Saleh, M.

Multi-Scale Criteria for Structural Capacity Evaluation of Flexible Pavements at Network Level
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ABSTRACT: The structural performance evaluation of the highway network is of significant importance for highway network asset managers. Pavement surface deflection has been used by several highway agencies to assess the structural condition of the pavement structure. Falling weight deflectometer, deflectograph and other devices are commonly used to measure the deflected shape of the pavement surface under loading. Researchers have developed several parameters that can be derived from the measured deflection bowl to assess pavement structural condition. However, there is no universally agreed parameter/s that can reliably rank the highway network sections based on its structural performance. In addition, each pavement type deflects differently under traffic loads, therefore, it is not feasible to have one single scale to evaluate and rank pavement structural capacity for all different types. In this research paper, different scales were developed to assess structural capacity of different flexible pavement structures. The area ratio, deflection ratio and their normalized values were derived from the deflection bowls of both field measured deflections and computer simulated data. Four different scales were developed to rank the structural condition of four different structures of flexible pavements. The normalized area and deflection ratios derived from computer simulations matched reasonably well with those derived from the FWD field measured data.

KEYWORDS: Deflection, FWD, Deflectograph, Normalized Area Ratio

BACKGROUND

Pavement deflection has been used widely as a nondestructive technique to evaluate the structural capacity of pavements at both the network and project levels. Benkleman beam and La Croix deflectograph were extensively used by many Highway agencies to measure pavement deflection to evaluate maintenance and rehabilitation requirements. Benkleman beam and La Croix can only measure maximum central deflection with no further information about the shape of the deflection basin. Benkleman beam was later instrumented so that it can record deflection bowl shape and the automated version is called deflectograph. Deflectograph has been used by many Transportation departments in Australia such as the Department of Transport and Main Roads since 1991. The Falling weight deflectometer, FWD, was introduced around 1968 in Denmark and became the main deflection measuring device in the United States by 1980 (1). The FWD device applies an impact load falling from certain height over a segmented plate and the deflections at the center of the load and at offsets commonly one foot apart (300 mm) from each other are measured through a set of geophones. The falling weight deflectometer has the advantage that it does not need a reference point and therefore provides more accurate deflection measurements. In addition, it closely simulates the effect of rolling traffic loads on the pavement surface. However, one major disadvantage of the FWD is that the device will need traffic control as it moves and stops frequently, thus it does not move at the same speed of traffic. Therefore, it is not possible to measure continuous pavement deflection with the FWD and this has led to the development of other devices that can travel at or near the speed of traffic (2,3). One of the most recent developments of traffic speed deflection measuring devices is the Danish Traffic Speed
Saleh, M.

Deflectograph (TSD). The TSD uses a series of Laser sensors mounted on a stiff beam to measure the deflection of the pavement surface. However, the use of TSD is still limited and only a few countries are operating this system parallel to the FWD to correlate the deflection measured from both devices and gain more understanding of the new system. The falling weight deflectometer has been used widely as a reliable tool to measure pavement surface deflection bowl. With the advent of personal computer and the development of multilayer elastic analysis software together with the development of accelerated test tracks, the deflection bowl was used to backcalculate layer moduli and several parameters were derived to provide evaluation to the structural condition of the pavement structure. However, the backcalculation technique is not feasible to be carried out at the network level and it is only more suitable for project level evaluation.

When pavement surface deflects under load, the deflected shape varies depending on the pavement structural capacity represented by pavement moduli and layers thicknesses, load magnitude and pulse duration. The deflection bowl can be divided into different zones with each zone has its pavement structural associations. For example, the maximum central deflection is more related to the entire pavement structure and it also reflects the condition of the subgrade. High central deflection is usually associated with weak subgrade or poor drainage condition. The maximum central deflection is also being used to divide pavement sections into homogeneous or uniform sections based on their structural response reflected by the maximum deflection. Figure 1 shows the maximum central deflections versus station/chainage in (km) along one of the highways in Queensland, Australia. Sections with high central deflections were investigated to assess subgrade strength. Most of the sections with high central deflections were found to have some drainage problems.

![Figure 1: Central deflection to assess subgrade strength and road sections uniformity](image-url)
The difference between the central deflection and the deflection at an offset of 300 mm from the center of the load \((D_0-D_{300})\) is called by some researchers base layer index (BLI) and is more related with the surface and base condition, while the parameter \((D_{300}-D_{600})\) is called middle layer index (MLI) and it is more related to the subbase whereas the \((D_{600}-D_{900})\) represents the lower layer index (LLI) and it reflects the condition of the subgrade. There are many other parameters that were derived from the deflection bowl such as normalized area parameter which is the total area of the deflection bowl normalized by the central deflection and this parameter is highly correlated with the pavement stiffness. Stiff pavements will display a large normalized area parameter, while weak pavement structures will display a small normalized area. Pavement curvature is another parameter that is widely used in Australia and is defined as the difference between the central deflection and the deflection measured at 200 mm from the center of the load \((D_0-D_{200})\). Pavement curvature is used to express the tensile strains and therefore the fatigue life of asphalt surface layer. Horak argued that variability has been observed in methods that rely on the 200 mm deflection because of the closeness of this point to the edge of the loading plate of the falling weight deflectometer and therefore the surface associated disturbances observed at the 200 mm geophone (4, 5). However, if deflections are measured by other devices such as deflectograph then there will be no plates and no disturbances with the \(D_{200}\) and the resulting surface curvature will be reflecting the surface condition.

Deflection ratio is also one of the most common parameters that are used by some highway agencies in Australia. Deflection ratio is defined as the ratio between the measured deflections at 250 mm offset from the center of the load to the central maximum deflection as shown by Equation 1 (6).

\[
D_r = \frac{D_{250}}{D_0}
\]

\(D_r\) = Deflection ratio

\(D_{250}\) = Deflection at 250 mm from the center of the load (mm)

\(D_0\) = Central maximum deflection (mm)

The Department of Transport and Main Roads (DTMR) in Queensland, Australia, uses the deflection ratio parameter to evaluate pavement structural capacity. The higher the deflection ratio, the stiffer and stronger is the pavement structure above the subgrade. It should be noted that the deflection ratio only accounts for deflection responses between 0 and 250 mm offset from the center of the load, therefore, it does not account for other pavement layers such as subbase or the subgrade condition. In addition, the deflection ratio parameter is based on two values \((D_0\) and \(D_{250}\)), therefore, when this parameter is calculated from field measurements, any error in the measured deflection data will significantly affect the value of this parameter. In this study, the normalized deflection ratio has been proposed to account for the subgrade condition as it will be explained in the following sections. The DTMR uses the deflection ratio \((D_r)\) based on FWD with 40 kN loading or deflectograph to provide some sort of classification of the structural condition of the pavement as shown below (6).

\(D_r \geq 0.8\) indicates a bound pavement.
0.6 ≤ D_r ≤ 0.7 indicates good quality unbound pavement with thin asphalt seal

D_r < 0.6 indicates a possible weak unbound pavement with thin asphalts.

NORMALIZED AREA PARAMETER AND AREA RATIO CONCEPT

Figure 2 shows two deflection bowls; one for a very weak pavement structure constructed over weak subgrade and the second bowl for a strong pavement structure over strong subgrade. The two deflection bowls were generated for a three layer flexible pavement system. Circlly software was used assuming cross anisotropic properties of the granular base and subgrade layers while asphalt layer was modeled as an isotropic material (7). It is obvious that strong pavements show very small deflection compared to weak pavements. In addition, deflection values for strong pavements are not significantly changing from one point to another away from the load. This is because strong pavements will spread the load over a wide area due to the high load bearing capacity and high shear strength of the pavement materials. For a weak pavement structure constructed over weak subgrade, the deflection peaks under the load and decreases rapidly away from the load. This rapid decrease in deflection is due to the weak structure of the pavement and the low load bearing capacity.

The area of one side of the deflection bowl will vary depending on the pavement structure and subgrade condition and it will not provide much useful information by itself, however, when the area is divided by the central deflection which is called normalized area parameter, it provides a
very useful information about pavement structural capacity. Normalized area parameter (AREA) is defined as the area of one side of the deflection bowl between offset 0 (directly under the center of the load) and 900 mm divided by the central deflection $D_0$. The normalized Area parameter derived from the FWD deflection bowl was initially proposed by Hoffman and Thompson (8), see Equation 2. Referring to Figure 2, the normalized area parameter can be formulated as follows:

$$AREA = \frac{50}{D_0} \left\{ \left( \frac{D_0 + D_{900}}{2} \right) + \sum_{i=50}^{850} D_i \right\}$$

Equation (2)

$D_0$= Central deflection at offset 0

$D_{900}$= The deflection at offset 900 mm from the load

$D_i$= Deflection at offset distance $i$ in (mm) from the load

For a very stiff strong pavement structure, it can be assumed that all the sensor deflections are almost equal, thus the normalized area tends to reach the upper limit of 900 mm$^2$/mm (approximately 36 inches). This would indicate an extremely stiff pavement structure regardless of the subgrade condition.

$D_0=D_{50}=D_{100}=\ldots D_{900}$

From Equation 2

$$AREA = \frac{50}{D_0} \left\{ \left( \frac{D_0 + D_{900}}{2} \right) + 17 * D_0 \right\} = 900 mm^2/mm$$

Circly Software was used to generate the deflection bowl for extremely weak pavement structure under FWD load. The pavement is assumed to be a two layer system with $E_1/E_2=1$. This means that the modulus of the base layer is similar to the subgrade and both have a vertical resilient modulus $E_v=15$ MPa, horizontal modulus $E_h=7.5$ MPa (cross anisotropic ratio $E_v/E_h=2$) and Poisson ratio of value 0.4. The anisotropic ratio is defined as the ratio of the vertical resilient modulus to horizontal resilient modulus. The anisotropic ratio of 2 is recommended by Australian guidelines for granular unbound materials (9). The thickness of the base was assumed to be 50 mm to reflect the extremely weak condition. The normalized area for this extremely weak pavement for the falling weight deflectometer load of 40 kN and plate diameter of 300 mm and contact pressure 565.9 KPa was calculated as $AREA = 270.4$ mm$^2$/mm. It should be noted that the normalized area parameter has not been widely utilized in pavement evaluation because there was no scale developed to rank pavement structures between these two extremes (weakest pavement structure and stiffest pavement structure) provided in the literature. Therefore, the area ratio parameter has been proposed in this paper as an alternative parameter.
Area Ratio Concept

Instead of using the normalized area parameter (AREA), the area ratio parameter is proposed in this paper. The area ratio parameter is defined as the ratio between the normalized area of any pavement structure to the normalized area parameter of the stiffest pavement. In this case, the area ratio of the weakest pavement structure based on the FWD equals 270.3/900 = 0.3. This means that if the normalized area of pavement section is less than or equal 0.3 of the normalized area of the stiffest pavement structure then this pavement is considered a very weak pavement structure. The area ratio parameter is a parameter that theoretically ranges from 0 to 1, while in the practical sense it ranges from 0.3 for very weak structures to less than 1 for stiff pavement structures. Therefore, for a 900 mm length of deflection bowl, the normalized area parameter for the stiffest pavement structure will equal 900 mm^2/mm. The area ratio parameter can be defined by Equation 3.

\[
A_r = \frac{50}{900 \times D_0} \left( \frac{D_0 + D_{900}}{2} + \sum_{i=50}^{850} D_i \right)
\]

Equation (3)

A_r = Area ratio parameter
D_0 = Maximum Central Deflection
D_{900} = Surface deflection at offset 900 mm
D_i = Surface deflection at offset (i) mm.

Relationship between Area Ratio (A_r) and Deflection Ratio (D_r)

In order to investigate if there is any relationship between deflection ratio and area ratio parameters, deflection bowl data was generated using Circly for 140 pavement sections with different thicknesses and stiffness properties. The pavement structure consists of four layer system as shown in Figure 3, with asphalt thickness ranges from 0 (surface treatments) to 240 mm (structural asphalt concrete) and the base and the subbase course thickness ranges from 300 to 500 mm.

The deflectograph load is modeled as shown in Figure 3 as standard full axle load with 80 kN and tire pressure 750 kPa. The area ratio parameter and deflection ratio were calculated from the synthetic data generated for the 140 pavement sections. The area ratio and deflection ratio were very strongly correlated as shown in Figure 4. The exponential function shown in Equation 4 provided an excellent fit to the data as shown in Figure 4. Despite the strong correlation between area ratio and deflection ratio parameter, the area ratio is more preferable since it addresses a larger length of the deflection bowl (from 0 to 900 mm) and therefore it considers all pavement layers above the subgrade. In addition, when these parameters are calculated from actual field data, the area ratio is less susceptible to measurement errors compared to the deflection ratio because the area ratio parameter is calculated based on several deflection measurements while the deflection ratio calculation is based on two points D_0 and D_{250}. 
Figure 3: Circly modeling for pavement structure and deflectograph loading

\[ A_r = 0.1816 \times e^{1.6789 D_r} \]
\[ R^2 = 0.973 \]

Equation (4)

**Area Ratio and Observed Pavement Condition**

The pavement condition data for a wide range of pavement structures in north Queensland was used to calibrate the area ratio calculated for different pavement sections. Based on the comparison between the pavement condition data as observed from digital video recording and the area ratio parameter calculated from the measured deflections, Table 1 was developed to provide a scale to classify the structural condition of the pavement structure. However, it should be noted that the area ratio only considers the structural condition of the pavement structure above the subgrade. Federal Highway Administration (FHWA) provided generalized conclusions of the structural pavement condition and the subgrade structural capacity based on both the normalized area and the maximum surface deflection (10,11). In a similar manner, the area ratio parameter and the maximum central deflection, \( D_0 \) can be used to provide an indication of the condition of the pavement structure and the supporting subgrade, respectively. For strong pavement structure and strong subgrade, the area ratio and \( D_0 \) parameters are expected to be high and low, respectively. On the other hand, weak pavement on a weak subgrade would exhibit low area ratio parameter and high \( D_0 \) value. The drawback of this method is that two parameters are needed to provide classifications of the pavement and the subgrade and this will make the classification at the network level more complicated.
Figure 4: Relationship between area ratio and deflection ratio based on Circly simulations

Table 1: Area ratio ranges and the associated road condition and the observed distresses

<table>
<thead>
<tr>
<th>Area Ratio ($A_r$)</th>
<th>Road Condition</th>
<th>Observed Distress</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 0.25$</td>
<td>Very Poor</td>
<td>Severe fatigue cracks with high intensity, deep ruts</td>
</tr>
<tr>
<td>$0.25 &lt; A_r \leq 0.35$</td>
<td>Poor</td>
<td>Moderate to high fatigue cracks, deep ruts</td>
</tr>
<tr>
<td>$0.35 &lt; A_r \leq 0.45$</td>
<td>Fair</td>
<td>Moderate fatigue cracks and moderate ruts</td>
</tr>
<tr>
<td>$0.45 &lt; A_r \leq 0.55$</td>
<td>Good</td>
<td>Some minor cracks and/or shallow ruts</td>
</tr>
<tr>
<td>$0.55 &lt; A_r \leq 0.65$</td>
<td>Very Good</td>
<td>Some minor cracks and/or shallow ruts</td>
</tr>
<tr>
<td>$0.65 &lt; A_r$</td>
<td>Excellent condition</td>
<td>Very minor</td>
</tr>
</tbody>
</table>

**Normalized Area Ratio**

As mentioned in the previous section, the area ratio parameter provides information about the pavement structural capacity above the subgrade. In order to determine the structural capacity of the entire pavement structure, both the pavement structure and the subgrade effect must be considered. By combining the area ratio and the maximum central deflection $D_0$ in one single parameter, more useful information about the entire pavement condition can be obtained. The normalized area ratio is determined by dividing the area ratio parameter as given by Equation 3
Saleh, M.

by the central deflection $D_0$, and it is designated as $(Ar')$. Equation 5 gives the value of the normalized area ratio from the deflection values between offset 0 to 900 mm from the center of the load.

$$ A_{r'} = \frac{50}{900} \frac{D_0}{D_0^2} \left\{ \left( \frac{D_0 + D_{900}}{2} \right) + \sum_{i=50}^{850} D_i \right\} $$

Equation (5)

For strong pavement structure over strong subgrade the value of the normalized area ratio will be large, however, for weak pavement structure over weak subgrade, the value of the normalized area ratio will be very small. Any other combinations of pavement structures and subgrade conditions will provide normalized area ratios between these two extremes. In a similar manner, the normalized deflection ratio can be determined by dividing the deflection ratio given by Equation 1 by the maximum central deflection ($D_0$). Figure 5 shows the relationship between the normalized area ratio and normalized deflection ratio for the same data used in Figure 4 based on the deflection bowls generated from Circly analysis. A linear relationship was found between the normalized area ratio and the normalized deflection ratio with a very strong correlation ($R^2=0.993$)

![Figure 5: Relationship between normalized area ratio and normalized deflection ratio based on Circly simulations](image)

Developing Multi-Scale Criteria for Structural Capacity Evaluation

It is important to note that different pavement structures will respond to the applied load differently; therefore, the measured deflection and the calculated normalized area ratio and normalized deflection ratio will be different for different pavement structures. For example, thin asphalt pavements or granular unbound pavements with surface treatments will have low normalized area ratio $(Ar')$ parameters compared to pavement structures with thick asphalt concrete layers or cement treated bases with structural asphalt concrete layers. This is because
the normalized area ratio parameters for thin asphalt pavements and granular pavements with
surface treatments are inherently low due to the low stiffness characteristics of these pavements.
Thus, in order to classify the structural capacity of the pavement network using the normalized
area ratio, the pavement structural composition must be taken into consideration.

In order to develop a scale for the normalized area ratio, four different types of flexible
pavements structures with different compositions and subgrade stiffnesses were analyzed using
CirclY computer simulations. The deflection bowls under the falling weight deflectometer load of
40 kN and tire pressure 565.9 kPa were generated. Table 2 shows only three types of these
pavements: Unbound granular pavement structure with surface treatment, unbound granular
cement concrete pavement with thin surfaced asphalt concrete layer (asphalt concrete thickness is 50 mm or less),
and structural asphalt pavements (asphalt concrete thickness>100 mm). For pavement structures
with cement stabilized base courses, fifty pavement sections were analyzed using CirclY, however, the pavement compositions are not shown in this paper due to the paper size
limitations. For each pavement type, a wide range of pavement sections vary from very weak to
strong pavement structures with different subgrade stiffnesses from very weak to strong
subgrades were considered in the analysis. CirclY analysis was conducted on these pavement
structures to simulate both FWD and deflectograph loadings. The normalized area ratio and
normalized deflection ratios were calculated for each pavement category and the data were
plotted as relationships between normalized area ratios versus normalized deflection ratios as
shown in Figures 6a to 6d.

Figure 6a: Relationship between normalized area ratio and normalized deflection ratio based on
CirclY simulations for unbound granular pavements with surface treatment
Figure 6b: Relationship between normalized area ratio and normalized deflection ratio based on Circly simulations for unbound granular pavements with 50 mm thin asphalt concrete layer.

Figure 6c: Relationship between normalized area ratio and normalized deflection ratio based on Circly simulations for structural asphalt pavements.
Figure 6d: Relationship between normalized area ratio and normalized deflection ratio based on Circly simulations for pavements with cement stabilized basecourse and thin or structural asphalt pavements.

It is clear from Figures 6a to 6d that each pavement type will have a certain range for the normalized area ratio and normalized deflection ratio. For pavement constructed mainly from granular unbound base/subbase course with surface treatments, the normalized area ratio ranges from 0.05 for very weak pavement constructed over weak subgrade to a maximum of 0.65 for very strong pavement over strong subgrade. In Figure 6a, four zones (Weak, Fair, Good and Strong) were tentatively marked based on the stiffnesses and thicknesses of the pavement layers as shown in Table 2. These marked zones provide a scale for each pavement type. For example, a normalized area ratio of 0.5 for unbound gravel pavement with surface treatment is considered strong pavement on strong subgrade, see Figure 6a. For the same normalized area ratio of 0.5, for thin asphalt pavement (asphalt concrete thickness ≤ 50 mm), the pavement structure is considered good as shown in Figure 6b, while for structural asphalt pavement (asphalt concrete thickness > 100 mm) is considered weak pavement structure over weak subgrade as shown in Figure 6c. Figure 6d shows the relationship between normalized area ratio parameter and normalized deflection ratio for pavements with cement stabilized base courses. Fifty pavement structures with a wide range of asphalt thicknesses from 0 to 200 mm and a wide range of cement stabilized bases properties ranging from very weak (E=800 MPa) to very strong (E=4000 MPa) were used to develop Figure 6d. Table 3, provides the different scales for classifying the structural capacity of different pavement structures. The normalized area ratio can easily be calculated for all pavement sections at the network level. Therefore, the structural capacity for each pavement section and pavement type can be ranked. Such ranking can provide road asset managers with a very excellent tool to evaluate the different strategies and prioritize them based on the structural performance of the road network. Very weak pavement structures are good candidates for major rehabilitation or reconstruction projects, while strong pavements are good candidates for preservation/preventive maintenance activities. Between these two extremes, pavement maintenance and rehabilitations can be determined based on the structural condition.
and other pavement conditions data. Pavement asset managers can effectively determine the percentage of their network that are in poor, fair, good and strong condition and they can make a good estimation of the required funding to keep their network in certain condition.

### Table 2: Normalized area and deflection ratios for different pavement types and compositions

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Code</th>
<th>Pavement Layers Moduli (MPa)</th>
<th>Layers Thicknesses (mm)</th>
<th>Ar'</th>
<th>Dr'</th>
<th>Pavement structural Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface treatment over granular base</td>
<td>AC</td>
<td>Base</td>
<td>Subgrade</td>
<td>h1</td>
<td>h2</td>
<td></td>
</tr>
<tr>
<td>UB01</td>
<td>0</td>
<td>100</td>
<td>15</td>
<td>0</td>
<td>200</td>
<td>0.044</td>
</tr>
<tr>
<td>UB02</td>
<td>0</td>
<td>350</td>
<td>30</td>
<td>0</td>
<td>300</td>
<td>0.144</td>
</tr>
<tr>
<td>UB03</td>
<td>350</td>
<td>50</td>
<td>0</td>
<td>300</td>
<td>0</td>
<td>0.239</td>
</tr>
<tr>
<td>UB04</td>
<td>0</td>
<td>500</td>
<td>100</td>
<td>0</td>
<td>500</td>
<td>0.630</td>
</tr>
<tr>
<td>Thin asphalts</td>
<td>TH01</td>
<td>2500</td>
<td>100</td>
<td>15</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>TH02</td>
<td>2500</td>
<td>350</td>
<td>30</td>
<td>50</td>
<td>300</td>
<td>0.273</td>
</tr>
<tr>
<td>TH03</td>
<td>2500</td>
<td>350</td>
<td>50</td>
<td>50</td>
<td>300</td>
<td>0.419</td>
</tr>
<tr>
<td>TH04</td>
<td>2500</td>
<td>500</td>
<td>100</td>
<td>50</td>
<td>500</td>
<td>0.941</td>
</tr>
<tr>
<td>Structural asphalt</td>
<td>B01</td>
<td>2500</td>
<td>100</td>
<td>15</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>B02</td>
<td>2500</td>
<td>350</td>
<td>30</td>
<td>150</td>
<td>300</td>
<td>0.686</td>
</tr>
<tr>
<td>B03</td>
<td>2500</td>
<td>350</td>
<td>50</td>
<td>150</td>
<td>300</td>
<td>0.953</td>
</tr>
<tr>
<td>B04</td>
<td>2500</td>
<td>500</td>
<td>100</td>
<td>250</td>
<td>500</td>
<td>2.456</td>
</tr>
</tbody>
</table>
Table 3: Pavement structural capacity classifications for different pavement types according to the normalized area ratio

<table>
<thead>
<tr>
<th>Flexible Pavement Type</th>
<th>Normalized Area Ratio Range</th>
<th>Pavement Structural Capacity Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbound granular with surface treatment</td>
<td>&lt;0.1</td>
<td>Weak</td>
</tr>
<tr>
<td></td>
<td>0.1 to 0.25</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>0.25 to 0.45</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>&gt;0.45</td>
<td>Strong</td>
</tr>
<tr>
<td>Unbound granular with Thin Asphalts</td>
<td>&lt;0.25</td>
<td>Weak</td>
</tr>
<tr>
<td></td>
<td>0.25 to 0.4</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>0.4 to 0.7</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>&gt;0.7</td>
<td>Strong</td>
</tr>
<tr>
<td>Structural Asphalts</td>
<td>&lt;0.6</td>
<td>Weak</td>
</tr>
<tr>
<td></td>
<td>0.6 to 1.0</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>1.0 to 1.5</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>&gt;1.5</td>
<td>Strong</td>
</tr>
<tr>
<td>Pavements with cement stabilized base</td>
<td>&lt;1.0</td>
<td>Weak</td>
</tr>
<tr>
<td></td>
<td>1.0 to 2.0</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>2.0 to 3.0</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>&gt;3.0</td>
<td>Strong</td>
</tr>
</tbody>
</table>

Field Verification Using Falling Deflectometer Data

Figures 7a and 7b are based on the falling weight deflectometer data carried out by two different agents in two different countries for granular pavements with chipseals or thin surfaced asphalts. In Figure 7a, the 40 kN load FWD test was carried out on 1200 flexible pavement sections with granular base course and thin surfaced asphalts or chip seals in the North region of Queensland, Australia, while Figure 7b is based on 120 FWD tests with 40 kN load carried out on flexible pavements with granular base course and chip seals or thin surfaced asphalt concrete in New Zealand. It can be seen that the range of the normalized area ratio is nearly similar to that developed from the theoretical computer analysis presented in Figures 6a and 6b. The minor differences between the theoretical and field section data could be due to some field sections might have some sort of bitumen stabilization or thicker asphalt layers. However, this difference is minor and the established criteria presented in Table 3 can be used to classify the structural capacity of these pavements.

Figure 7c shows the relationship between normalized area ratio and normalized deflection ratio for 1964 FWD tests carried out on flexible pavements with structural asphalt concrete layer (asphalt concrete thickness >100 mm) over granular base course. The range of the normalized area ratio is again similar to those theoretically developed by Circly computer simulations as shown in Figure 6c. Figure 7d shows the realationship between normalized area ratio and normalized deflection ratio based on 1916 FWD tests for flexible pavements consists of asphalt concrete over cement stabilized basecourse pavements in North Queensland, Australia. The range of the normalized area ratio based on field testing by the FWD is quite similar to the Circly computer simulated values shown in Figure 6d.
Figure 7a: Relationship between $A_r'$ and $D_r'$ for 1200 FWD tests for flexible pavements with granular base pavements and surface treatment in North Queensland, Australia.

Figure 7b: Relationship $A_r'$ and $D_r'$ for 120 FWD tests for flexible pavements with surface treatment over granular base pavements in New Zealand.
CONCLUSIONS

The area ratio and normalized area ratio parameters were introduced as simple deflection bowl parameters that can be calculated at the network level. The area and normalized area ratios were derived from synthetic deflection bowl data generated from a large number of pavement sections for different pavement types including granular unbound pavements with surface treatments or thin asphalts, flexible pavements with structural asphalt concrete layers over unbound granular base courses and pavements with cement stabilized bases. The area and normalized area ratios were found to be well correlated with the deflection ratio and normalized deflection ratio, respectively. However, because the deflection ratio only addresses a small portion of the deflection bowl, it cannot reflect the properties of all pavement layers. In addition, the deflection
ratio relies on two values only, therefore, it is more prone to field measurement errors. For these reasons, the area ratio and the normalized area ratio parameters are preferred. Four different scales for four different types of flexible pavements were developed to provide ranking of the structural capacity. The normalized area ratio parameter provides an excellent tool for road asset manager to rank and classify the structural condition of the pavement network and therefore plan their budget and maintenance and rehabilitation strategies.

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