly built at the time of FWD testing.

The most likely outcome using FWD testing during the construction is the identification of a sub-lot based on analysis of the FWD results and construction records. Corrective action for the sub-lot may then include re-work, remove and replace or the installation of subsoil drains along the localised section.

CONCLUSIONS AND RECOMMENDATIONS

Deflection testing during construction as a quality control tool is widely used both locally and internationally. More specifically, DTMR requires that FWD testing be done on the working platform underneath HILI pavements. It is recommended that the Foundation Surface Modulus concept to analyse FWD data during construction is used to ensure that the desired structural integrity of the foundation layers is being achieved during construction. The effectiveness of this approach was illustrated with a case study whereby a non-conforming section was identified by using the FSM concept and further investigated. The method appears to be reliable and can be easily be implemented on site without the need for sophisticated software. It is also recommend that the evaluation criteria, especially the target adjustment factors, be refined for local conditions through further research.

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