AUSTROADS Pavement Design

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Group Technical Manager
Fulton Hogan Ltd
Load, W

Pavement

Subgrade

P0

P1
Load, W

Pavement

Subgrade

Compression

Tension

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Pavement Life Cycle Strategies

Performance Measure

Life Cycle Analysis Period (years or esa)
Two design processes for Flexible Pavements

Empirical Design Chart

• flexible pavements consisting of unbound granular materials, sprayed seal surface

Mechanistic

• flexible that contain one or more bound layers
AUSTROADS Guide Figure 8.4

MINIMUM THICKNESS OF BASE MATERIAL

Design Traffic (ERAs)

10^3 2 4 6 8 10^5 2 4 6 8 10^7

Thickness of Granular Material (mm)

0 100 200 300 400 500 600 700 800 900 1000

CBR

>30 20 15 10 7 6 4 3 2

8
Fundamentals of Mechanistic Design

• Pavement performance related to elastic strain

• Advantages
  – rational / scientific
  – flexible
  – portable

• Really semi-empirical
Definitions of Stress & Strain

Strain \((\varepsilon)\)
- unit movement / unit length
- dimensionless (\(\mu\text{m/m}\))

Elastic strain
- 100% rebound after load is removed

Recoverable (resilient) strain
- strain that rebounds after load is removed

Residual (permanent) strain

Stress \((\sigma)\)
- unit load / unit area
- \(\text{kN/m}^2 = \text{kPa}\)

Modulus
- stress / strain
- Elastic modulus
- Flexural modulus
- Resilient modulus
Mechanistic Design Process

Design Traffic (ESA)
Single tyre – Single Axle
Direction of Travel

$\varepsilon_1 = \text{Permanent strain} \quad \varepsilon_2 = \text{Resilient strain}$
Dual tyre – Single Axle
Equivalent Standard Axle (esa)

Individual tyre’s effect

Combined effect
Direction of Travel

Tandem

$\varepsilon_3$ = Permanent strain  $\varepsilon_4$ = Resilient strain

Individual effect

Combined effect

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## Equivalent Standard Axle (esa)

<table>
<thead>
<tr>
<th>Tyre &amp; Axle Configuration</th>
<th>Reference Axle Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single tyre - single axle</td>
<td>53</td>
</tr>
<tr>
<td>Dual tyre - single axle</td>
<td>80</td>
</tr>
<tr>
<td>Dual tyre - tandem axle</td>
<td>135</td>
</tr>
<tr>
<td>Dual tyre - tri-axle</td>
<td>181</td>
</tr>
</tbody>
</table>

- Number of standard axles to cause same damage = \[
\left( \frac{\text{Actual axle load}}{\text{Reference axle load}} \right)^4
\]
Traffic Loading

- For seal design: use equivalent light vehicles - convert heavy vehicles to elv
- For highway pavement design: ignore light vehicles, use only HCVs, converted to Equivalent Standard Axles (esa)
- For ports & log handling yards, DON’T use esa or 4th power rule for converting loads!
- For airports, special loading formula
Mechanistic Design Process

- Design Traffic (ESA)
- Proposed Pavement Model
Pavement Model

- ESA loading
- layers defined by E, ν, h
  - anisotropic (value depends on direction)
    - subgrade
    - unbound
  - isotropic (same in any direction)
    - asphalt
    - cemented

ESA Load

E1, ν1, h1
E2, ν2, h2
E3, ν3, h3
En, νn, hn
## Typical, Reasonable Input Values

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (MPa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt (&gt; 75 mm thick)</td>
<td>1500 – 4500</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>depends on mix properties &amp; vehicle speed</td>
<td></td>
</tr>
<tr>
<td>Unbound Base</td>
<td>200 – 450(!)</td>
<td>0.35</td>
</tr>
<tr>
<td>Unbound Subbase</td>
<td>150 – 300</td>
<td>0.35</td>
</tr>
<tr>
<td>Subgrade</td>
<td>10 – 250</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Sub-layering

Asphalt Modulus = 3200 MPa

Granular Layer Modulus = 400 MPa

Subgrade Modulus = 100 MPa
Selected subgrade materials

- 1992 Guide: $E_v = 10 \times \text{Design Subgrade CBR for entire layer thickness}$
- Concern that this resulted in higher moduli than granular materials
- New procedure developed to sublayer select material,
  \[
  E_{select} = E_{insitu} \times 2^{(\frac{\text{selected subgradematerial thickness}}{150})}
  \]
- Modulus is limited by modulus of underlying insitu subgrade
- Modulus doubles every 150 mm thickness of select material, up to max 10 x CBR
New granular sublayering rules

divide total granular thickness into 5 equally thick layers

<table>
<thead>
<tr>
<th>Sublayer</th>
<th>Thickness (mm)</th>
<th>Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T/5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>T/5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>T/5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>T/5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>T/5</td>
<td></td>
</tr>
</tbody>
</table>

First step: calculate modulus of top sublayer
Modulus of top granular sublayer
vertical modulus of top sub-layer, minimum of

<table>
<thead>
<tr>
<th>Thickness of Overlying Material</th>
<th>Modulus of Cover Material (MPa)</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 mm</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>75 mm</td>
<td>350</td>
<td>330</td>
<td>310</td>
<td>290</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>100 mm</td>
<td>320</td>
<td>280</td>
<td>260</td>
<td>240</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>125 mm</td>
<td>280</td>
<td>240</td>
<td>210</td>
<td>190</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>150 mm</td>
<td>250</td>
<td>200</td>
<td>160</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>175 mm</td>
<td>220</td>
<td>160</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>200 mm</td>
<td>200</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>&gt;=250</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>

1. Cover material is either asphalt or cemented material or a combination of these materials.

and that determined using the following formula:

\[
E_{\text{Top granular sublayer}} = E_{\text{Subgrade}} \times 2^{\left(\frac{\text{granular thickness}}{125}\right)}
\]
doubling of modulus every 125mm
New granular sublayering rules

Modulus of each Sublayer calculated from ratio of modulus of top granular sublayer and subgrade:

\[ R = \left( \frac{E_{\text{top granular sublayer}}}{E_{\text{subgrade}}} \right)^{\frac{1}{5}} \]

\[ R = \left( \frac{150}{30} \right)^{\frac{1}{5}} \]

\[ = 1.38 \]

<table>
<thead>
<tr>
<th>Sublayer</th>
<th>Thickness (mm)</th>
<th>Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>109</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>41</td>
</tr>
</tbody>
</table>

Subgrade modulus = 30
Definition of Project Reliability

Because of this lack of certainty in performance of the constructed pavement, an appropriate measure of anticipated performance of the proposed pavement is its Project Reliability:

“The Project Reliability is the probability that the pavement when constructed to the chosen design will outlast its design traffic before major rehabilitation is required”
## Typical Desired Project Reliabilities

### Table 2.1

**Typical Project Reliability Levels**

<table>
<thead>
<tr>
<th>Road Class</th>
<th>Project Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway</td>
<td>95-97.5</td>
</tr>
<tr>
<td>Highway: lane AADT &gt; 2,000</td>
<td>90-97.5</td>
</tr>
<tr>
<td>Highway: lane AADT ≤ 2,000</td>
<td>85-95</td>
</tr>
<tr>
<td>Main Road: lane AADT &gt; 500</td>
<td>85-95</td>
</tr>
<tr>
<td>Other Roads: lane AADT ≤ 500</td>
<td>80-90</td>
</tr>
</tbody>
</table>
Desired reliability achieved by using reliability factors in the performance relationships

\[ N = RF \left[ \frac{k}{\mu \varepsilon} \right]^m \]

Reliability Factor varies with selected desired project reliability
Cemented materials

Characterisation for Pavement Design

- isotropic ($E_v=E_h$)
- elastic modulus
- Poisson’s ratio 0.2
Improved guidance on presumptive moduli for cemented materials

- Subbase gravels, 4-5% cement: $E = 2,000\,\text{MPa}$
- Crushed rock, 2-3% cement: $E = 3,500\,\text{MPa}$
- Base with 4-5% cement: $E = 5,000\,\text{MPa}$
- Lean mix concrete (rolled): $E = 7,000\,\text{MPa}$
- Lean mix concrete (screeded): $E = 10,000\,\text{MPa}$
Cemented materials fatigue relationship

- Modified to allow to design to desired project reliability, includes Reliability Factor (RF)

\[ N = RF \left[ \frac{\left(\frac{113,000}{E^{0.804}} + 191\right)}{\mu\varepsilon} \right]^{12} \]

<table>
<thead>
<tr>
<th>Desired Project Reliability</th>
<th>80%</th>
<th>85%</th>
<th>90%</th>
<th>95%</th>
<th>97.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7</td>
<td>3.3</td>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>
Asphalt

Characterisation for Pavement Design

- isotropic ($E_v = E_h$)
- elastic modulus
- Poisson’s ratio 0.4
asphalt fatigue relationship

- modified to allow to design to desired project reliability, includes Reliability Factor (RF)

\[ N = RF \left[ \frac{6918(0.856 V_B + 1.08)}{S_{mix}^{0.36} \mu e} \right]^5 \]

<table>
<thead>
<tr>
<th>Desired Project Reliability</th>
<th>Int'l</th>
<th>80%</th>
<th>85%</th>
<th>90%</th>
<th>95%</th>
<th>97.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 to 10</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
<td>0.67</td>
<td></td>
</tr>
</tbody>
</table>
Mix Stiffness

- Resilient modulus is a measure of ‘stiffness’
- As stiffness increases, load is spread over a wider area
- $S_{\text{mix}} (t, T) \propto \sigma/\varepsilon$
- $S_{\text{mix}} (t, T) = \text{mix stiffness at a particular rate of loading (}t\text{) and temperature (}T\text{)}$
Gyratory Compaction

Ram Pressure

Angle of Gyration

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Advantages of Gyratory Compaction

- Better replication of mixes laid in the field
- Opportunity to vary compaction conditions
- Gives information on mix compactibility
- Rational
- Affordable
- Safe

- Allows fuller characterisation of mixes at design stage:
  - air voids at several compaction levels
  - compaction to refusal density (250 cycles)
  - assessment of mix compactability
- Allows optimisation of aggregate blend
Resilient Modulus Test

- Apply vertical load, P, at a specified rate (Pulse repetition period, 3.0 ± 0.05 seconds) and for a specified time (Rise time, 0.04 ± 0.005 seconds)
- Different rates of loading and different load pulse times simulate different loading conditions.
MATTA

• IPC Universal Materials Testing Apparatus
• Indirect tensile test setup, for measuring stiffness modulus
• Normally measured at 25 °C, but different temperatures can be specified depending on field conditions.
## FH MATTA Results

<table>
<thead>
<tr>
<th>Mix Bitumen</th>
<th>14-16 mm B60</th>
<th>14-16 mm B80</th>
<th>20 mm B80</th>
<th>40 mm B80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus Bitumen</td>
<td>2300 MPa @ 5.8%</td>
<td>1570 MPa @ 5.8%</td>
<td>1570 MPa @ 5.6%</td>
<td>2930 MPa @ 4.5%</td>
</tr>
<tr>
<td>Location</td>
<td>Auckland</td>
<td>Southland</td>
<td>Nth Hrbr</td>
<td>Southland</td>
</tr>
<tr>
<td>Modulus Bitumen</td>
<td>3350 MPa @ 5.4%</td>
<td>2970 MPa @ 5.5%</td>
<td>2880 MPa @ 5.1%</td>
<td>3390 MPa @ 4.8%</td>
</tr>
<tr>
<td>Location</td>
<td>Waikato</td>
<td>Nelson</td>
<td>Nelson</td>
<td>Dunedin</td>
</tr>
</tbody>
</table>
Increase Resilient Modulus by:

- Reducing bitumen content
  - Relative to Marshall optimum binder content
- Increasing bitumen viscosity
  - Decreasing penetration grade
- Coarser gradation
- Increasing compactive effort (to a critical limit for some mixes)
- Reducing temperature
- Aging (generally increases modulus)
Effect of Temperature on Modulus

- 120 Gyratory compaction cycles
- 80/100 pen bitumen
- Auckland basalt
- Air voids:
  - Mix 10 = 4.8%
  - Mix 16 = 4.8%
  - Mix 20 = 4.6%
Repeat Load Triaxial Apparatus

On-sample Axial Strain Measurement

- LVDT extension bracket screwed to brass target glued on test specimen
- LVDT core extensions
- Minature LVDT
- LVDT clamp screwed to target glued on test specimen
Non-linearity of Unbound Aggregates

For most bound materials, modulus is independent of confining pressure, but does vary with load duration (speed).

For unbound aggregates, modulus depends on confining pressure (kPa), load magnitude (kN) & duration (speed).

Modulus increases as confining / applied pressure increases.
Mechanistic Design Process

Design Traffic (ESA)

Proposed Pavement Model

CIRCLY

Calculate Critical Strains
3 Distress modes, 3 critical strains

1. Tensile strain at bottom of asphalt - **asphalt fatigue**
2. Tensile strain at bottom of cemented material - **cement mat fatigue**
3. Compressive strain at top of subgrade - **rutting & shape loss**

Denotes likely locations of critical strains due to applied loading.
Critical Strains

- Critical strains
  - subgrade
  - cemented layers
  - asphalt
CIRCLY

- Accumulates ‘damage’ contributed by each axle load in the traffic spectrum at each analysis point
- Cumulative Damage Factor (CDF) is the sum of damage factors over all the loadings
  - Pavement reaches its design life when CDF = 1.0
  - If CDF < 1.0, then pavement has excess capacity, & CDF gives proportion of life consumed
  - If CDF > 1.0, then pavement could fail early!
Asphalt Layer Thickness & Strains

Asphalt layer thickness

Compress Strain
Tension Strain

50 mm
75 mm
Environment issues dominate

Structural issues dominate

25 50 75 100
Asphalt layer thickness

25 50 75 100
Asphalt layer thickness

Compressive strain

Typical Multi-layer Flexible Pavement - Design Parameters
Typical Multi-layer Flexible Pavement - Design Parameters

- **Thickness AC**
- **Tensile strain**
- **Granular layers**
- **Subgrade**

**Environment issues dominate**

**Structural issues dominate**

- **Compressive strain**

**Asphalt layer thickness**

25, 50, 75, 100
Typical Multi-layer Flexible Pavement - Design Parameters

- Thickness AC
- Tensile strain
- E_B 200 MPa
- E_B 400 MPa
- 25, 50, 75, 100
- Asphalt layer thickness
- Compressive strain
- Granular layers
- Subgrade

Thickness AC
Humbolt & Mertens, 2006
Mechanistic Design Process

1. Design Traffic (ESA)
2. Proposed Pavement Model
3. Calculate Critical Strains
4. Apply Performance Criteria
Performance Criteria

\[ N = \left( \frac{8511}{\mu \varepsilon} \right)^{7.14} \]

\[ N = \left( \frac{9300}{\mu \varepsilon} \right)^{7} \]

Subgrade
Subgrade Strain Criterion

Test Pavement Number

Vertical Compressive Subgrade Strain (µm/m)

Cumulative Load Repetitions

- Shell, 1978
- NZ Primary, 1983
- NZ Secondary, 1983
- AUSTROADS, 1992
- AUSTROADS 2001

- Dormon & Metcalf, 1965
- Pidwerbesky
Performance Criteria

\[ N = \left[ \frac{113000E^{0.804} + 191}{\mu\varepsilon} \right]^{12} \]

Cemented
Modified Materials

- Small proportion of binder (< 2%)
- Improved properties
  - PI, workability, reduced water susceptibility
- Provides stable working platform
- Primarily compressive mode of failure
- Cracking not significant
Cemented Materials

- Greater proportion of binder
- Adds significant strength
- Relies on slab action
- Attracts stress
- Prone to fatigue cracking
- Prone to shrinkage cracking
Definition of Modified Materials

Increasing Binder Content

Unbound | Modified | Cemented | Lean-mix | Concrete

< 80 kPa | > 80 kPa

Tensile Strength

Dunlop (1978)
Performance Criteria

\[ N = \left( \frac{8511}{\mu \varepsilon} \right)^{7.14} \]

\[ N = \left( \frac{9300}{\mu \varepsilon} \right)^{7} \]
Performance Criteria

\[
N = \left[ \frac{6918 (0.856 V_B + 1.08)}{S_{Mix}^{0.36} \mu \varepsilon} \right]^{5}
\]

\[
N = RF \left[ \frac{6918 (0.856 V_B + 1.08)}{S_{Mix}^{0.36} \mu \varepsilon} \right]^{5}
\]

Asphalt
Tyre/Axle Load Configuration

Uniform stress (equal to tyre pressure)

1800 mm

330 mm

330 mm

Asphalt

Granular Material

Cemented Material

Subgrade

1. Tensile strain at bottom of asphalt
2. Tensile strain at bottom of cemented material
3. Compressive strain at top of subgrade

--- Critical locations

165 mm
Mechanistic Design Process

1. Design Traffic (ESA)
2. Proposed Pavement Model
3. Calculate Critical Strains
4. Apply Performance Criteria
5. Determine Theoretical Service Life (esa)
Mechanistic Design Process

Design Traffic (ESA)

Proposed Pavement Model

Calculate Critical Strains

Apply Performance Criteria

Determine Theoretical Service Life (ESA)

Not OK
Mechanistic Design Process

1. Design Traffic (ESA)
2. Proposed Pavement Model
3. Calculate Critical Strains
4. Apply Performance Criteria
5. Determine Theoretical Service Life (ESA)

Input to Decision
Subgrade Evaluation

- One strategy is to compact subgrade at an Equilibrium Moisture Content (EMC)
- Number of methods to establish design subgrade strength
  - e.g. measure on nearby pavement with similar materials & conditions
  - vertical modulus = 10xCBR & horiz modulus = 5xCBR
  - poisson's ratio = 0.45
- Potential to reduce costs by using a design strength other than soaked CBR
Rutting Resistance of Asphalt

- Larger mix size
- Angular/textured aggregates
- Stiffer/plastomeric binders
- Coarser grading
- Reducing air voids (min 3%)
- Increase filler
Fatigue Resistance of Asphalt

- Elastomeric binders
- Increase binder content
- Reduce air voids (min 3%)
Durability of Asphalt

- Reduce air voids
- Softer binders
- Increase binder film thickness
Skid Resistance of Asphalt

- Larger mix size
- Coarser grading
- Angular/rough aggregate
- Higher Polished Stone Value (PSV) of larger aggregate component only
Workability of Asphalt

- Increase VMA
- Higher binder content
- Softer binders
- Reduce filler
- Rounded aggregate
Moisture in the Pavement

A small amount is okay, and is beneficial

Too much - disastrous!

Everything in Moderation!
Pavement stress dissipation

Radius of contact
about 100 mm
Pressure > 100 psi

Radius of stress
about 300 mm
Pressure ≈ 10 psi

Radius of stress
about 500 mm
Pressure ≈ 4 psi

Granular layer(s)

Subgrade
Pavement saturation

Numerous contact points each, under high stress in a well compacted granular material

In a saturated system the applied load is transmitted equally in all directions, forcing the aggregate particles apart.
Saturated pavement rutting & heaving

Distance of heave from wheelpath is relative to depth/extent of failure

Heave

Subgrade shear failure due to saturation
300 mm rain in 3 days!
If the voids at the interface become near saturated the hydraulic stress will tend to debond the surfacing which is not confined by the load.

Air voids will be concentrated at the layer interface because the overlay mix will not conform identically to the texture of the substrate material.

Model of asphalt interfaces and potential hydraulic debonding stress
Pavement Construction Quality

• Density - % of Max Density & Optimum Moisture
  – Nuclear Density Meter
  – sand cone displacement
• In situ CBR and Plate Bearing tests
• Dynamic Cone (Scala) penetrometer
• Performance properties - Field tests
  – NOT Clegg Hammer - measures consistency of the surface finish
  – Deflection bowls - including Benkelman Beam
• Laboratory tests
Deflection Testing Equipment

• Full scale, heavy load devices:
  – Benkelman Beam
  – Deflectograph
  – Falling Weight Deflectometer

• Single point portable devices:
  – Clegg hammer
  – Prima
**Prima 100 Portable FWD Device**

**TYPICAL PLOT PRIMA LOAD & DEFLECTION v LOAD DURATION**

- Force (kPa)
- Deflection (µm)

AC; Run 1 Ch 10 Pt

---

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Deflection Bowl Analysis

Deflection (mm) vs. Distance from Centre of Load (m)
Curvature Function (CF) of a deflection bowl

- $D_0$ = maximum deflection for a test point
- $D_{200}$ = deflection measured where the test load is 200 mm from the point of maximum deflection (in the direction of travel).
Characteristic Deflections & Curvatures

Determined for each sub-section
Homogeneous sub-sections have:
• Coefficient of Variation (CoV) < 0.25
• Characteristic deflection (CD) or curvature (CC) is equal to average deflection or curvature (μ) + a factor (f) x standard deviation (σ):

\[ \text{CD or CC} = \mu + f \times \sigma \]

– f is selected based on reliability required
Coefficient of Variation (CoV)

- Statistical measure of consistent quality of construction
- Std dev of values divided by average value x 100%
  - ± 1 Standard deviation includes 68% of values
- Typical maximum values for CoV are < 25 or 30%
  - If deflection high, reduce to 20%
Coefficient of Variation

- Previous distribution:
  - Average = 1.0 mm
  - Std. Dev. = 0.1 mm
  - CoV = 10%
- This distribution:
  - Average = 1.0 mm
  - Std. Dev. = 0.2 mm
  - CoV = 20%
- Greater variation!
## Factor ‘f’ for Characteristic Values

<table>
<thead>
<tr>
<th>Road Functional Class</th>
<th>f</th>
<th>% of all deflection measurements which will be covered by the Characteristic Deflection*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 6</td>
<td>2.00</td>
<td>97.5</td>
</tr>
<tr>
<td>2, 7, 8 and 9</td>
<td>1.65</td>
<td>95</td>
</tr>
<tr>
<td>3, 4 and 5</td>
<td>1.30</td>
<td>90</td>
</tr>
</tbody>
</table>

\[
\text{CD or CC} = \mu + f \times \sigma
\]

* after identifying areas to be patched/reconstructed
Example Calculation of Characteristic Deflection (CD)

Sub-section: Average Deflection $\mu_D = 1.0$ mm

Standard Deviation $\sigma_D = 0.1$ mm

Require 95% confidence, for $f$

$$CD = \mu_D + f \times \sigma_D$$