Guide for design of concrete pavements in areas of settlement

Version 1.0
RMS Guide for design of concrete pavements in areas of settlement

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Executive Summary

In the past few decades, Roads and Maritime Services (RMS) and its predecessors have constructed several sections of concrete pavement each year. This trend is expected to continue in the future on major highways given the life-cycle cost advantage of concrete pavements in many instances.

In NSW, many sections of the road network maintained by RMS pass through areas where settlement of pavements is likely to occur. In many of these areas concrete pavements have been used or may potentially be used.

The RMS ‘Guide for Design and Performance of Concrete Pavements in Areas of Settlement’ is used to assess the suitability of concrete pavements in areas of potential settlement. Soft soils and underground mining areas are included in the analysis.

The information used in the preparation of the Guide is based on theory and the performance of existing concrete pavements in areas subject to settlement. The Guide focuses in particular on concrete base pavements with a lean mix concrete subbase. Two special types of pavements (Type 1 and Type 2) for areas of significant differential settlement are also briefly discussed.

Three levels of analysis are outlined in the Guide, and these are summarised as follows:

- Simplified assessment for settlement over soft soils (see Section 9)
- Special analysis for underground mining (see Section 10)
- Finite element analysis for complex settlement loading conditions

The Guide presents the various functions of the ‘Thickness Design for Settlement Spreadsheet’ for the assessment of the long-term performance of a concrete pavement in areas of differential settlement (refer to Appendix D for details).

Numerous symbols and terms are used in this Guide and these are defined in Section 14. For other terms not defined in Section 14, refer to the Austroads Glossary to Terms (Austroads, 2010).

This Guide should not be used for sites subject to transverse slope movements.

This Guide includes allowable values for differential settlement for five types of standard concrete pavements, one special concrete pavement and one special composite pavement.
RMS Guide for design of concrete pavements in areas of settlement

Table of Contents

Foreword and disclaimer .......................................................... i
Acknowledgements ........................................................................ i
Executive Summary ...................................................................... iii

1. Purpose .................................................................................. 1
2. Introduction ............................................................................. 1
3. Performance of concrete pavements ........................................ 3
4. Special concrete pavement to optimise the performance in settlement areas ...... 6
5. General performance ranking of various concrete pavements ...................... 6
6. Comparison of underground mining as against volume changes in subgrade .... 10
7. Design criteria ......................................................................... 14
   7.1 Overview ............................................................................... 14
   7.2 Typical location of critical design criteria .................................. 19
8. Soft soils .................................................................................. 21
   8.1 General ................................................................................ 21
   8.2 Life of concrete pavements built over soft soils ......................... 23
   8.3 Initial appraisal .................................................................... 24
9. Simplified assessment for settlement over soft soils ................................ 25
   9.1 Overview ............................................................................... 25
   9.2 Basis for pavement requirements ........................................... 32
      9.2.1 Upper bound value for relative movement between concrete base and subbase .............................................. 32
      9.2.2 Calculation of minimum compressive strength for concrete subbase .................................................. 33
      9.2.3 Compressive failure/stepping in upper subgrade layer which is bound ........................................... 35
      9.2.4 Differential settlement limits for fast and slow rates of settlements .................................................... 36
10. Underground mining ............................................................... 46
    10.1 Special analysis .................................................................. 46
    10.2 Special pavements ............................................................. 46
    10.3 Impact of traffic safety and drainage ...................................... 47
    10.4 Reducing impacts related to cuttings .................................... 48
    10.5 Minimising risk of failures ................................................... 48
    10.6 Upper limit of extraction of coal ........................................... 49
    10.7 Monitoring .......................................................................... 49
11. Basic conditions for adequate in service performance ............................. 51
12. Sensitivity analysis ................................................................. 52

Version 1.0

Page v
List of Figures

Figure 1: Total and differential settlement. ..................................................................................1
Figure 2: Basic deformation shapes of concrete pavement caused by differential settlement. .................................................................................................................................2
Figure 3: Horizontal strain reversals which can occur with underground mining in the upper subgrade. ...........................................................................................................................10
Figure 4: Idealised settlement bowl in the direction of traffic.......................................................14
Figure 5: Horizontal strain and horizontal movement in upper subgrade layer due to differential settlement in the longitudinal direction in relation to settlement profile.................15
Figure 6: The development of stepping failure in a bound layer. ..............................................18
Figure 7: Differential horizontal movement in the transverse direction caused by horizontal transverse movement of the upper subgrade. (Note: The slope of the failure angle is expected to be of the order of 15 to 25º.) ........................................................................19
Figure 8: Typical locations of critical stresses, strains and horizontal movements. .................19
Figure 9: Identifying when primary settlement is reached and secondary creep settlement commences.............................................................................................................................21
Figure 10: Effect of delay in paving on design life for CRCP for various thicknesses of base concrete (Bc) for hypothetical settlement scenario. .................................................................22
Figure 11: Settlement bowl showing the difference between $R_{\text{min(local)}}$ and $R_{\text{min(overall)}}$......24
Figure 12: Individual settlement bowls within a general bowl..................................................25
Figure 13: Relationship between T and D for longitudinal and transverse settlement. .............26
Figure 14: Examples of fast and slow rates of settlement..............................................................27
Figure 15: Process for the assessment of PCP and PCP-R, PCP-D, JRCP and CRCP over soft soils. Refer to Table 5 for Actions A to E........................................................................................................28
Figure 16: Sketch of isolation of pavement in a rock cutting in the vicinity of underground mining where large-scale settlement is expected.................................................................48
Figure 17: Possible layout of mining so settlement is within acceptable limits (sketch). ..............49
List of Tables

Table 1: Special pavements where the effects of differential settlement is significant............5
Table 2: Generalised suitability/ranking of concrete pavements with settlement for various scenarios..............................................................................................................................7
Table 3: Typical range of various factors for settlement of concrete pavements caused by underground mining and consolidation of soft soils......................................................................................................................12
Table 4: Typical locations of critical stresses. ........................................................................20
Table 5: Actions to the assessment process from Figure 15. ...............................................29
Table 6: Pavement requirements to be satisfied for initial screening process for concrete pavements over soft soil subgrades for PCP, PCP-R, PCP-D, JRCP and CRCP (all with concrete subbases).............................................................................................................30
Table 7: Maximum allowable settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP and PCP-R)...........................................................................................................................................................36
Table 8: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP and PCP-R)...........................................................................................................................................................37
Table 9: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for PCP and PCP-R). ........................................................................................................................................................................38
Table 10: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for PCP and PCP-R). ........................................................................................................................................................................39
Table 11: Maximum allowance settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP-D).........................................................................................................................................................................40
Table 12: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP-D).........................................................................................................................................................................40
Table 13: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for PCP-D). ........................................................................................................................................................................40
Table 14: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for PCP-D). ........................................................................................................................................................................40
Table 15: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for JRCP). ........................................................................................................................................................................41
Table 16: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for JRCP). ........................................................................................................................................................................41
Table 17: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for JRCP). ........................................................................................................................................................................42
Table 18: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for JRCP). ........................................................................................................................................................................42
Table 19: Maximum allowable settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for CRCP).

Table 20: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for CRCP).

Table 21: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for CRCP).

Table 22: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for CRCP).
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1. Purpose

This Guide provides information about the expected performance of concrete pavements in areas of settlement as well as a methodology to assess if a particular concrete pavement configuration is capable to perform adequately in areas that are prone to differential settlement.

In the interest of keeping the Guide focussed on the practical needs of the concrete pavement practitioner, the Guide does not attempt to cover all aspects of differential settlement.

This Guide should not be used for sites subject to transverse slope movements.

This Guide includes allowable values for differential settlement for five types of standard concrete pavements, one special concrete pavement and one special composite pavement.

2. Introduction

Concrete pavements do not easily follow differential settlements of the subgrade. Depending on the magnitude of the differential settlements, high stresses can develop from a combination of settlement, dead load, temperature and traffic loading induced influences, which may lead to premature structural failure. As described by Vos (1985) the concrete pavement will offer resistance to the imposed curvature arising from settlement, reducing the maximum curvature of the slab and in that way the maximum induced tensile stress. At the same time, lifting of the slab from the subgrade will increase traffic load induced stresses.

For the calculation of the tensile stresses due to differential settlement, the model shown in Figure 1 is used.

![Figure 1: Total and differential settlement.](image-url)
It is differential settlement rather than uniform settlement that is of concern for concrete pavements. In general, when settlement occurs there are always areas of differential settlement at least in the transition zones between areas of pavement subject to no settlement and areas of pavement subject only to uniform settlement. So for convenience, the word settlement is often used throughout this document to refer to differential settlement. Though differential settlement can occur in both longitudinal and transverse directions in this Guide, the settlement bowl is analysed primarily in the longitudinal direction.

Differential settlement under a concrete pavement results in the layers of the pavement being forced to deform in either a concave or convex shape due to the self-weight of the concrete. The two basic deformation shapes, relative to the final vertical alignment of the formation, are shown in Figure 2.

![Concave Shape](image1) ![Convex Shape](image2)

Figure 2: Basic deformation shapes of concrete pavement caused by differential settlement.

Deformation shapes can be in the longitudinal direction (direction of traffic) and/or the transverse direction (perpendicular to direction of traffic) and result in bending stresses in the concrete base and subbase.

These bending stresses are a function of the curvature ($\kappa$) of the pavement which is defined as $\kappa = 1/(\text{radius of curvature}) = 1/R$

As well as understanding the effect of vertical settlement in the subgrade it is also necessary to be aware of associated horizontal movements which cause axial stresses and axial strains (both tensile and compressive) in concrete pavements.

The criteria for assessing the impact of settlement on concrete pavements are related to:

- Curvature, $1/R$, noting the higher the curvature, that is the lower the radius of curvature, the higher and hence more critical are the bending stresses in the concrete pavement.
- Horizontal movements in the upper subgrade. Note that these can be highly significant for underground mining which occurs under or near a carriageway.
- A combination of curvature and horizontal movements of the upper subgrade where both are in the longitudinal direction. This combined effect is only significant for CRC layers and so applies to CRC base and CRC subbase (in Types 1 and 2 pavements respectively as detailed in Table 1) in crest areas of settlement bowls.

Refer to Appendix A for more details on the limits for the criteria.
3. Performance of concrete pavements

The five standard types of concrete pavements used in this Guide are: PCP, PCP-R, PCP-D, JRCP and CRCP. All of these will perform differently when subjected to differential settlement and so each of them will have its own set of criteria with corresponding structural performance limits.

Case studies of concrete pavements show that CRCP and dowelled jointed pavements (JRCP and PCP-D) can tolerate settlement in the two basic deformation shapes (concave and convex). Under certain circumstances excessive surface roughness will develop before settlement significantly affects the structural integrity of the pavement.

On the other hand, PCP and PCP-R, in general, are not suitable in areas of convex settlement, either in the longitudinal direction or in the transverse direction due to:

- The likelihood of corner slab breaking and diagonal cracking.
- Excessive joint openings at transverse contraction joints such as at crests in the settlement bowl where there is differential settlement in the longitudinal direction. Such joint openings cause a reduction in shear transfer between adjacent slabs and an increase in the potential for erosion and fatigue cracking of the base concrete.

PCP and PCP-R can only be used where the radius of curvature in the longitudinal direction is very large (i.e. greater than at least 850 m). Therefore PCP and PCP-R pavements are not suitable over soft soil subgrades or expansive soils.

Soft soils often show variability in thickness and/or soil properties.

Expansive soils on the other hand, can be particularly damaging to the concrete pavement because of their shrink/swell behaviour. The likelihood of corner breaking in areas of convex shape will cause diagonal and longitudinal cracking in the crest regions of settlement bowls. Expansive soils are tolerable only where they are sufficiently deep, such that they have volume stability as a result of constant moisture content and/or sufficient overlying mass.

PCP-D and JRCP are not considered able to tolerate large reversals in horizontal movement of the subgrade in the longitudinal direction. The reversal in horizontal movement can occur with underground mining and possibly also with seasonal changes in expansive subgrades without adequate cover. Unless joint sealing of transverse joints is of such quality that it prevents ingress of debris into transverse joints. PCP-D and JRCP perform better where slab lengths are short.

PCP and PCP-R are not suitable with either underground mining or where no adequate cover over expansive subgrades can be accommodated. The concrete pavement types are not able to meet the restrictions on transverse joint opening except where horizontal movement in the longitudinal direction is small and therefore, where the maximum horizontal tensile strains in the longitudinal direction of the upper subgrade are very low. For PCP and PCP-R this typically restricts underground mining to areas well away from carriageways with the possible exception of mining being limited to constructing tunnels for mine access under a carriageway.

Horizontal movements in the transverse direction and therefore differential horizontal movement over a section of pavement in the transverse direction, such as can occur with underground mining, are a concern for PCP-D, JRCP and CRCP. However, for relatively small transverse movements, slight rotation of the base slabs relative to one another in the
horizontal plane are able to accommodate the differential horizontal movement over a section of pavement. This is due to the relief or give arising from the closing and opening of transverse joints in the concrete base, noting that concrete bases may be more critical with horizontal differential movements in the transverse direction than concrete subbases. Concrete bases are less strain tolerant due to their higher modulus. On the other hand if shrinkage cracking is low in subbase concrete due to its moist environment there will be less relief in the subbase due to opening and closing of transverse cracks. There may also be very localised shear cracking of a minor nature at points of contact along transverse joints/cracks in base and subbase concrete (ie on inside edges of transverse curvature in the horizontal plane).

Transverse horizontal movements must be controlled to avoid excessive compressive and/or shear stress in a concrete pavement layer. Tolerable values of maximum differential horizontal movement in the transverse direction for the different concrete pavement types are given in Appendix A.

In general with settlement, CRCP performs better than JRCP, and JRCP is better than PCP-D. This needs to be offset against any damaged sections of JRCP and PCP-D being easier and less disruptive to remove and replace.

CRCP can be slab jacked without much difficulty. Slab jacking will improve support, riding quality and/or surface drainage. Nevertheless, pressure grouting in crests of settlement bowls may involve substantial lengths of this treatment to keep the radius of curvature to tolerable levels.

While concrete subbases under concrete bases are beneficial for concrete pavements for non-settlement situations, they do create some restrictions with settlement because of the need to limit the relative movement between the concrete base and the concrete subbase to ensure adequate support for the base during and following settlement. CRCP is the most tolerant concrete pavement for relative movement between base and subbase, but where CRCP is unsuitable, Type 1 or a composite pavement (Type 2) is preferred. This type of pavement is unlikely to be constructed due to its cost and is only included here for completeness. The description of special pavements is shown in Table 1.

The restrictions related to the use of concrete subbases are not critical for pavements meeting the requirements of Table 5, which is part of the initial screening process for simple cases of settlement over soft soils to ensure limits related to horizontal movements are not exceeded. Where the limits in Table 5 are not met, there also needs to be an assessment according to this Appendix A to determine whether or not the limits related to horizontal movements are satisfied. In some situations, increasing pavement thickness may be required. However, it may be that a concrete pavement is not suitable as it may not be possible or feasible to meet these limits even with an increase in pavement thickness.

Type 1 has no restriction on the relative movement between any adjacent pavement layers.

Composite pavement Type 2 is considered to be the most expensive option and is also the most tolerant in terms of allowing larger horizontal movements of the upper subgrade. Provided there is a high percentage of longitudinal steel in the CRC subbase, pavement Type 2 is capable of withstanding a maximum horizontal movement of 100 to 150 mm.

Composite pavement Type 2 will also require an erosion resistance (ie lean mix concrete) subbase layer together with the Slip-Moderately Deformable Granular Subgrade Layer of at least 300 mm. Possibly at least 1000 mm of granular material below the slip-moderately deformable granular subgrade layer that can distort with horizontal movements will also be required. For this reason Pavement Type 2 is not a cost effective option.
Table 1: Special pavements where the effects of differential settlement is significant

<table>
<thead>
<tr>
<th>Concrete Pavement Type 1(^a)</th>
<th>Composite Pavement Type 2(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base:</strong> CRC(^h) or Short Slab JRC</td>
<td></td>
</tr>
<tr>
<td><strong>Interlayer:</strong> 50 to 100 mm Asphalt, or 150 to 200 mm non-erodible granular material(^c)</td>
<td></td>
</tr>
</tbody>
</table>
| **Subbase:** Concrete  
\(f'_c\) at first summer after commencement of settlement > 30 MPa  
**Slip – Moderately Deformable Granular Subgrade Layer**  
Upper (Unbound) Subgrade \(^f\) |
| **Base:** Asphalt (125 to 175 mm) |
| **Subbase:** CRC Subbase Layer\(^b\)  
with Erosion Resistant Lower Subbase Layer\(^d\)  
**Slip - Moderately Deformable Granular Subgrade Layer** \(^e\) |
| **Upper (Unbound) Subgrade** \(^f\) |

Notes:

a. The minimum thicknesses of base and subbase must satisfy the relevant requirements of this Guide.
b. In general, CRC layers need to have high \(f'_c\), say \(\geq 60\) MPa (28 day age) at the first summer after start of settlement for long settlement bowls, to prevent failures in the tension zones either side of a compression zone. For long bowls which are only shallow, ie large \(T/2\) to low \(D\) for Type 1 (with CRC base) and Type 2 pavements, the \(f'_c\) may be less than 60 MPa provided the maximum tolerable horizontal tensile strain in the longitudinal direction of the upper subgrade is 0.6 mm/m, as this is considered to prevent yielding of the longitudinal steel in the CRC layer. A Finite Element Analysis may show that a higher value of tensile strain can be tolerated (as the limit of 0.6 mm/m ignores any slippage between the pavement and the upper subgrade, that is it assumes all horizontal movement that occurs in the upper subgrade also occurs in the CRC base).
c. Provided this granular material will not undergo significant dilation/decompaction due to horizontal movements related to the settlement.
d. The Erosion Resistant Lower Subbase Layer needs to be able to resist pumping. Being at some depth from the surface, it may not need to have the same erosion resistance as for subbases in a typical concrete pavement. This layer may also perform the function of the Slip – Moderately Deformable Granular Subgrade Layer, provided it has a maximum particle size of 5 mm, sufficient resistance to erosion, and relatively low coefficient of friction and hence low cohesion with the layer above.
e. A Slip – Moderately Deformable Granular Subgrade Layer needs to have a relatively low coefficient of friction and hence low cohesion with the upper subgrade. In general this layer is needed for settlement bowls longer than 150 m.
f. In general, for bowls of significant length, an upper subgrade cannot be stabilised so as to avoid this layer undergoing compressive failure in the compression zone, from friction caused by settlement in conjunction with or without compressive stress from high temperature (and high moisture), leading to this layer developing a sudden step or a hump resulting in uneven support of the pavement, and possibly a step of the overlying pavement layers. For large horizontal movements of the upper subgrade, say 100 to 150 mm, it is considered that there must be at least 1000 mm of granular material below the slip-moderately deformable granular subgrade layer that can distort with horizontal movements.
4. Special concrete pavement to optimise the performance in settlement areas

Special concrete pavement Type 1 should be specified where a conventional concrete pavement is not considered suitable because:

- The minimum radius of curvature in concave or convex direction is expected to be small
- Large horizontal movements are anticipated
- The relative horizontal movement between a pavement and the subgrade is high
- High design reliability is involved

Where the maximum horizontal movement of the upper subgrade in the longitudinal direction is greater than 100 mm but less than 150 mm, the only concrete pavement considered suitable is a Type 2 pavement. Further analysis will be required to determine the appropriateness of the maximum horizontal movement of 100 to 150 mm in the longitudinal direction of the upper subgrade for a Type 2 pavement.

More work is needed to determine appropriate upper limits for the maximum horizontal movement of the upper subgrade for Type 1 pavement.

5. General performance ranking of various concrete pavements

Table 2 gives an indication of the suitability or ranking of various concrete pavements for settlement. This is only a generalised treatment of some of the key aspects that affect the performance of concrete pavements in differential settlement, and so it only gives an initial introductory understanding.

In the case of underground mining, the effect of anomalous or irregular behaviour is ignored in Table 2. Special analysis is required to assess the risk of this behaviour. For areas where underground mining causes large settlements and/or long settlement bowls, no rigid concrete pavements may be suitable.
Table 2: Generalised suitability/ranking of concrete pavements with settlement for various scenarios.
(Note: For this table PCP and PCP-R, PCP-D, SHORT AND LONG SLAB JRCP and CRCP all have a lean mix concrete subbase)

<table>
<thead>
<tr>
<th>Pavement type</th>
<th>Low radius of curvature (Refer Section C2 of Appendix C)</th>
<th>Horizontal movement of the upper subgrade (Longitudinal and/or transverse, where longitudinal is the direction of traffic)</th>
<th>Relative movement between concrete base and concrete subbase</th>
<th>Reversal of horizontal movements (^b) of the upper subgrade (that can occur with underground mining or over highly expansive subgrade)</th>
<th>Long settlement bowls (provided they are shallow) (^f)</th>
<th>Ride/shape correction with AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCP and PCP-R (^c)</td>
<td>Not Suitable: For convex settlement unless minimum radius of curvature is very large</td>
<td>Rank G</td>
<td>Rank F</td>
<td>Not Suitable, except for very small movements</td>
<td>Not Suitable, except for very shallow bowls</td>
<td>Rank F</td>
</tr>
<tr>
<td></td>
<td>Suitable: For convex settlement, minimum radius of curvature is very high, in which case:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rank G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suitable: Where settlement is only in the transverse direction (ie perpendicular to the direction of traffic) and this is only concave:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rank E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCP-D</td>
<td>Rank E</td>
<td>Rank F</td>
<td>Rank E</td>
<td>Rank F</td>
<td>Not Suitable</td>
<td>Rank E</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------------</td>
<td>--------</td>
</tr>
<tr>
<td>LONG SLAB: JRCP (slabs &gt; 6.25 m)</td>
<td>Rank D</td>
<td>Rank E</td>
<td>Rank C</td>
<td>Rank E</td>
<td>Rank E</td>
<td>Rank F</td>
</tr>
<tr>
<td>SHORT SLAB: JRCP (slabs ≤ 6.25 m)</td>
<td>Rank C</td>
<td>Rank D</td>
<td>Rank D</td>
<td>Rank D</td>
<td>Rank D</td>
<td>Rank E</td>
</tr>
<tr>
<td>CRCP</td>
<td>Rank B</td>
<td>Rank B</td>
<td>Rank B</td>
<td>Rank B</td>
<td>Rank D</td>
<td>Rank B</td>
</tr>
<tr>
<td>TYPE 1 (CRC/Short Slab JRC Base AC Interlayer Concrete Subbase)</td>
<td>Rank A</td>
<td>Rank B</td>
<td>Not Applicable</td>
<td>For CRC base: Rank A</td>
<td>For short slab JRC base: Rank C</td>
<td>Rank D</td>
</tr>
<tr>
<td>TYPE 2 (AC Base CRC Subbase)</td>
<td>Rank A(^d)</td>
<td>Rank A(^d,e)</td>
<td>Not Applicable</td>
<td>Rank A(^e)</td>
<td>Rank D(^e)</td>
<td>Rank A</td>
</tr>
</tbody>
</table>

\(d\) Note: This has less traffic stress in the CRC subbase than for a CRC base in CRCP.

\(e\)
Notes:

a. Rank A has the best-expected performance followed by Rank B and so on. The rankings are only broad generalisations to show the general relativities between the various pavements. These rankings do not indicate whether a particular pavement is suitable, as settlement may be just too severe for a concrete pavement to be used.

b. Reversal in horizontal movement, which can occur with underground mining and expansive subgrades, may (with PCP-D, JRCP, and Type 1 with short JRC slabs) cause jamming of dowels at transverse joints during a settlement compression phase following an expansion phase. This is particularly the case where transverse joint sealants do not keep out debris during the expansion phase (and also prior to settlement).

c. In general, while PCP and PCP-R virtually cannot tolerate any settlement in the longitudinal direction due to their vulnerability to convex settlement, they are able to tolerate a degree of settlement in the transverse direction provided this is virtually only of a concave shape.

d. Type 1 has no restriction on the relative movement between any adjacent pavement layers.

e. For a Type 2 pavement: it is considered that longitudinal movements up to 150 mm in the upper subgrade may be tolerable in certain situations. Maximum horizontal movements of the order of 100 to 150 mm are tolerable, provided there is a high percentage of longitudinal steel in the CRC subbase, the total thickness of the erosion resistant lower subbase layer together with the slip-moderately deformable granular subgrade is at least 300 mm, and there is also at least 1000 mm of granular material below the slip-moderately deformable granular subgrade layer that can distort with horizontal movements. However, even if the maximum longitudinal movement at the top of the subgrade is less than 100 mm, it is still necessary to do an analysis with the Guide to determine whether a Type 2 pavement can be used, as other criteria may not be met.

f. A Type 2 pavement, with thick AC (ie at least 175 mm) with thick CRC subbase (ie at least 250 mm) which has a high percentage of longitudinal steel (ie high $p$) and/or has a high $f^*_{sy}$, and where the ratio of CRC thickness to AC thickness is relatively large (greater than 1.4), may have a better, ie higher, ranking than shown in the table (ie A plus).

For settlement bowls longer than the limits shown in Table 6 there is more likelihood of large horizontal movements in the upper subgrade causing high axial stresses and creating risk of failure such as buckling or compressive failure of the concrete base and/or compressive failure of the concrete subbase.
6. Comparison of underground mining as against volume changes in subgrade

There are some basic differences between the nature of settlement caused by underground mining and the settlement caused by volume changes in the soft soils or expansive soil subgrades.

Firstly, in underground mining, there can be variations in the nature of horizontal strains at the top of subgrade at a given location over time. For example, during mining and/or for some period afterwards, some locations can experience four different stages:

Stage A: Tension due to tensile strains associated with crests and troughs
Stage B: Zero strains (neutral) at the junction of a tension zone with a compression zone, near the point of contraflexure
Stage C: Compression due to compressive strains associated with troughs
Stage D: Return to neutral.

This is illustrated in Figure 3 for one location where the vertical arrow (with multi arrow heads) shows the effects of stages in mining (and for some period after mining ceases) on horizontal strains, which go from tension at Stage A of mining to neutral at Stage B to compression at Stage C and finally back to neutral at Stage D.

In Figure 3 the point being examined may not exactly fall in a vertical line, as there are different horizontal movements with each stage.

![Horizontal strain reversals which can occur with underground mining in the upper subgrade.](image)

In contrast to settlement due to underground mining, settlement caused by volume changes of subgrades, such as caused by consolidation of soft soils, may cause no change in the type of horizontal strain at a particular location but only an increase in the magnitude of strain with time.

Firstly, where there is shrink/swell behaviour due to expansive soils a concrete pavement may experience alternating convex and concave behaviour over time especially in the transverse direction. This is because a subgrade may both shrink and swell relative to its original volume at the time of construction of the pavement.

Secondly, there are some basic differences in the general magnitude of the various factors associated with settlement between that caused by underground mining and that caused by volume changes in the subgrade. Many of these differences are because underground mining is typically at a great depth and of a very large scale, whereas volume changes in subgrades are typically of a shallower nature and on a smaller scale.
Table 3 shows the basic differences, in magnitude of various factors, for the two types of settlement.

In simplistic terms there are basic differences in the critical conditions associated with failure of concrete pavements between settlement due to underground mining, such as where coal is at a depth of say 200 m to 500 m below the surface with a seam thickness of the order of 1 m to 3 m, and that due to volume changes of soft soil subgrades.

In general, bending stresses due to curvature are more critical where volume changes in the subgrade have occurred such as from settlement of soft soils. However, curvature may still be critical for underground mining.

Axial stresses from friction can be more critical for underground mining than for settlement of soft soils. Nevertheless, axial stresses due to friction can be critical in some situations where settlement of soft soils has occurred.

Settlement caused by underground mining is typically at a great depth and of a very large scale, whereas volume changes in subgrades are typically of a shallower nature and on a smaller scale.

With underground mining there are also issues of irregular behaviour such as those associated with valley closure and geological faults
Table 3: Typical range of various factors for settlement of concrete pavements caused by underground mining and consolidation of soft soils.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type of settlement:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Underground mining of coal</td>
</tr>
<tr>
<td>Maximum depth of differential settlement ($D$)</td>
<td>Medium – Very High</td>
</tr>
<tr>
<td>Minimum radius of curvature ($R$)</td>
<td>Medium – Very High</td>
</tr>
<tr>
<td>Curvature (1/R) (noting lower values are more critical)</td>
<td>Low – Medium</td>
</tr>
<tr>
<td>Rate of settlement</td>
<td>Fast to Very Fast</td>
</tr>
<tr>
<td>Tensile stress in base from bending due to settlement</td>
<td>Low - Medium</td>
</tr>
<tr>
<td>Length of settlement bowl (and hence length of compression and tension zones)</td>
<td>Medium - Very High</td>
</tr>
<tr>
<td>Maximum horizontal strain (longitudinal) in the upper subgrade (both tensile and compressive strains)</td>
<td>Medium - Very High</td>
</tr>
<tr>
<td>Maximum horizontal movement of subgrade</td>
<td>Medium - Very High</td>
</tr>
<tr>
<td>Maximum differential horizontal movement of concrete pavement in the transverse direction</td>
<td>Medium – Very High</td>
</tr>
<tr>
<td>Relative horizontal movement between base concrete and subbase concrete</td>
<td>Medium - Very High</td>
</tr>
<tr>
<td>Maximum axial compressive stress due to friction from settlement (in troughs - in both concrete base and subbase)</td>
<td>Medium - Very High</td>
</tr>
<tr>
<td>Risk of buckling of concrete base (in compression zone)</td>
<td>High - Very High</td>
</tr>
<tr>
<td>PCP and PCP-R (in convex settlement): Risk of:</td>
<td></td>
</tr>
<tr>
<td>• Corner breaking and/or diagonal cracking (in any direction)</td>
<td>High – Very High</td>
</tr>
<tr>
<td>• Significant loss of aggregate interlock (in longitudinal direction)</td>
<td>Very High</td>
</tr>
</tbody>
</table>
### Table 3: Continued

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type of settlement:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Underground mining of coal</td>
</tr>
</tbody>
</table>

#### PCP-D and JRCP (in tension zone): Risk of damage due to reversals in horizontal movement

<table>
<thead>
<tr>
<th>Factor</th>
<th>Underground mining of coal</th>
<th>Consolidation of soft soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium – High</td>
<td>Low – Medium</td>
<td></td>
</tr>
</tbody>
</table>

#### CRCP (in tension zone): Risk of:

- Corrosion of longitudinal steel
- Significant loss of shear transfer at transverse cracks
- Yielding of steel
- Overstressing of the base concrete

<table>
<thead>
<tr>
<th>Factor</th>
<th>Underground mining of coal</th>
<th>Consolidation of soft soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium – High</td>
<td>Low – Medium</td>
<td></td>
</tr>
<tr>
<td>Medium – High</td>
<td>Low – Medium</td>
<td></td>
</tr>
<tr>
<td>Medium – High</td>
<td>Low – Medium</td>
<td></td>
</tr>
<tr>
<td>Medium – High</td>
<td>Low – Medium</td>
<td></td>
</tr>
</tbody>
</table>

### Notes:

- The ranges given are only a broad generalisation to show the general relativities between the two types of settlement. Therefore the words 'low', 'medium', 'high', and 'very high' are used to show typical relative values and do not indicate whether a particular factor is critical or not. Therefore this Table does not replace the need for a full evaluation in accordance with this Guide.

- The range for the various factors for underground mining may be less critical overall where sufficient coal pillars are kept in place to create a long shallow bowl or a series of short shallow bowls, particularly those related to horizontal movements and horizontal strains.

- This list is not exhaustive and so other areas of the Guide need to be consulted for a more thorough understanding of the differences between the two types of settlement.

- Factors associated with risk may be able to be eliminated eg with regard to yielding of steel in CRCP, providing higher values of $p$ may eliminate the risk of steel yielding.
7. Design criteria

7.1 Overview

A settlement bowl in the longitudinal direction (direction of traffic) is assumed to follow a cosine curve as shown in Figure 4. Tension occurs in the crest regions and compression occurs in the trough region.

For CRCP the tension and compression zones will not perfectly match those of the upper subgrade due to the action of the longitudinal steel.

Shapes of differential settlement in the transverse direction typically follow an arc of a circle (see Figure 13).

The shape of the curve is related to the minimum radius of curvature caused by the self-weight of the pavement.

Criteria for assessing the impact of settlement on concrete roads are related to:

- Curvature (defined as the inverse of the radius), noting the higher the curvature, the more critical the bending stresses are in the concrete pavement.
- Horizontal movements in the upper subgrade either in the longitudinal direction and/or transverse direction. These horizontal movements can be highly significant for underground mining which occurs under or near a carriageway.
- A combination of curvature and horizontal movements in the upper subgrade where both are in the longitudinal direction in crest areas of settlement bowls. This combined effect is only significant for CRCP base in a CRCP and the special composite pavement Type 2.

In Figure 5(c), the horizontal movement of upper subgrade in the longitudinal direction is relative to the middle of the settlement bowl, that is the movement is positive if it is moving towards the middle of the trough.

Maximum horizontal movement of the upper subgrade (ie the peak value in the figure for each side of the settlement bowl) is at the junctions of the tension and compression zone on each side of the settlement bowl, this is typically near the points of contraflexure on either side of the settlement bowl.

Note that the values and shape of the curves are only to give a general overview and so no specific values can be derived from them.
The following criteria define the conformance requirements for concrete pavements in areas of settlement:

I. Criteria Related to Curvature:
   a. A minimum radius of curvature in the troughs and crests of a settlement bowl is required to ensure:
      • there is adequate rideability (longitudinal direction only),
      • there is adequate contact of the pavement with the subgrade (in all directions), and
• the slabs in the base concrete can be considered flat (in all directions).

b. A minimum thickness of base concrete, $B_{fs}$, to allow for the changed stresses caused by settlement in all directions (ie longitudinal, transverse and skew) to ensure adequate fatigue life taking into consideration the additional bending stresses from settlement related to self-weight of the concrete (all directions), and a minimum thickness of base concrete, $B_{st}$, to ensure the base after experiencing bending stress from settlement related to self-weight of the concrete, maintains the same capacity for stresses from heavy axle groups in conjunction with positive temperature differentials, that it had prior to settlement.

PCP and PCP-R are not suitable in areas of convex settlement shape due to corner slab breaking and diagonal cracking, unless settlement is very small (refer to Table 7 and Table 9:).

II. Criteria Related to Horizontal Movements

a. A maximum length of the compression zone (ie trough zone) is required to prevent:

• Compressive failure and/or buckling of the concrete base (longitudinal direction) in the middle region of a trough, where buckling refers to the base concrete lifting at one or more transverse joints in PCP, PCP-R, PCP-D, JRCP or transverse cracks in CRCP.

• Compressive failure and/or buckling of concrete subbase layer (longitudinal direction) in the middle region of a trough. Figure 6 shows a stepping failure for a bound layer caused by friction related to horizontal movements. Such stepping failures can occur in a concrete subbase and in a bound subgrade layer.

In both cases, the compressive stress/force is from friction (created by horizontal movement of the upper subgrade in the longitudinal direction) in combination with the compressive stress/force in the concrete base and subbase caused by high temperature (and high moisture).

b. A maximum limit for horizontal movement of the upper subgrade, in the longitudinal direction, to ensure adequate support of pavement.

c. A maximum limit for relative horizontal movement in the longitudinal direction, between the base concrete and subbase concrete, to ensure adequate support of the concrete base by the subbase. This is not relevant for Type 1 and Type 2 pavements.

d. A maximum limit for differential horizontal movement of the upper subgrade in the transverse direction (perpendicular to the direction of traffic), $D_{hu}$, to prevent excessive shear stress and/or resultant high axial stress in the longitudinal direction and/or high bending stress in the horizontal plane. Also in the case of PCP and PCP-R it is needed to prevent loss of aggregate interlock on outside horizontal curve edges created by the transverse horizontal movement of the upper subgrade.

e. Figure 7 shows the terms used to analyse differential horizontal movement in the transverse direction.

f. For PCP and PCP-R (in the longitudinal direction, in the middle region of the settlement crest area), a maximum horizontal tensile strain in the upper subgrade is allowed to ensure the maximum transverse joint opening in the concrete base is not excessive so as to maintain adequate aggregate interlock at the joints.
g. For PCP-D and JRCP (in the longitudinal direction, in the middle region of the settlement crest area), a maximum horizontal tensile strain in the upper subgrade is allowed to ensure the transverse joint opening is not excessive for the dowels. This in general is not critical as the tolerable joint opening for these pavements is high. Opening of transverse joints for PCP-D and JRCP is generally only a possible concern where there is reversal of movements, for example where there is an opening followed by closing.

h. For CRCP in the longitudinal direction in the crest area (ie in the tension zone):
   - A maximum transverse crack opening to prevent corrosion of the longitudinal steel and significant loss of shear transfer across transverse cracks, in the settlement crest area(s).
   - Sufficient longitudinal steel in the concrete base to prevent yielding of the steel across transverse cracks in settlement crest area(s).

III. Criteria related to a combination of curvature and horizontal movements of the upper subgrade where both are in the longitudinal direction

   This combined effect is only significant in crest areas of settlement bowls for CRCP layers and so only applies to CRCP base in CRCP and CRCP subbase (in the case of Type 2 pavement) in crest areas of settlement bowls.

a. A maximum length of tension zone to prevent excessive cracking and premature fatigue cracking of concrete base due to extra tensile stresses from friction (created by the horizontal movement of the upper subgrade in the longitudinal direction) in conjunction with bending stresses from settlement (due to self-weight of the concrete) and stresses caused by offset traffic loads.
Stage 1 – Development of Failure Plane

Stage 2 – Uplift at one Side of Bound Layer and Development of Vertical Break

Stage 3 – Final Step Height

Figure 6: The development of stepping failure in a bound layer.
7.2 Typical location of critical design criteria

Figure 88 shows the typical locations of some of the design criteria for PCP, PCP-R, PCP-D, JRCP and CRCP. This figure is only a guide, as in practice settlement bowls are not smooth. The actual $R_{\text{min(local)}}$ is smaller and thus more critical than the derived $R_{\text{min(overall)}}$ from a fitted cosine curve, where the fitted curve is based on the bowl length and the maximum differential settlement.

While different types of concrete pavement may be subjected to a similar type of impact, the significance of such impacts can vary substantially between the types of concrete pavements.
The numbers in the figure are purely descriptive and do not indicate ranking in severity, as the severity can vary substantially between different types of concrete pavement, and also depends on many factors as discussed in this Guide.

The numbers simply refer to the possibility of failure. Failure requires the tolerable limit of the appropriate criteria to be exceeded.

### Table 4: Typical locations of critical stresses.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>For all concrete bases, bending stresses from convex settlement due to self-weight of the concrete base and also bending from an offset wheel load(s) will cause an increase in tensile stress at top of the base, and can cause fatigue cracking of the base. This may be more critical for CRCP where tensile stresses from friction can be high due to the influence of the longitudinal steel. However, if CRCP forms small slabs and provided there is no risk of punch-out failures of the CRCP base then fatigue cracking of CRCP is not expected.</td>
</tr>
<tr>
<td>2</td>
<td>Increased tensile bending stress from settlement (due to self-weight of the concrete base) and corner traffic loading may cause corner breaking and diagonal cracking in PCP and PCP-R.</td>
</tr>
<tr>
<td>3</td>
<td>Where friction from settlement is high there may be fatigue cracking in CRCP because of higher tension (T) from friction due to the influence of longitudinal steel together with bending stresses from traffic load(s). However bending stresses from settlement (due to self-weight of the concrete) are compressive on the bottom of the slab and so reduce fatigue cracking.</td>
</tr>
<tr>
<td>4</td>
<td>Maximum horizontal movement of upper subgrade at each boundary of tension and compression zones on each side of the trough. These are generally in the vicinity of each point of contra flexure of the upper subgrade and result in reduced support of all concrete pavements, and possible rocking of “slabs” of all concrete pavements, ie PCP, PCP-R, PCP-D, JRCP and CRCP. Maximum relative movement between the concrete base and concrete subbase may be excessive resulting in loss of support.</td>
</tr>
<tr>
<td>5</td>
<td>Increased tensile bending stress at the bottom of the base concrete (from settlement and traffic load(s)) causing reduction in fatigue life of all concrete pavements, ie PCP, PCP-R, PCP-E, JRCP and CRCP. Compression of slabs in the trough due to friction related to settlement is not allowed for in the Guide. This is conservative, assuming an appropriate level of risk. However, it only requires removal of a base slab or a transverse slice of a slab to break this compression and therefore the benefit from it.</td>
</tr>
<tr>
<td>6</td>
<td>Compression due to friction may cause compressive failure/buckling of base concrete and/or compressive failure of subbase concrete of all concrete pavement types (ie PCP, PCP-R, PCP-D, JRCP and CRCP).</td>
</tr>
<tr>
<td>7</td>
<td>Extra opening of transverse joints/cracks which may be excessive for PCP, PCP-R and CRCP (whereas for PCP-D and JRCP, the dowels enable the pavement to tolerate large openings) Also with CRCP, the tension from friction will cause tensile stress in longitudinal steel in CRCP at the transverse cracks, which may be enough to cause yielding or rupture of this steel at the transverse cracks.</td>
</tr>
</tbody>
</table>
8. Soft soils

8.1 General

In soft soils differential settlement can be minimised by delaying the paving of concrete base and concrete subbase. Figure 9 shows that the rate of settlement with soft soils up until the point when primary settlement is completed is relatively fast, and can be accelerated where necessary by suitable ground treatment methods.

![Diagram](https://example.com/diagram.png)

Figure 9: Identifying when primary settlement is reached and secondary creep settlement commences.

The major component of primary settlement is caused by the expulsion of water. After primary consolidation has been completed the excess pore pressure is minimal and only secondary creep settlement occurs. The rate of settlement during secondary creep consolidation is significantly slower than during primary consolidation, as can be seen by the noticeable flattening of the slope of the curve. During the secondary creep consolidation phase a reorientation of the soil grain occurs.

Delaying the placement of base until after primary consolidation has finished (ie once secondary creep consolidation has started) may result in:

- a concrete pavement being specified, when otherwise it would be unsuitable, or
- if paving is further delayed during the secondary creep settlement phase, substantial reductions in base concrete thickness in comparison to what otherwise would be required.

Figure 10 shows the relationship between the base concrete thickness and the delay in paving following the start of secondary creep consolidation for a hypothetical pavement type and settlement scenario.
The variation in $\Phi_{cc} = -15\%$

$MR_b = 4.5$ MPa and is constant over the design life

$R_{40} = R_{\text{min(local)}}$ at 40 years since start of paving

The $R_{\text{min(local)}}$ following 10 years from the start of secondary creep settlement was calculated and found to be 1053 m for this hypothetical scenario. The design life varies according to the thickness of the base ($B_c$) and the delay in paving. At all times during the life of the pavement, there also needs to be a certain $R_{\text{min}}$ to ensure there is adequate rideability (in the longitudinal direction), adequate contact of the pavement with the subgrade (in all directions) and a certain degree of toughness in all directions (refer to Appendix A).

To have an appreciation of the effect of delaying paving operations on base thickness ($B_c$), three CRCPs are analysed based on a hypothetical settlement scenario using Figure 10.

The first example is a CRCP with base thickness ($B_c$) of 220 mm with a delay in paving of only 2 months since the start of secondary creep consolidation. Figure 10 shows this pavement has a 9 year design life, noting the corresponding $R_{40} (= R_{\text{min(local)}}$ at 40 years since paving) = 1575 m which in this situation is not reached as the pavement fails at 9 years

The second example is a CRCP base thickness ($B_c$) of 260 mm with a delay in paving of only 2 months since the start of secondary creep settlement. Figure 10 shows this pavement has a 32 year design life, noting the corresponding $R_{40} (= R_{\text{min(local)}}$ at 40 years since paving) = 1575 m which in this situation is not reached as pavement fails at 32 years.

The third example is a CRCP base thickness ($B_c$) of 240 mm with a delay in paving of 6 months since start of secondary creep settlement. Figure 10 shows this pavement has a 40 year design life, with $R_{40} (= R_{\text{min(local)}}$ at 40 years since paving) = 1965 m.
In the absence of other information it is considered a variation in the creep factor $\Phi_{cc}$ of –15% should be used, where $\Phi_{cc}$ is determined (see Appendix A). In brief $\Phi_{cc} = k_2k_3\Phi_{cc.b}$ where $\Phi_{cc.b}$ = the basic concrete creep factor is the ratio of ultimate creep strain to elastic strain for a specimen loaded at 28 days under a constant stress of $0.4 \times f'_c$ (AS5100.5).

For example, a 220 mm base concrete will have a 40 year design life if paving is delayed by 16 months from the start of secondary creep consolidation. However, if the delay was reduced to 2 months it would reduce the design life to 9 years.

There may be substantial reductions in base concrete thickness if the delay in paving since start of secondary creep consolidation is increased by several months. For example, for a 30 year design life the base concrete needs to be approximately 260 mm for a delay of 3 months in paving relative to the start of secondary creep settlement but if the delay in paving is 8 months the base concrete reduces to 220 mm). The required minimum base thickness is very sensitive to the design life of the pavement and the time of paving relative to the start of secondary creep consolidation.

While a preliminary analysis may indicate concrete pavement may be able to withstand a particular settlement rate; it is also necessary to ensure $R_{\text{min}}$ at the end of the design period is not less than the minimum tolerable value to ensure adequate rideability (in the longitudinal direction), adequate contact of the pavement with the subgrade (in all directions), and adequate toughness (in all directions), refer to Appendix A.

The delay in paving the base is to ensure that the subbase gains sufficient strength before the addition of the base. This is such that the subbase is able to withstand the increase in compressive stress, from friction due to the horizontal movements of the upper subgrade as a result of settlement, caused by the extra weight of the base concrete. Note that the subbase can only partially 'shed' a significant axial compressive force from friction up into the base, where the coefficient of friction between the base and subbase, ie $\mu_{b-sb}$ is significant relative to that between the subbase and the select subgrade, ie $\mu_{sb-sssl}$.

8.2 **Life of concrete pavements built over soft soils**

The extra bending stresses from settlement of soft soils due to self-weight of the concrete are found in general to keep increasing over the life of the pavement. This is the case even after taking into account the creep/stress relaxation properties of concrete. While the stress relaxation of concrete significantly reduces the bending stresses for a particular increment of bending strain resulting from settlement, the accumulated bending stress in the concrete will continue to increase over the life of a concrete pavement built over soft soil.

Over time not only do bending stresses from settlement increase from self-weight of concrete, so to do traffic volumes (where there may also be an increase in load per axle group). This means that where the performance of a pavement is considered to be good after 15 to 20 years, this may give little indication of the performance of the same pavement over the next period of say 10 to 20 years.

Using concrete that continues to gain strength over time is helpful in dealing with the increases in bending stress from settlement due to self-weight of concrete in conjunction with
increasing traffic volumes (and any increase in axle loads) over time. In other words, the strength that the concrete reaches in a pavement at an age of say 20 years can have a very significant effect on the performance of concrete undergoing settlement over the remaining 10 to 20 years (making a total life of 30 to 40 years).

8.3 Initial appraisal

With soft soils it is possible to determine if settlement is:
1. Of a minor nature with no need for a special analysis or
2. Significant or possibly significant, such that an analysis in accordance with this Guide is necessary, or
3. So severe that a concrete pavement is clearly not suitable.

Underground mining requires a separate analysis and this is discussed in Section 10.

The initial appraisal for concrete pavements over soft soils requires estimates of:
- Settlement shape and direction relative to the road alignment
- Length of each settlement bowl
- Rate of settlement (whether fast or slow, see Figure 14)
- Settlement at the end of the design life since placing of the concrete pavement.

The local variation in the radius of curvature is also taken into account. Figure 11 illustrates the variation in minimum radius of curvature of an actual settlement profile with a theoretical fitted cosine curve based on the bowl length and maximum differential settlement. Figure 11 shows $R_{\text{min(local)}}$ of the actual profile is lower and therefore, more severe than $R_{\text{min(overall)}}$, which is the theoretical value based on a fitted cosine curve.

![Figure 11: Settlement bowl showing the difference between $R_{\text{min(local)}}$ and $R_{\text{min(overall)}}$.](image-url)
9. Simplified assessment for settlement over soft soils

9.1 Overview

Typically where there is differential settlement in the longitudinal direction, the overall shape resembles a cosine curve, while in the transverse direction, the overall shape resembles an arc of a circle. In the skew direction, each situation needs to be assessed to determine whether a cosine or an arc is appropriate.

Figure 12 shows the length of the settlement bowl and the differential settlement for the basic cosine curve types for longitudinal settlement and the arc of a circle for transverse settlement.

An analysis is required to determine whether the settlement is one general bowl with localised effects to be considered as more than one bowl with each having localised effects.

For curvature it is critical to have an estimate of $R_{\text{min}}$, that is the lowest $R_{\text{min(local)}}$ and so it is important not to overlook smaller bowls (see Figure 12).

For horizontal movements, a small section of convex settlement does not necessarily cause a compression length to be discontinued.

![Figure 12: Individual settlement bowls within a general bowl.](image)

In Figure 13 the sketches show relative change from original profile to profile after settlement, where the original profile refers to profile just after paving of the concrete base. Also, pavement crossfalls are not shown in Figure 13, as what is relevant is the change in shape caused by settlement.
Length of Settlement Bowl

Half wavelength

Max depth of differential settlement

a) Longitudinal direction (cosine curve)

b) Two examples of concave transverse settlement (where curves in both situations can be either catenary or an arc of a circle)

c) Two examples of convex transverse settlement (catenary/arc of circle)

Figure 13: Relationship between T and D for longitudinal and transverse settlement.

A fast rate of settlement, such as occurs with underground mining, is where the majority of differential settlement, occurs within any two year period after paving. A slow rate of settlement, in general, is where the maximum depth of differential settlement over all 3 year periods since paving is no more than half the settlement over 40 years since start of settlement. Figure 14 shows examples of fast and slow rates of settlement, where the maximum differential settlement at 40 years is the same.

The impact of differential settlement depends on whether the rate of settlement is fast or slow. For criteria based on curvature (ie 1/R), where the rate of settlement is slow, then a greater differential settlement can be tolerated because of benefits due to the stress
relaxation of bending stresses within the concrete, so that for the same bending strain, the associated bending stress is reduced.

![Diagram of settlement over time](image)

**Figure 14:** Examples of fast and slow rates of settlement.

The ‘Thickness Design for Settlement Spreadsheet’ can be used to analyse different rates of settlement to determine the effect of stress relaxation of bending stresses on the pavement design life.

Table 6 lists the values for various parameters that need to be satisfied for a simplified assessment procedure for concrete pavements over soft soils. This covers a range of scenarios.

Appendix A lists the requirements for the control of the effect of horizontal movements only. The criteria related to radius of curvature also need to be checked.

In some situations increasing base thickness may be required. The ‘Thickness Design for Settlement Spreadsheet’ can be used to determine if an increase in base thickness is required. Tables 7 to 21 outline the criteria for assessing concrete pavements over soft soils.

In general, PCP, PCP-R, PCP-D, JRCP and CRCP are suitable pavement types over soft soil subgrades if the requirements detailed in Tables 7 to 21 are satisfied. This assumes differential horizontal movements in the transverse direction will be minor and can be ignored.

The flow chart in Figure 15 shows the assessment procedure to assess if a concrete pavement can be used over soft soils. This flow chart assumes that the differential horizontal movements in the transverse direction are minor, and that the concrete pavement satisfies conventional design practice (see Appendix A for limits).
Figure 15: Process for the assessment of PCP and PCP-R, PCP-D, JRCP and CRCP over soft soils. Refer to Table 5 for Actions A to E.
Table 5: Actions to the assessment process from Figure 15.

<table>
<thead>
<tr>
<th>Actions</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Analyse in accordance with this Guide to determine whether or not criteria related to horizontal movements are satisfied. In some situations increasing pavement thickness may be required. However, it may not be possible or feasible to meet these criteria even with an increase in pavement thickness.</td>
</tr>
<tr>
<td>B</td>
<td>Analyse in accordance with this Guide to determine whether or not criteria related to horizontal movements and curvature are satisfied. In some situations increasing pavement thickness may be required. The ‘Thickness Design for Settlement Spreadsheet’ shows whether an increase in B&lt;sub&gt;bc&lt;/sub&gt; and/or B&lt;sub&gt;ct&lt;/sub&gt; is needed to ensure adequate life under traffic and curvature. However, it may not be possible or feasible to meet these criteria even with an increase in pavement thickness.</td>
</tr>
<tr>
<td>C</td>
<td>Concrete pavement is not suitable for site.</td>
</tr>
<tr>
<td>D</td>
<td>Concrete pavement is suitable for site.</td>
</tr>
<tr>
<td>E</td>
<td>Analyse in accordance with this Guide to determine whether or not criteria related to curvature are satisfied. The ‘Thickness Design for Settlement Spreadsheet’ shows whether an increase in B&lt;sub&gt;bc&lt;/sub&gt; and/or B&lt;sub&gt;ct&lt;/sub&gt; is needed to ensure adequate life under traffic and curvature. In some situations increasing base thickness may be required. However, it may not be possible or feasible to meet curvature criteria even with an increase in base thickness. For PCP &amp; PCP-R for curvature only, there is only a need to assess thickness requirements for curvature for concave shape in transverse direction where traffic is medium or heavy (see Appendix D).</td>
</tr>
</tbody>
</table>
Table 6: Pavement requirements to be satisfied for initial screening process for concrete pavements over soft soil subgrades for PCP, PCP-R, PCP-D, JRCP and CRCP (all with concrete subbases).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value/Property</th>
</tr>
</thead>
</table>
| Length of settlement bowl (ie 2T) | CRCP: Max. 150 m<sup>a,b</sup>  
JRCP: Max. 110 m<sup>a</sup>  
PCP-D: Max. 55 m<sup>a</sup>  
PCP and PCP-R: Max. 40 m<sup>a</sup> |
| Minimum base thickness (to ensure axial stresses from horizontal movements due to settlement are not excessive) Base thickness must also satisfy conventional design practice. | PCP and PCP-R: 225 mm<sup>c</sup>  
PCP-D, JRCP and CRCP: 200 mm<sup>c</sup> |
| Modulus of Rupture (\(M_R\)) of base concrete (to satisfy axial stresses from horizontal movements from settlement) \(M_R\) must also satisfy conventional design practice. | Min. 4.5 MPa |
| Thickness of subbase concrete (to ensure axial stresses from horizontal movements due to settlement can be withstood) Subbase thickness must also satisfy conventional design practice. | Min. 150 mm<sup>d</sup> |
| Compressive strength (\(f'_c\)) of subbase Concrete at the first summer after start of settlement of concrete base (to satisfy stresses from settlement) \(f'_c\) the subbase concrete must also satisfy conventional design practice. | Min. 20 MPa<sup>e</sup> |
| Upper subgrade (unless compressive failure and associated stepping of upper subgrade is considered sufficiently low risk) Upper subgrade must be granular where 2T greater than 30 m<sup>f</sup> (The corresponding limitation on usage of bound upper subgrade where 2T less than 30 m may be able to be relaxed for CRCP, provided maximum horizontal movement in the upper subgrade is less than 20 mm) | |
Table 6: Continued

Notes:

a) For settlement bowls which are longer, a number of criteria can be critical, which means the Guide has to be consulted to determine whether a concrete pavement can be used and if so what pavement design is necessary.

b) For CRCP for settlement bowls greater than about 75 m, where the bending stress due to settlement in crest regions is significant, there may be excessive cracking in the crest regions unless both $MR_n$ and $f_c'$ for the base are high (see Appendix C3).

c) For medium and heavy traffic (provided $R_{mn}$ is not too low (refer to Appendix C2) and the rate of settlement is not too fast) the base may need to be thicker than 250 mm. However bases greater than about 250 mm can develop excessive stress from bending for low $R_{mn}$ and fast rates of settlement. Therefore for low $R_{mn}$ and/or fast rate of settlement a concrete base may not be suitable (whether or not this is the case can be determined using the ‘Thickness Design for Settlement Spreadsheet’).

d) Bases thicker than 250 mm may require concrete subbases to be thicker than 150 mm (and/or require high strength concrete, ie high $f_c'$ for subbase, so that it is greater than 20 MPa at the first summer after the start of settlement of the base concrete). This is due to the generation of higher axial compressive stresses in the subbase concrete from a thicker base from horizontal movement of the upper subgrade, due to generation of greater frictional force in the subbase concrete from the increased mass of the base. Delaying the paving of the base concrete may be necessary to ensure the subbase concrete has gained sufficient strength prior to the paving of base so that the subbase is able to withstand the increase in axial compressive stress from friction caused by settlement due to extra mass of the base concrete. There is an upper limit of subbase thickness, say 250 mm, for low $R_{mn}$ and/or fast rates of settlement, to ensure against excessive stress in the subbase concrete from bending from self-weight due to settlement.

e) Where the ratio of base to subbase thickness is greater than about 1.8, noting 270 mm base over 150 mm subbase has a ratio of $270/150 = 1.8$, the minimum compressive strength of the subbase concrete, (ie minimum $f_c'$ of the subbase), at the first summer after start of settlement of the base concrete may need to be increased (and/or the subbase thickness needs to be greater).

f) Where only a small length of pavement will be subjected to settlement, the axial compressive stress in a bound upper subgrade layer from friction due to settlement will only be small and so there is little risk of a stepping failure in a bound layer under the concrete pavement. In general, for bowls of significant length, the upper subgrade (including any select subgrade and any working platform) must be granular, ie not bound or stabilised, so as to avoid this layer undergoing compressive failure in the compression zone, from friction caused by settlement and compressive stress from high temperature (and high moisture), causing a sudden step resulting in uneven support of the pavement, and possibly a step of the overlying pavement layers. However where horizontal movements are so low that there can only be a small contraction of the bound upper bound layer prior to failure which is available for release at a failure slope, then longer lengths of bound upper subgrade may be acceptable. Where special analysis of long settlement bowls shows that longer lengths of bound upper subgrade will not have any compressive failure and/or if it fails it will only create a small step and so cause only a minor disturbance in the overlying concrete pavement with no risk to traffic safety then the upper subgrade can be bound. CRCP is more tolerant of a bound upper subgrade layer, so that the limit of 30 m may be able to be relaxed.

g) The limits of the Table are to ensure limits related to horizontal movements in the longitudinal direction of the upper subgrade are met.
9.2 Basis for pavement requirements

9.2.1 Upper bound value for relative movement between concrete base and subbase

The upper bound value for relative movement between concrete base and concrete subbase is assumed to be:

\[
SQWER = \frac{2.94 \times \mu_{sb-ssl} \times T^2 \times [t_{mb} + t_{msb}]}{E_{msb} / CR_{sb} \times t_{msb}}
\]

so

\[
T \leq \left( \frac{SQWER \times E_{msb} \times t_{msb}}{(2.94 \times CR_{sb} \times \mu_{sb-ssl} \times [t_{mb} + t_{msb}])^0.5} \right)^{0.5}
\]

Where \( T \) is in m, \( t_{mb} \) is in mm, \( t_{msb} \) is in mm, \( E_{msb} \) is in MPa and \( SQWER \) is in mm.

This assumes there is no shedding of any axial force from the subbase to the base and hence there is also no horizontal movement of the base, this is a conservative assumption for the value of \( T \).

It is also considered conservative at high pavement temperatures (and moisture), as it is expected that there may be more closure of transverse joints/cracks in the base than in the transverse cracks in the subbase, provided transverse joints/cracks in the base are free to contract, which reduces the relative movement between the base and subbase caused by horizontal movements from settlement.

Consider the following pavement example:

- Base thickness = 250 mm (having a thicker base is more critical for upper bound value for relative movements between base and subbase, than a thinner base)
- Subbase thickness = 150 mm
- \( f_c \) of subbase at time of settlement of base concrete = 20 MPa
- \( CR_{sb} \) = 3.0 (which in general is conservative)
- coefficient of friction (subbase-subgrade) = 2.3 (that for friction between a concrete layer over a sprayed seal with 5 mm aggregate over granular material), see Table 3
- \( f_{cm} = 1.2 \times 20 = 24 \) MPa, for \( CoV = 10\% \)
- \( E_{msb} = 2400^{1/2} \times 0.043 \times 24^{0.5} = 24,800 \) MPa

This means for CRCP, where maximum upper bound value for relative movement between base and subbase is considered to be 20 mm, this corresponds to:

\[
T = \left[ \frac{20 \times 24800 \times 150}{2.94 \times 3 \times 2.3 \times (150 + 250)} \right]^{0.5} = 90 \text{ m},
\]

The above value makes no allowance for the effect of longitudinal steel reducing compressive zone of CRCP base, and therefore \( 2T = 192 \) m. However, CRCP also has the possibility in crests of settlement bowls, that is in tensile zones, of having:

- excessive crack opening of transverse cracks,
- yielding of longitudinal steel, and
- excessive cracking and premature fatigue cracking of concrete base,
so it is considered that $2T$ needs to be kept within 150 m unless a full finite element analysis of the pavement is carried out.

For JRCP, where the maximum upper bound value for relative movement between base and subbase is considered to be 7.5 mm, this corresponds to:

$$T = \left[ \frac{7.5 \times 24800 \times 150}{2.94 \times 3 \times 2.3 \times (150 + 250)} \right]^{0.5} = 55 \text{ m, hence } 2T = 110 \text{ m}$$

For PCP-D, where maximum upper bound value for relative movement between base and subbase is considered to be 2 mm, this corresponds to:

$$T = \left[ \frac{2 \times 24800 \times 150}{2.94 \times 3 \times 2.3 \times (150 + 250)} \right]^{0.5} = 28.5 \text{ m, hence } 2T = 57 \pm 55 \text{ m}$$

PCP-R is less tolerant of horizontal strains due to possibility that a loss of aggregate interlock occurs in tensile zones, and so PCP-R has the same limit given below for PCP for $2T$.

For PCP, where maximum upper bound value for relative movement between base and subbase is considered to be 1 mm, this corresponds to:

$$T = \left[ \frac{1 \times 24800 \times 150}{2.94 \times 3 \times 2.3 \times (150 + 250)} \right]^{0.5} = 20.2 \text{ m, hence } 2T = 40 \text{ m}$$

The relative movement of the base with the subbase cannot exceed the relative movement of the subbase with the upper subgrade. Therefore, if such movements are low then the upper limit for $2T$ for relative movement between the base and subbase can be relaxed accordingly.

On the basis of a particular limit on the relative movement between base and subbase, thinner bases and/or thicker subbases can tolerate larger settlement bowls. However, any reduction in relative movement between base and subbase by using a thinner base thickness, is expected to reduce the capacity of the base to handle extra stresses created by the relative movement. Therefore, using a thinner base with a correspondingly allowable longer settlement bowl for a specified tolerable relative movement between base and subbase would have to be offset against the possibility of significantly reduced fatigue life of the base concrete. Therefore, where the actual base is less than 250 mm, it is appropriate that calculations to determine the maximum $2T$ are based on a base thickness of 250 mm. This keeps the relative movement between base and subbase within reasonable limits.

**9.2.2 Calculation of minimum compressive strength for concrete subbase**

The minimum $f'_{ck}$ of subbase concrete depends on the compressive stress in the subbase caused by friction due to settlement plus temperature and moisture.

The maximum compressive stress in concrete subbase from friction (assuming no shedding of axial force from subbase to base), and assuming that at the critical cross section the thicknesses of the base and subbase are the mean base and subbase thickness respectively, is:

$$f'_{ck} = \frac{p \times g \times u_s \times T \times (t_b + t_s)}{2 \times 10^6 \times t_s}$$

For example, for $2T = 150 \text{ m}$, and hence $T = 75 \text{ m}$, and $\mu_{sb-sg} = 2.3$, $t_{sub} = 230 \text{ mm}$,
The maximum compressive stress in the subbase concrete is
\[ t_{\text{sub}} = 150 \text{ mm}, \]  
\[ = 2400 \times 9.81 \times 2.3 \times 75 \times (230 + 150)/(2 \times 10^6 \times 150) = 5.1 \text{ MPa}. \]

This force is unlikely to contribute to buckling of the subbase and is within the tolerable stress for typical subbase provided curvatures from settlement do not cause much extra stress. The shedding of force, and hence stress, from the subbase to the base is ignored.

The formula for compressive stress from friction is independent of modulus as it assumes full mobilisation of friction which is conservative.

The stress generated from the effect of temperature is calculated as follows:
\[ C = k \times \Delta T \times E_{sb} \]

Where:
- \( k \): Coefficient of thermal expansion (approximately \( 10 \times 10^{-6} \) per °C)
- \( \Delta T \): Temperature differential (°C)
- \( E_{sb} \): Modulus of Elasticity of subbase (MPa)

Assuming a density of concrete of 2,400 kg/m³ and in the first summer after start of settlement for base concrete where \( f_{c}^{'} \) of subbase concrete = 20 MPa,
\[ E_{sb} = 2400^{1.5} \times 0.043 \times 20^{0.5} = 22,609 \text{ MPa}, \text{ say 22,600 MPa} \]

A temperature rise of 15°C generates a compressive stress of \( 15 \times 10^6 \times 22,600 \text{ MPa} = 3.4 \text{ MPa} \) assuming all transverse cracks are closed by horizontal movements from settlement before being subjected to the higher temperature.

Thus, for a settlement bowl of \( 2T = 150 \text{ m} \), the total axial compressive stress in the subbase is \( 3.4 + 5.1 = 8.5 \text{ MPa} \). This stress is less than the maximum compressive stress of the subbase (\( f_{c}^{'} = 20 \text{ MPa} \)).

Whereas for \( 2T = 25 \text{ m} \), and if \( f_{c}^{'} \) of subbase concrete is 10 MPa at the first summer after start of settlement for base concrete \( E_{sb} = 16,000 \text{ MPa} \), \( C = 150 \times 10 \times 10^6 \times 16,000 \text{ MPa} = 2.4 \text{ MPa} \), assuming all transverse cracks are closed by horizontal movements from settlement before being subjected to the higher temperature (and moisture).

This makes axial compressive stress in the subbase concrete from friction
\[ = 2400 \times 9.81 \times 2.3 \times (25/2) \times (230+150)/2 \times 10^6 \times 150 = 0.9 \text{ MPa} \]  
which makes axial compressive stress from temperature and friction = 2.4 + 0.9 MPa = 3.3 MPa which is less than \( f_{c}^{'} = 10 \text{ MPa} \).

Further work is needed to ensure that there is no unacceptable risk of buckling in the concrete subbase.

The maximum axial compressive stress from friction due to settlement in a CRCP base for \( 2T = 150 \text{ m} \), and \( T = 75 \text{ m} \) (making no allowance for effect of longitudinal steel reducing compressive zone of CRCP base), and if \( \mu_{b-sb} = 1.7 \):  
\[ = 2400 \times 9.81 \times 1.7 \times 75/(2 \times 10^5) = 1.5 \text{ MPa} \]  
(assuming uniform thickness of base)

This is considered to be sufficiently low so that there is no risk of buckling of the CRCP base for \( 2T = 150 \text{ m} \), and so the limit on relative movement between base and subbase concrete
governs. This stress from friction due to settlement is additional to axial compressive stress from temperature (and moisture). These latter stresses from temperature (and moisture) do not necessarily apply fully when there is no settlement as they firstly have to cause take-up of any transverse crack openings. However with settlement, these stresses may be more significant as horizontal movement from early stages of settlement may be sufficient to cause closure of shrinkage cracks so that basically all the high temperature causes stress rather than some of it being taken up in closing of shrinkage cracks.

The above calculations shows that for long settlement bowls there may be precompression from friction due to settlement at least while settlement is ongoing, after which there may be significant reduction due to creep. Therefore, during settlement and for sometime after settlement, in troughs there can be better fatigue life from traffic than indicated by the extra tensile stresses from bending due to settlement which reduces fatigue life. However relying on the pre-compression from friction due to settlement related to horizontal movement is not reliable as removal of just one “slab” for rehabilitation or other reason will ‘break’ the level of any pre-compression. In crests, fatigue life from traffic can be reduced by the axial tensile force from friction from settlement.

9.2.3 Compressive failure/stepping in upper subgrade layer which is bound

Settlement bowls of significant length may require bound subgrade layers, particularly for PCP, PCP-R and PCP-D, to avoid stepping in the pavement surface due to compressive failure in the upper subgrade. Where the upper subgrade is granular, horizontal movements from settlement simply creates slight increases in thickness of the upper subgrade, as the subgrade material is compressed over the length of the compression zone which is not disruptive to the pavement. Whereas, when the upper subgrade layer is bound, there is a build up in axial compressive stress that can cause compression failure and therefore, a stepping failure in the upper subgrade, typically in the middle region of the settlement trough. Its exact location will depend on the variability in strength and thickness of the bound upper subgrade layer.

The maximum compressive stress in the bound selected subgrade layer from horizontal movements of settlement

\[ \sigma_{\text{sl-sg}} = \mu_{\text{sl-sg}} \times (t_{\text{mb}} + t_{\text{msb}} + t_{\text{msl}}) \times \rho \times g \times T / (2 \times t_{\text{msl}} \times 1000) \]

This assumes the density of all materials is 2400 kg/m³, and \( t_{\text{msl}} \) is the thickness of the selected subgrade layer at the critical cross section.

So for \( T = 75 \) m, \( t_{\text{mb}} = 250 \) mm, \( t_{\text{msb}} = 150 \) mm, \( t_{\text{msl}} = 150 \) mm, and \( \mu_{\text{sl-sg}} = 1.0 \), then maximum compressive stress in the bound selected subgrade layer

\[ 1.0 \times (0.250 + 0.150 + 0.150) \times 2400 \times 9.81 \times 75 / (2 \times 150 \times 1000) \]

\[ = 3.2 \text{ MPa} \]

This approach is conservative as it ignores any shedding of axial force from the bound upper selected subgrade layer into the overlying layers due to friction at each layer interface, which reduces the axial compressive stress in the bound upper select subgrade layer. Given the relatively high moduli of concrete base and concrete subbase to the modulus of the bound upper subgrade, this shedding may be substantial. Also the above analysis assumes full mobilisation of friction (ie there is sufficient horizontal movement) to create significant stress in a bound select subgrade layer such that there is significant risk of stepping. Nevertheless it shows that bound upper subgrade material which is typically of compressive strength of the order of 1 to 2 MPa may be at risk of stepping failure, where horizontal movements are sufficiently large to fully mobilise friction.
In addition there is compressive stress from high temperature (and moisture).

Say the modulus of the bound selected subgrade layer is 3000 MPa, and temperature rise is 25°C (which includes an allowance for moisture) and Coefficient of Thermal Expansion = 12 x 10^{-6} per °C, then compressive stress from temperature (and moisture)

\[ \sigma = 25 \times 12 \times 10^{-6} \times 3000 = 0.9 \text{ MPa} \]

Therefore maximum compressive stress from friction from settlement and temperature = 3.2 MPa (from friction) + 0.9 MPa (from temperature) = 4.1 MPa which can cause compressive failure, stepping and therefore uplift at the surface. In general, the bound upper select layer will exhibit compressive strength less than 3.2 MPa in which case it will step at a lower stress (and therefore before full mobilisation of friction and/or a lower temperature).

This indicates that bound selected layers are unsuitable particularly for PCP, PCP-R and PCP-D for concrete pavements undergoing settlement unless settlement bowls are short and/or there is little horizontal movement of the upper select layer.

For JRCP and CRCP their reinforcement may reduce the impact of stepping on the safety of motorists, but even then it is considered not advisable to use bound selected subgrade layers where settlement is expected except over small lengths. Where horizontal movements are small, longer lengths can be used.

Limiting bound upper selected layers to only small lengths of settlement ensures that any step will be also small. In any case, JRCP and CRCP pavements are considered the most robust for any potential step. However in general bound select layers are not appropriate where there is a risk of significant stepping, for all concrete pavements.

**9.2.4 Differential settlement limits for fast and slow rates of settlements**

This section detailed the total settlement limits on soft soils for fast and slow rates for different lengths of the settlement bowls and for various concrete base types. When using the tables in this Section the last length of settlement bowl is set by the maximum values in Table 6. For each pavement type, a pair of tables are presented for settlement if the longitudinal and transverse directions.

**Table 7: Maximum allowable settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP and PCP-R).**

<table>
<thead>
<tr>
<th>Length of settlement bowl: 2T (m)</th>
<th>Total Settlement (= 1.5D) After 40 years since paving of base (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>3 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>6 mm</td>
</tr>
</tbody>
</table>
Table 8: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP and PCP-R)

<table>
<thead>
<tr>
<th>Half chord length (T m)</th>
<th>Differential settlement (= D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After 40 years since paving of base (for a catenary/circular arc)</td>
</tr>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>10 m</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>15 m</td>
<td>5.5 mm</td>
</tr>
</tbody>
</table>

When using the limits in Tables 6 and 7 the following applies: \( R_{\text{min(overall)}} = 2 \times R_{\text{min(local)}} \)

where tolerable \( R_{\text{min(local)}} \) = 10,000 m for fast rate of settlement, and 5,000 m for slow rate of settlement, making \( R_{\text{min(local)}} \) = 20,000 m for fast rate of settlement, and 10,000 m for slow rate of settlement.

In the case of expansive soils, Tables 6 and 7 could be used where the limits for settlement are used for heave with an appropriate rate of settlement (ie heave). Otherwise the designer should use of the ‘Thickness Design for Settlement Spreadsheet’.

Other notes applicable to Tables 6 and 7 are as follows:

- Derived assuming total settlement = 3/2 x differential settlement.
- If total settlement is greater than maximum differential settlement see Figure 1.
- Where the design life is 30 years or less, this becomes ‘After 30 years since paving of base’
- For cosine curve:
  \[
  D = 2 \times T^2 / \left( \pi^2 \times R_{\text{min(overall)}} \right) = T^2 / \left( \pi^2 \times R_{\text{min(local)}} \right)
  \]
  and therefore, total settlement is:
  \[
  = 1.5 \times 2T^2 / \left( \pi^2 \times R_{\text{min(overall)}} \right) = 1.5 \times 2T^2 / \left( \pi^2 \times 2R_{\text{min(local)}} \right) = 1.5 \times T^2 / \left( \pi^2 \times R_{\text{min(local)}} \right)
  \]
  where \( T, D \) and \( R_{\text{min}} \) are in metres.

For example, \( 2T = 40 \) m, ie \( T = 20 \) m and fast rate of settlement, \( R_{\text{min(local)}} = 10,000 \) m, and total settlement is:
\[
= 1.5D = 1.5 \times T^2 / \left( \pi^2 \times R_{\text{min(local)}} \right) = \left[ 1.5 \times 20^2 / \left( \pi^2 \times 10,000 \right) \right] \times 10^3 \text{ mm} = 6 \text{ mm}
\]
- For a catenary and a circle, where the ratio of \( D \) to \( T \) is small:
  \[
  D = T^2 / \left( 2 \times R_{\text{min(overall)}} \right) = T^2 / \left( 2 \times 2 \times R_{\text{min(local)}} \right) = T^2 / \left( 4 \times R_{\text{min(local)}} \right)
  \]
For example, if $T = 10$ m and there is a slow rate of settlement $R_{\text{min(local)}} = 5,000$ m, and differential settlement $(D) = T^2/(4 \times R_{\text{min(local)}}) = [10^2/(4 \times 5000)] \times 10^3$ mm = 5 mm

Table 9: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for PCP and PCP-R).

<table>
<thead>
<tr>
<th>Length of settlement bowl 2T (m)</th>
<th>Total Settlement (= 1.5D) After 40 years since paving of base (mm) (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement Slow rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>0.5 mm 1 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>2 mm 4 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>3 mm 6 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>6 mm 12 mm</td>
</tr>
</tbody>
</table>

It is noted that these limits are the same as for Table 7 and where the design traffic exceeds $10^6$ DESA and with concave settlement in the transverse direction is likely to occur and such that the limits in Table 7 and 10 are met, and limits in Table 8 are not met, then the allowable settlement will need to be lower than the values in Table 9 for concave settlement, to ensure the base thickness, which is the greater of $B_s$ and $B_t$, is reasonable. Also, these limits for concave settlement are higher for PCP and PCP-R than those for convex settlement in the transverse direction. Analysis in accordance with the ‘Thickness Design for Settlement Spreadsheet’ is needed for concave settlement to determine whether or not criteria related to curvature are satisfied. In some situations increasing pavement thickness may be required. However, it may not be possible or feasible to meet the curvature criteria even with an increase in base thickness.

When using the limits in Tables 8 and 9 the following applies: $R_{\text{min(overall)}} = 2 \times R_{\text{min(local)}}$

where for a concave shape (in transverse direction):

- tolerable $R_{\text{min(local)}} = 2500$ m for fast rate of settlement for both PCP and PCP-R
- $R_{\text{min(local)}} = 1700$ m for slow rate of settlement for PCP
- $R_{\text{min(local)}} = 850$ m for slow rate of settlement for PCP-R.

and for a convex shape (in transverse direction):

- tolerable $R_{\text{min(local)}} = 10,000$ m for fast rate of settlement (all directions) and 5000 m for slow rate of settlement (all directions). As noted in Table 9, the limits for convex settlement are the same as in Table 8.

In the case of expansive soils, Table 10 could be used where the limits for settlement are used for heave with an appropriate rate of settlement (ie heave). Otherwise it requires use of the ‘Thickness Design for Settlement Spreadsheet’.
Table 10: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for PCP and PCP-R).

<table>
<thead>
<tr>
<th>Half chord length T (m)</th>
<th>Differential Settlement (= D) After 40 years since paving of base (mm) (for a catenary/circular arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>Concave shape: 2 mm for PCP and PCP-R</td>
</tr>
<tr>
<td></td>
<td>Convex shape: as per Table 7</td>
</tr>
<tr>
<td>10 m</td>
<td>Concave shape: 10 mm for PCP and PCP-R</td>
</tr>
<tr>
<td></td>
<td>Convex shape: as per Table 7</td>
</tr>
<tr>
<td>15 m</td>
<td>Concave shape: 22 mm for PCP and PCP-R</td>
</tr>
<tr>
<td></td>
<td>Convex shape: as per Table 7</td>
</tr>
</tbody>
</table>

Table 11: Maximum allowance settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP-D).

<table>
<thead>
<tr>
<th>Length of settlement bowl 2T (m)</th>
<th>Total Settlement (= 1.5D) After 40 years since paving of base (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>3 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>6 mm</td>
</tr>
<tr>
<td>50 m</td>
<td>9 mm</td>
</tr>
<tr>
<td>55 m</td>
<td>11 mm</td>
</tr>
</tbody>
</table>
Table 12: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for PCP-D).

<table>
<thead>
<tr>
<th>Half chord length T (m)</th>
<th>Differential Settlement (= D) After 40 years since paving of base (for a catenary/circular arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>10 m</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>15 m</td>
<td>5.5 mm</td>
</tr>
</tbody>
</table>

In the case of expansive soil, Table 12 could be used where the limits for settlement are used for heave with an appropriate rate of settlement (i.e., heave). Otherwise, it requires use of the ‘Thickness Design for Settlement Spreadsheet’.

Table 13: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for PCP-D).

<table>
<thead>
<tr>
<th>Length of settlement bowl 2T (m)</th>
<th>Total Settlement (= 1.5D) After 40 years since paving of base (mm) (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>9 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>13 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>24 mm</td>
</tr>
<tr>
<td>50 m</td>
<td>37 mm</td>
</tr>
<tr>
<td>55 m</td>
<td>45 mm</td>
</tr>
</tbody>
</table>
Table 14: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for PCP-D).

<table>
<thead>
<tr>
<th>Half chord length T (m)</th>
<th>Differential Settlement (= D) After 40 years since paving of base (mm) (for a catenary/circular arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>10 m</td>
<td>10 mm</td>
</tr>
<tr>
<td>15 m</td>
<td>22 mm</td>
</tr>
</tbody>
</table>

When using Table 13 for traffic volumes exceeding 10^6 DESA the allowable settlement will need to be lower than the limits in both Tables 13 and 14, to ensure the base thickness, which is the greater of $B_{fr}$ and $B_{st}$, is reasonable. Analysis in accordance with the ‘Thickness Design for Settlement Spreadsheet’ is needed to determine whether or not criteria related to curvature are satisfied. In some situations increasing pavement thickness may be required. However, it may not be possible or feasible to meet the curvature criteria even with an increase in base thickness.

For slow rates of settlement for PCP-D, the values for total settlement are half of the values for JRCP and CRCP, so that the tolerable $R_{\text{min(local)}}$ is 1700 m for slow rate of settlement where there is no reinforcement, whereas for JRCP and CRCP for slow rate of settlement, tolerable $R_{\text{min(local)}}$ is 850 m.

For fast rates of settlement there is no difference between PCP-D with JRCP and CRCP as the tolerable $R_{\text{min(local)}}$ of 2500 m is greater than the 1700 m cut-off for reinforcement.

In the case of expansive soils, Tables 13 and 14 could be used where the limits for settlement are used for heave with an appropriate rate of settlement (ie heave). Otherwise it requires use of the ‘Thickness Design for Settlement Spreadsheet’.

The values in the longitudinal direction in Table 13 are derived assuming total settlement = 1.5 x differential settlement, noting total settlement is greater than maximum differential settlement (see Figure 1).
Table 15: Maximum allowable settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for JRCP).

<table>
<thead>
<tr>
<th>Length of settlement bowl 2T (m)</th>
<th>Total Settlement (= 1.5D) After 40 years since paving of base (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>3 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>6 mm</td>
</tr>
<tr>
<td>50 m</td>
<td>9 mm</td>
</tr>
<tr>
<td>75 m</td>
<td>21 mm</td>
</tr>
<tr>
<td>100 m</td>
<td>38 mm</td>
</tr>
<tr>
<td>110 m</td>
<td>45 mm</td>
</tr>
</tbody>
</table>

For a cosine curve where for example 2T = 50 m, ie T = 25 m and there is a fast rate of settlement \( R_{\min(\text{local})} = 10,000 \) m, and so total settlement is:

\[
= 1.5D = 1.5 \times T^2 / \left( \pi^2 R_{\min(\text{local})} \right) = \left[ 1.5 \times 25^2 / \left( \pi^2 \times 10,000 \right) \right] \times 10^3 = 9 \text{ mm}
\]

Table 16: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for JRCP).

<table>
<thead>
<tr>
<th>Half chord length T (m)</th>
<th>Differential Settlement (= D) After 40 years since paving of base (for a catenary/circular arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>10 m</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>15 m</td>
<td>5.5 mm</td>
</tr>
</tbody>
</table>
For a catenary and a circle, where the ratio of $D$ to $T$ is small:

$$D = T^2 / \left(2R_{\text{min(overall)}}\right) = T^2 / \left(2 \times 2R_{\text{min(local)}}\right) = T^2 / \left(4R_{\text{min(local)}}\right)$$

For example, for $T = 10$ m and slow rate of settlement and so $R_{\text{min(local)}} = 5000$ m, and the differential settlement ($D$) = $T^2 / \left(4R_{\text{min(local)}}\right) = \left[10^2 / (4 \times 5000)\right] \times 10^3 = 5$ mm

**Table 17: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for JRCP).**

<table>
<thead>
<tr>
<th>Length of settlement bowl $2T$ (m)</th>
<th>Total Settlement ($= 1.5D$) After 40 years since paving of base (mm) (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>9 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>13 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>24 mm</td>
</tr>
<tr>
<td>50 m</td>
<td>37 mm</td>
</tr>
<tr>
<td>75 m</td>
<td>85 mm</td>
</tr>
<tr>
<td>100 m</td>
<td>150 mm</td>
</tr>
<tr>
<td>110 m</td>
<td>180 mm</td>
</tr>
</tbody>
</table>

**Table 18: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for JRCP).**

<table>
<thead>
<tr>
<th>Half chord length $T$ (m)</th>
<th>Differential Settlement ($= D$) After 40 years since paving of base (mm) (for a catenary/circular arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>10 m</td>
<td>10 mm</td>
</tr>
<tr>
<td>15 m</td>
<td>22 mm</td>
</tr>
</tbody>
</table>
Where the design traffic exceeds $10^6$ DESA the allowable settlement will need to be lower than the limits in both Tables 17 and 18, to ensure the base thickness, which is the greater of $B_{fs}$ and $B_{st}$, is reasonable. Analysis in accordance with the ‘Thickness Design for Settlement Spreadsheet’ is needed to determine whether or not criteria related to curvature are satisfied. In some situations increasing pavement thickness may be required. However, it may not be possible or feasible to meet the curvature criteria even with an increase in base thickness.

Table 19: Maximum allowable settlement in longitudinal direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for CRCP).

<table>
<thead>
<tr>
<th>Length of settlement bowl: $2T$ (m)</th>
<th>Total settlement ($= 1.5D$) After 40 years since paving of base (for a cosine curve)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>12.5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>25 m</td>
<td>2 mm</td>
</tr>
<tr>
<td>30 m</td>
<td>3 mm</td>
</tr>
<tr>
<td>40 m</td>
<td>6 mm</td>
</tr>
<tr>
<td>50 m</td>
<td>9 mm</td>
</tr>
<tr>
<td>75 m</td>
<td>21 mm</td>
</tr>
<tr>
<td>100 m</td>
<td>38 mm</td>
</tr>
<tr>
<td>150 m</td>
<td>85 mm</td>
</tr>
</tbody>
</table>

Table 20: Maximum allowable settlement in transverse direction for soft soils for all traffic levels at which no special design for settlement is needed for criteria related to curvature (for CRCP).

<table>
<thead>
<tr>
<th>Half chord length: $T$ (m)</th>
<th>Differential settlement ($= D$) After 40 years since paving of base (for a catenary/circular arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast rate of settlement</td>
</tr>
<tr>
<td>5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>10 m</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>15 m</td>
<td>5.5 mm</td>
</tr>
</tbody>
</table>
Table 21: Maximum allowable settlement in longitudinal direction for soft soils for criteria related to curvature (for CRCP).

<table>
<thead>
<tr>
<th>Length of settlement bowl 2T (m)</th>
<th>Total settlement (= 1.5D) After 40 years since paving of base (mm) (for a cosine curve)</th>
<th>Fast rate of settlement</th>
<th>Slow rate of settlement</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 m</td>
<td>2 mm</td>
<td>7 mm</td>
<td></td>
</tr>
<tr>
<td>25 m</td>
<td>9 mm</td>
<td>28 mm</td>
<td></td>
</tr>
<tr>
<td>30 m</td>
<td>13 mm</td>
<td>40 mm</td>
<td></td>
</tr>
<tr>
<td>40 m</td>
<td>24 mm</td>
<td>71 mm</td>
<td></td>
</tr>
<tr>
<td>50 m</td>
<td>38 mm</td>
<td>111 mm</td>
<td></td>
</tr>
<tr>
<td>75 m</td>
<td>85 mm</td>
<td>251 mm</td>
<td></td>
</tr>
<tr>
<td>100 m</td>
<td>150 mm</td>
<td>440 mm</td>
<td></td>
</tr>
<tr>
<td>150 m</td>
<td>340 mm</td>
<td>1005 mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 22: Maximum allowable settlement in transverse direction for soft soils for criteria related to curvature (for CRCP).

<table>
<thead>
<tr>
<th>Half chord length T (m)</th>
<th>Allowable differential settlement (= D) After 40 years since paving of base (mm) (For a catenary/circular arc)</th>
<th>Fast rate of settlement</th>
<th>Slow rate of settlement</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m</td>
<td>2 mm</td>
<td>7 mm</td>
<td></td>
</tr>
<tr>
<td>10 m</td>
<td>10 mm</td>
<td>29 mm</td>
<td></td>
</tr>
<tr>
<td>15 m</td>
<td>22 mm</td>
<td>66 mm</td>
<td></td>
</tr>
</tbody>
</table>

When using Tables 21 and 22 for traffic volumes exceeding $10^6$ DESA the allowable settlement will need to be lower than the limits in both Tables 21 and 23, to ensure the base thickness, which is the greater of $B_B$ and $B_ST$, is reasonable. Analysis in accordance with the ‘Thickness Design for Settlement Spreadsheet’ is required to determine whether or not criteria related to curvature are satisfied. In some situations increasing pavement thickness may be required. However, it may not be possible or feasible to meet the curvature criteria even with an increase in base thickness.
10. **Underground mining**

10.1 **Special analysis**

Table 3 shows the significance of various factors related to pavements where the effects of differential settlement are significant. In this context, special analysis for pavements above underground mining is needed because of:

- Fast rates of settlement - there is little benefit from creep/stress relaxation in reducing bending stresses from settlement.
- Long settlement bowls - where it is necessary to investigate such things as possibility of stepping and/or buckling in compression zones, eg trough areas of settlement bowls, and excessive axial tensile stress in tension zones, eg crest areas of settlement bowls.
- Large longitudinal movements and/or transverse movements - with transverse movements it is necessary to investigate whether shear and bending stresses in the horizontal plane are excessive.
- Large relative movements between base concrete and subbase concrete.
- Large reversible horizontal movements.
- Anomalous or irregular behaviour due to such factors as valley closure, and/or movements associated with geological features such as faults.

Consideration should be given to:

- Reduce the impact of irregular behaviour from mining on pavements, and to place limits on tolerable damage to drainage and drainage structures. Impacts due to irregular movements can be very difficult to manage due to difficulties in prediction in terms of location, type, magnitude and timing.
- Take measures to ensure traffic safety in case of stepping of concrete base and bound (including concrete) subbases and bound subgrade layers and/or buckling of concrete base/subbase, but also with changes in crossfall and sight distance.
- Take preventive methods to limit damage to drainage structures.

In addition, there is also an upper limit on the length of a settlement bowl that can be tolerated because of the axial stresses created by large horizontal movements. These axial stresses limit the type and magnitude of mining where it is necessary for the pavement to remain structurally sound. Therefore, even where the $R_{\text{min}(\text{local})}$ from settlement is tolerable, the length of the settlement bowl can be too large.

Special analysis also applies where the mining is not directly under the pavement, but is sufficiently close to cause some settlement and/or horizontal movements in the region of the pavement (whether in the longitudinal direction or in the transverse direction).

10.2 **Special pavements**

For underground mining, the special composite pavement Type 2 offers the best performance of the whole group of concrete pavements as it:

- Is able to tolerate a relatively large horizontal movement in the upper subgrade in the longitudinal direction.
• Has less restriction on the relative movement between base and subbase.
• Is able to tolerate some reversal of horizontal movement.

Given that a Type 2 pavement has a limit on the maximum length of settlement bowl to ensure against risk of buckling and then only if:

• The maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m to prevent yielding of longitudinal steel, and excessive cracking and premature fatigue cracking of CRCP subbase in crest regions. Finite element analysis may show that a higher limit is permissible, noting such modelling can take into account slippage between the pavement and the subgrade which reduces tensile stress in the CRCP subbase in the crest.

• The maximum horizontal movement of the upper subgrade in the longitudinal direction is ≤ 150 mm. Maximum horizontal movements of the order of 100 to 150 mm are considered tolerable, only if there is a high percentage of longitudinal steel in the CRCP subbase and the total thickness of the erosion resistant lower subbase layer together with the slip-moderately deformable granular subgrade is at least 300 mm, and there is also at least 1000 mm of granular material below the slip-moderately deformable granular subgrade layer that can distort with horizontal movements.

\[ D_H < 1.7L_H^2 / \pi^2 W_H \] for summer cast concrete, and \[ D_H < 0.9L_H^2 / \pi^2 W_H \] for winter cast concrete to keep contact stresses on inside curve edges in the horizontal plane within adequate limits. Special analysis is required to allow some relaxation of this limitation.

Further work is needed for underground mining to assess potential shear failure for large \( L_H \).

In many instances a Type 2 Pavement will not be suitable and it may be necessary to use a fully flexible pavement where none of the select subgrade and subgrade layers are bound by stabilised to ensure against stepping failures at the surface from stepping failure in a bound subgrade layer. In areas of high traffic a full depth asphalt pavement on a granular (upper supporting) subgrade may be necessary.

Further analysis is needed using a finite element model to determine what length of settlement bowl can be tolerated for a Type 2 pavement before buckling may occur. This model will need to take into account, the extra resistance provided by the asphalt base as well as the extra axial stress in the CRCP subbase due to the extra weight of the asphalt base.

10.3 Impact of traffic safety and drainage

Some of the impacts on traffic safety and drainage may be so pronounced that underground mining:
• cannot proceed,
• needs to be restricted using a special extraction strategy to minimise impact to a satisfactory level, or
• requires special drainage design to avoid or limit the impacts to drainage and drainage structures to satisfactory or tolerable levels.

Therefore, special care is needed to assess the effects of general settlement and also the risk of anomalous behaviour on traffic safety and drainage.
10.4 Reducing impacts related to cuttings

Figure 16 shows a diagram illustrating how a concrete pavement can be partly isolated in a cutting from underground mining from rock batters and rock floors. This is done by:

- widening rock cuttings, and
- excavating rock and coarse material to a relatively large depth below the finished pavement levels, and replacing this rock and coarse material with granular material with smaller maximum size.

![Diagram of pavement isolation in a rock cutting](image)

Figure 16: Sketch of isolation of pavement in a rock cutting in the vicinity of underground mining where large-scale settlement is expected.

This is such that, in effect the upper subgrade through the cutting has some similarities to a granular embankment. This may not only isolate the pavement to some extent from a number of the stresses and strains that may otherwise occur from settlement. Additionally it may also reduce the number of drainage structures, such as culverts, subsoil drainage, kerbing and gully pits, that would otherwise be needed and which may be damaged by mining. The use of wide cuttings, not just in rock, but also within soil, may also mean that underground drainage pipes can be isolated to a significant extent from the pavement and be also easier to repair should they be damaged by underground mining.

In summary, using wide cuttings and the isolation of the pavement from any underlying rock is expected to reduce the impact of settlement on the pavement, surface and subsurface drainage structures.

10.5 Minimising risk of failures

Where proposed underground mining is within the tolerable limits shown in Appendix A, the design of concrete pavements still requires assessment of:

- Risk of stepping and/or buckling in compression zones.
- Potential irregular behaviour and to determine design solutions, if any.

In general, stepping/buckling from horizontal longitudinal movements is considered far more critical than shear failure from horizontal transverse movements, as stepping/buckling can occur quickly and be dangerous to traffic, whereas shear failure from transverse movement is a lower energy failure and is not considered in general to be a risk to traffic safety.
10.6 Upper limit of extraction of coal

Besides any requirements/limitations from the above discussion, there is a maximum length of settlement bowl with underground mining because of criteria related to horizontal movements:

- In both longitudinal and transverse directions.
- In the longitudinal direction in conjunction with radius of curvature.

This combined effect is only significant for CRCP layers and so only applies to CRCP base in CRCP and CRCP subbase (in the case of a Type 2 pavement) in the longitudinal direction in crest areas of settlement bowls.

Given the structural failures that can occur in concrete pavements over long settlement bowls, underground mining may not be at all possible in some situations, and in other situations it may need to be restricted. For example, by leaving a sufficient number coal pillars in place (see Figure 17) to keep stresses from settlement within acceptable limits during all phases of mining.

![Figure 17: Possible layout of mining so settlement is within acceptable limits (sketch).](image)

Where underground mining will only cause settlement bowls that are shallow, such that may occur when mining is some lateral distance from the pavement or when mining does occur under the pavement and sufficient coal is left in place, so that horizontal movements in the longitudinal direction in the upper subgrade are only small, then longer bowls may be possible.

10.7 Monitoring

Where underground mining is to be carried out, even where differential settlement is expected to be within acceptable levels, there may still be a risk of stepping and/or buckling in the pavement, which could create a hazard for motorists. Therefore once mining commences the pavement should be regularly monitored for risk of stepping/buckling until there has been at least one hot and wet summer following cessation of settlement. This is so that appropriate speed restrictions can be put in place and remedial action can be undertaken where necessary, noting that both high temperature and high moisture increase risk of buckling/stepping.

After mining ceases, the stresses due to mining will reduce due to stress relaxation and so monitoring only needs to continue until the first critical hot and wet summer passes or
sufficient time, of the order of three years, has elapsed since cessation of mining so there is no future risk of buckling/stepping.

Prior to coal extraction, a rehabilitation strategy should be developed to deal with possible failures. Substantial pavement repairs, such as slab replacement and/or undergrouting, may be able to be programmed later (and possibly after all movement has stabilised).

Since underground mining may also affect drainage, drainage structures and traffic safety, special monitoring is also required to prevent critical levels being reached for drainage and traffic safety (also refer to Section 13).
11. Basic conditions for adequate in service performance

In general, concrete pavements may offer adequate structural performance in areas of differential settlement provided that:

- The base concrete has a high Modulus of Rupture ($MR$) which increases in value with time.
- A base concrete has a high value for the ratio $MR/E$ as this is advantageous in reducing bending stress from settlement due to self-weight of the concrete and traffic loads. For example, a concrete base (and a CRCP subbase in a Type 2 pavement) with $MR_b/E_b > 2 \times 10^4$ is significantly more advantageous than if it is $1.5 \times 10^4$ (noting a number of tolerable limits in the Guide are based on an $MR_b$ of 4.5 MPa with $E_b$ of 30,000 MPa).
- The subbase concrete is at least 150 to 200 mm thick, and has increasing $f'_c$ with time and a delay in paving the concrete base may be beneficial to allow sufficient strength development in the subbase.
- The coefficients of friction are low between:
  a. base and subbase (low $\mu_{b-sb}$), provided this does not lead to excessive axial stress in the subbase concrete
  b. subbase and select subgrade (low $\mu_{sb-ug}$)
- The concrete subbase should be placed over a select granular layer to improve uniform support.
- The concrete base must be reinforced if:
  a. $R_{\text{min(local)}}$ is less than 1700 m in either convex or concave curvature
  b. the maximum horizontal movement of the upper subgrade is greater than say 5 mm
12. Sensitivity analysis

A sensitivity analysis should be carried out where the length of a settlement bowl is not known, using:

- potential lengths of settlement bowl
- a range of possible settlements over the design period
- different pavement types and concrete strengths
- various rates of settlement
- a range of base thicknesses.

This analysis can be used to determine the appropriate balance between risks, cost and pavement life for a variety of suitable concrete pavement types, such that the most appropriate concrete pavement is selected, provided there is a suitable concrete pavement option available.
13. **Safety and drainage**

Determining the tolerable limits for disturbances to drainage (both surface and subsoil drainage), changes in sight distance and crossfall in situations of settlement, is beyond the scope of the Guide and needs to be addressed separately.

In assessing any potential settlement, the following need to be assessed in addition to the issues dealt with in the Guide:

- Effect on road user safety due to changes in ride quality, sight distance, crossfall, and shadow effects at night.
- The effect of subsidence on the operation of surface and subsurface drainage.
- Damage to drainage structures due to changes in curvature and/or vertical and horizontal movements.
- Damage due to relative movement and/or rotations between a concrete pavement and drainage structures and kerbing.
- The use of more frequent crossovers on dual carriage highways to better manage traffic after a subsidence incident.

In many cases a road design engineer must be engaged to review the effects subsidence would have on maintaining the posted speed limits and road surface profile.
14. Glossary of terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross sectional area of a concrete layer along the width of the pavement</td>
</tr>
<tr>
<td>AC</td>
<td>Asphaltic concrete. Also referred to as dense graded asphalt. It is often short named as asphalt.</td>
</tr>
<tr>
<td>Ag</td>
<td>Gross cross-sectional area of a member. This is used to calculate ( t_h ).</td>
</tr>
<tr>
<td>Anomalous Behaviour</td>
<td>See irregular behaviour</td>
</tr>
<tr>
<td>Axial Stresses</td>
<td>Stresses along the horizontal axis of a pavement</td>
</tr>
<tr>
<td>( B_c )</td>
<td>Minimum construction thickness of the base concrete</td>
</tr>
<tr>
<td>( B_e )</td>
<td>Base concrete thickness that satisfies the erosion analysis from traffic</td>
</tr>
<tr>
<td>( B_f )</td>
<td>Base concrete thickness that satisfies the fatigue analysis from traffic</td>
</tr>
<tr>
<td>( B_{fs} )</td>
<td>Base concrete thickness determined to accommodate the settlement flexural stresses’ due to the self-weight of the slab in addition to the flexural stress requirements from the fatigue analysis</td>
</tr>
<tr>
<td>( B_{st} )</td>
<td>Base concrete thickness determined to accommodate the cumulative effect of fatigue, differential settlement in conjunction with positive temperature gradient</td>
</tr>
<tr>
<td>Chord Length</td>
<td>Horizontal distance between two points on a circle or a catenary, which is depicted as ( 2T ) (such that the half chord length is ( T )). Where the surface due to settlement does not form a full symmetrical arc, the chord length ( (2T) ) is determined by continuing the arc’s mathematical path to create a symmetrical shape, ie a symmetrical crest or symmetrical trough, as is relevant, and using this enlarged arc to derive the radius of curvature of the arc.</td>
</tr>
<tr>
<td>Compression Zone</td>
<td>Region of horizontal compressive stresses in pavement structure.</td>
</tr>
<tr>
<td>Concave Shape</td>
<td>Trough of settlement bowl curving inwards (this refers to the change in shape as a pavement settles on the pre-existing vertical alignment).</td>
</tr>
<tr>
<td>Convex Shape</td>
<td>Crest of a settlement bowl curving outwards (this refers to the change in shape as a pavement settles on the pre-existing vertical alignment).</td>
</tr>
<tr>
<td>CRCP</td>
<td>Continuously reinforced concrete base</td>
</tr>
<tr>
<td>CRCP</td>
<td>Continuously reinforced concrete pavement</td>
</tr>
<tr>
<td>Creep</td>
<td>The gradual increase in strain over time for concrete which is subjected to a constant sustained stress. For concrete after many years this strain can be of the order of three times the strain at time of loading. See also Stress Relaxation</td>
</tr>
</tbody>
</table>
| Creep Ratio (CR) | \[ CR = 1 + \left[ k_s k_4 + \Phi_{ec}(1 + \text{variation in } \Phi_{cc}) \right]. \]

The CR refers to the effective change in strain due to creep, with the Effective Modulus of the concrete base \( = E_b/CR_b \), and the Effective Modulus of the concrete subbase \( = E_{sb}/CR_{sb} \). It also refers to the change in bending stress of the concrete base (or concrete subbase) for a particular increment of bending strain or for a constant curvature, caused by settlement, due to stress relaxation for concrete. See also Stress Relaxation |
<p>| ( CR_b ) | Creep ratio of the concrete base |
| ( CR_{sb} ) | Creep ratio of the concrete subbase |
| Crest | Region of a convex shape in a settlement bowl. |</p>
<table>
<thead>
<tr>
<th><strong>Coefficient of Variation (C_v)</strong></th>
<th>Ratio of standard deviation to average. Symbol may be expressed as CoV.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Curling</strong></td>
<td>The upward or downward movement of the corner of a concrete ‘slab’ due to moisture and/or temperature differentials within the concrete</td>
</tr>
<tr>
<td><strong>Curvature (κ)</strong></td>
<td>The reciprocal of the radius of curvature $= 1/R$</td>
</tr>
<tr>
<td><strong>$D$</strong></td>
<td>Maximum differential settlement of a settlement bowl</td>
</tr>
<tr>
<td><strong>d</strong></td>
<td>Diameter of a steel dowel</td>
</tr>
<tr>
<td><strong>$D_H$</strong></td>
<td>Maximum differential horizontal movement of a concrete base due to transverse movements</td>
</tr>
<tr>
<td><strong>$E_b$</strong></td>
<td>Elastic modulus of base concrete. Unless otherwise stated it refers to the characteristic modulus of elasticity at a concrete age of 28 days.</td>
</tr>
<tr>
<td><strong>$E_{b28}$</strong></td>
<td>Characteristic modulus of elasticity of concrete base at an age of 28 days</td>
</tr>
<tr>
<td><strong>$E_{bp}$</strong></td>
<td>Characteristic modulus of elasticity of concrete base at the beginning of a time period</td>
</tr>
<tr>
<td><strong>Edge Creep</strong></td>
<td>Vertical settlement of edge of embankment, where, following the paving of a concrete pavement, the edge of an embankment settles more than the centreline of the embankment</td>
</tr>
<tr>
<td><strong>Effective Negative Temperature Differential of Base Concrete</strong></td>
<td>Actual temperature at the top of the base concrete minus the actual temperature at the bottom of the base concrete minus the temperature differential needed to make the slab ‘flat’</td>
</tr>
<tr>
<td><strong>Effective Modulus (EM)</strong></td>
<td>$EM = \text{Elastic Modulus } / \left(1 + k_3 k_2 + \Phi_{cc,h}\right)$</td>
</tr>
</tbody>
</table>
| **Mean elastic modulus of base at the relevant age ($E_{mb}$)** | $E_{mb} = \rho^{1.5} \times 0.043 \times (f_{mc})^{0.5}$  
where the coefficient of variation of the strength = 10%, then $f_{mc} = 1.2 \times f'_c$, 
and $E_{mb} = \rho^{1.5} \times 0.043 \times (1.2 \times f'_c)^{0.5}$  
$f_{mc}$ is the elastic modulus of concrete |
<p>| <strong>$E_{mbh}$</strong>                    | Average elastic modulus of the reinforced base concrete at the relevant age |
| <strong>$E_{mx}$</strong>                     | Average elastic modulus of the steel |
| <strong>Mean elastic modulus of the subbase concrete at the relevant age ($E_{msb}$)</strong> | $E_{msb} = \rho^{1.5} \times 0.043 \times (f_{cm})^{0.5}$ |
| <strong>$E_s$</strong>                        | Elastic modulus of the steel |
| <strong>$E_{sb}$</strong>                     | Elastic modulus of the subbase concrete. Unless otherwise stated it refers to the characteristic modulus of elasticity at a concrete age of 28 days. |
| <strong>ESA</strong>                          | Equivalent Standard Axle, which is 8.2 tonnes on a single axle with dual tyres |
| <strong>Fast Rate of Settlement</strong>      | Where the majority of differential settlement occurs within two years after paving |
| <strong>$f_b$</strong>                        | Bond stress for mature concrete (MPa) |
| <strong>$f'_c$</strong>                       | Characteristic compressive strength of concrete at an age of 28 days, unless otherwise stated |</p>
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{cf}$</td>
<td>Flexural tensile strength of concrete, see Modulus of Rupture</td>
</tr>
</tbody>
</table>
| $f_{cm}$ | Average compressive strength of concrete at the relevant age  
$$= f'_c \left[1 - (1.645 \times \text{Coefficient of Variation})\right]$$  
if Coefficient of Variation = 10%, this makes  
$$f_{cm} = f'_c \left[1 - (1.645 \times 0.10)\right] = 1.20 \times f'_c$$ |
| $f_{ct}$ | Tensile strength of concrete (MPa). $f_{ct}$ can be taken as approximately 60% of $MR_b$, see Austroads pavement design method (Austroads, 2012) |
| $F_H$ | Horizontal shear force on each side of the section of pavement which is subjected to horizontal movement in the transverse direction |
| $f_{sy}$ | Yield stress of steel |
| HVAGs | Heavy vehicle axle groups |
| Irregular Behaviour | Behaviour that is difficult to predict and is often associated with underground mining due to factors such as valley closure and movement associated with geological features such as faults. |
| JRC | Jointed reinforced concrete base with dowels, hence JRC base is a jointed reinforced concrete base with dowels |
| JRCP | Jointed reinforced concrete pavement with dowels |
| $K$ | Modulus of rupture constant for relating $f'_c$ to $MR_b$, where $MR_b = K(f_c')^{0.5}$ |
| $k$ | Effective elastic modulus of subgrade support (kPa/mm) |
| $k_2, k_3$ | Creep Ratio coefficients,  
$k_2$ depends on the environment and the period under constant strain (i.e. the conditions for stress relaxation) or constant stress (i.e. the conditions for creep), and  
$k_3$ is the coefficient of maturity |
| $L_H$ | Half the longitudinal wavelength length of a section of pavement which is subjected to horizontal movement |
| Light Traffic | Design traffic that is less than $1 \times 10^6$ DESAs |
| Longitudinal direction | Direction parallel to the centreline of the road, i.e. direction of traffic |
| LSF | Load safety factor. This factor is used to increase the magnitude of axle loads on design |
| LSF\_no settlement | Load safety factor for pavement thickness design with no consideration of differential settlement |
| LSF\_settlement | Load safety factor for pavement thickness design taking into account the effect of differential settlement |
| $M$ | Depth of hypothetical bridging layer of subgrade material that undergoes bending with plane strain in association with settlement of soft soils, under the assumption that there is no friction or cohesion with the underlying layer |
| Movement Along the Settlement Profile | Actual movement along the actual settlement profile, and so is larger than the horizontal movement |
| $MR_b$ | Modulus of Rupture of concrete base. Unless otherwise stated it refers to the characteristic MR of base concrete at an age of 28 days (i.e. $f_{cf}$ at 28 days). |
| $MR_{b,28}$ | Modulus of Rupture of concrete base at an age of 28 days, also called $f_{cf}$ at 28 days. |
### Modulus of Rupture of Concrete Base at the Beginning of a Time Period

- **$MR_{bp}$**: Modulus of Rupture of concrete base at the beginning of a time period, also called $f_{cf}$ at the start of a time period.

### Horizontal Moment on Each Side of a Section of Pavement Which Is Subjected to Horizontal Movement in the Transverse Direction

- **$MR_H$**: Horizontal moment on each side of a section of pavement which is subjected to horizontal movement in the transverse direction.

### Modulus of Rupture of Concrete Subbase

- **$MR_{sb}$**: Modulus of Rupture of concrete subbase. Unless otherwise stated it refers to the characteristic MR of subbase concrete at an age of 28 days (i.e., $f_{cf}$ at 28 days).

### Temperature Differential Where the Temperature at the Top of the Base Is Lower Than the Temperature at the Bottom of the Base

- **$MR_{sb}$**: Modulus of Rupture of concrete subbase. Unless otherwise stated it refers to the characteristic MR of subbase concrete at an age of 28 days (i.e., $f_{cf}$ at 28 days).

### Cross-sectional Area of the Longitudinal Steel Per Unit Area of the Base Concrete

- **$p$**: Cross-sectional area of the longitudinal steel per unit area of the base concrete (i.e., steel proportion) as a percentage, e.g., if the steel proportion of the cross section of the base is 0.0067, then as a percentage this is 0.67%, so $p = 0.67$.

### Plain Concrete Pavement with Dowels at Every Transverse Joint

- **PCP-D**: Plain concrete pavement with dowels at every transverse joint.

### Plain Concrete Pavement Reinforced with Steel Mesh

- **PCP-R**: Plain concrete pavement reinforced with steel mesh.

### Temperature Differential Where the Temperature at the Top of the Base Is Higher Than the Temperature at the Bottom of the Base

- **$MR_{sb}$**: Modulus of Rupture of concrete subbase. Unless otherwise stated it refers to the characteristic MR of subbase concrete at an age of 28 days (i.e., $f_{cf}$ at 28 days).

### Radius of Curvature of a Steel Dowel Bar Across a Joint in Base Concrete (PCP-D or JRCP)

- **$r$**: Radius of curvature of a steel dowel bar across a joint in base concrete (PCP-D or JRCP).

### Unit Mass of Concrete (e.g., 2400 kg/m³)

- **$ρ$**: Unit mass of concrete (e.g., 2400 kg/m³).

### Radius of Curvature

- **$R$**: Radius of curvature.

### Radius of Curvature After 40 Years of Being Placed Over Soft Soil

- **$R_{40}$**: Radius of curvature after 40 years of being placed over soft soil.

### Relative Humidity

- **$RH$**: Relative humidity.

### Minimum Radius of Curvature for a Settlement Profile With Either a Concave or Convex Shape. It Is Also Used for Assessing Horizontal Transverse Movements, i.e., Perpendicular to Direction of Traffic

- **$R_{min}$**: Minimum radius of curvature for a settlement profile with either a concave or convex shape. It is also used for assessing horizontal transverse movements, i.e., perpendicular to direction of traffic.

### Minimum Radius of Curvature Anywhere Along a Settlement Profile

- **$R_{min(local)}$**: Minimum radius of curvature anywhere along a settlement profile.

### Minimum Radius of Curvature, Calculated Simply on the Basis of Overall Characteristics of a Settlement Bowl, i.e., on the Value for T and D, and Overall Shape of Curve (Such as Cosine or Circular or Catenary). It Does Not Take into Account Localised (i.e., ‘Non-Smooth’) Variations From a Smooth Curve, Whether It Be Cosine or Circular or Catenary

- **$R_{min(overall)}$**: Minimum radius of curvature, calculated simply on the basis of overall characteristics of a settlement bowl, i.e., on the value for T and D, and overall shape of curve (such as cosine or circular or catenary). It does not take into account localised (i.e., ‘non-smooth’) variations from a smooth curve, whether it be cosine or circular or catenary.

### Radius of Curvature ($R$) at $x$ Years, Where Both $R$ and $x$ Are Relative to the Start of Secondary Creep Settlement

- **$Rx$**: Radius of curvature ($R$) at $x$ years, where both $R$ and $x$ are relative to the start of secondary creep settlement.

### Differential Settlement Along a Settlement Profile

- **$s$**: Differential settlement along a settlement profile.

### Theoretical Value of Variable Stress From Traffic for $B_c$ Which Gives the Same Fatigue Life Without Any Settlement Stress, As the Actual Stress From Traffic, $S_e$, Which Is a Variable Stress, in Conjunction With Settlement Stress, Which Is a Constant Stress

- **$S_{equi-e}$**: Theoretical value of variable stress from traffic for $B_c$ which gives the same fatigue life without any settlement stress, as the actual stress from traffic, $S_e$, which is a variable stress, in conjunction with settlement stress, which is a constant stress.

### Variable Stress From Traffic for $B_c$

- **$S_e$**: Variable stress from traffic for $B_c$.

### Deformation Shape in the Vertical Direction Caused by Settlement. In General, It Is Often Assumed to Be Similar to a Cosine Curve Along the Longitudinal Direction, (i.e., in the Direction of Traffic), and a Circle/Catenary Along the Transverse Direction, (i.e., Perpendicular to the Direction of Traffic).

- **Settlement Bowl**: Deformation shape in the vertical direction caused by settlement. In general, it is often assumed to be similar to a cosine curve along the longitudinal direction, (i.e., in the direction of traffic), and a circle/catenary along the transverse direction, (i.e., perpendicular to the direction of traffic).

### Shear Force Carried by the Longitudinal Steel in a Continuously Reinforced Concrete Pavement

- **$SF_{steel}$**: Shear force carried by the longitudinal steel in a continuously reinforced concrete pavement.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFCP</td>
<td>Steel fibre reinforced concrete pavement</td>
</tr>
<tr>
<td>SFCP-D</td>
<td>Steel fibre reinforced concrete pavement with dowels at every transverse joint</td>
</tr>
<tr>
<td>SFCP-R</td>
<td>Discrete slabs of steel fibre reinforced concrete pavement reinforced with steel mesh</td>
</tr>
<tr>
<td>SFRC</td>
<td>Steel fibre reinforced concrete</td>
</tr>
<tr>
<td>Slow Rate of Settlement</td>
<td>Where the maximum depth of differential settlement over all three year periods since paving is no more than half the differential settlement over 40 years since start of settlement</td>
</tr>
<tr>
<td>Stress Relaxation of Concrete</td>
<td>A reduction in stress for concrete subjected to constant strain, such as that caused by a certain magnitude of settlement or deformation. For example, where concrete conforms to the settlement profile due to self-weight of the concrete, this causes bending stress which then reduces over time. Therefore stress relaxation is a manifestation of creep. Now settlement over soft soils is not typically a one-off event but instead increases over time. Each increment of strain from bending due to settlement (due to self-weight of the concrete) will experience a relaxation in stress over time so that the reduction in bending stress for a particular increment of strain after the passing of time is related to the time since the particular increment of strain occurred. The bending stress at any particular time at the critical position in the base is the sum of the bending stresses at this critical position caused by each increment of settlement, after taking into account the stress relaxation for each increment of strain at the critical position, with the first increment of strain having the most time for stress relaxation and so on.</td>
</tr>
<tr>
<td>$T$</td>
<td>Half the wavelength of cosine curve (noting $2T = \text{wavelength}$), or half the chord length of a circle or catenary (noting $2T = \text{chord length}$).</td>
</tr>
<tr>
<td>$t_b$</td>
<td>Thickness of base concrete</td>
</tr>
<tr>
<td>Temperature Differential of Base Concrete</td>
<td>Temperature at the top of the base concrete minus the temperature at the bottom of the base concrete</td>
</tr>
<tr>
<td>Tension Zone</td>
<td>Tension zone of the upper subgrade unless otherwise indicated. (The tension zone of CRCP base/subbase can be larger than the tension zone of the upper subgrade, due to the interaction between tension and compression zones of CRCP over the whole settlement bowl as a function of the longitudinal steel).</td>
</tr>
<tr>
<td>$t_h$</td>
<td>Hypothetical thickness of a member used in determining creep (and stress relaxation), taken as $2 \times \frac{A_s}{u_c}$.</td>
</tr>
<tr>
<td>$t_{sub}$</td>
<td>Average thickness of base concrete</td>
</tr>
<tr>
<td>$t_{mb}$</td>
<td>Average thickness of subbase concrete</td>
</tr>
<tr>
<td>$t_{maxi}$</td>
<td>Average thickness of select subgrade layer</td>
</tr>
<tr>
<td>Toughness</td>
<td>The amount of spare bending moment capacity in a slab of concrete after allowing for stresses due to non-traffic load factors such as:</td>
</tr>
<tr>
<td></td>
<td>• bending due to settlement (caused by self weight of concrete),</td>
</tr>
<tr>
<td></td>
<td>• temperature differentials between the top and bottom of a slab,</td>
</tr>
<tr>
<td></td>
<td>• ‘built-in’ curvature from construction (due to variations in setting temperature between the top and bottom of a slab) and</td>
</tr>
<tr>
<td></td>
<td>• moisture variations between top and bottom of a slab</td>
</tr>
<tr>
<td>Transverse direction</td>
<td>Direction perpendicular to the centreline of the road, (ie perpendicular to the direction of traffic)</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Trough</td>
<td>The region of a concave shape in a settlement bowl. This refers to change in shape as the settlement bowl is superimposed on the pre-existing vertical alignment</td>
</tr>
<tr>
<td>$t_{sb}$</td>
<td>Thickness of subbase concrete</td>
</tr>
<tr>
<td>$t_{sb, min}$</td>
<td>Minimum construction thickness of the subbase concrete</td>
</tr>
<tr>
<td><strong>Type 1</strong></td>
<td>Specially designed pavement for settlement which includes an interlayer of asphaltic concrete or non-erodible granular material between the concrete base and concrete subbase. The base is either CRCP or short slab JRC</td>
</tr>
<tr>
<td><strong>Type 2</strong></td>
<td>Specially designed composite pavement which includes an asphalt base over a CRCP subbase</td>
</tr>
<tr>
<td>$u_e$</td>
<td>Exposed perimeter of a member cross section. This is used to calculate $t_{sb}$</td>
</tr>
<tr>
<td><strong>Undergrouting</strong></td>
<td>(mudjacking) Injection of non-erodible cementitious material beneath a base layer of concrete to restore surface levels and provide uniform support</td>
</tr>
<tr>
<td>$W$</td>
<td>Weight per metre width of a concrete slab (either base or subbase) in N/m</td>
</tr>
<tr>
<td>$W_H$</td>
<td>Width of concrete pavement including tied concrete shoulders</td>
</tr>
<tr>
<td>$x$</td>
<td>Time (in years) to reach a determined radius of curvature ($R_x$) since the start of secondary creep settlement</td>
</tr>
<tr>
<td>$Z$</td>
<td>Tensile stress due to positive temperature differential</td>
</tr>
<tr>
<td>$\varepsilon_b$</td>
<td>Vertical or horizontal Strain in the concrete base</td>
</tr>
<tr>
<td>$\varepsilon_{sb}$</td>
<td>Vertical or horizontal Strain in concrete subbase</td>
</tr>
<tr>
<td>$\mu_{b-sb}$</td>
<td>Coefficient of friction between the base and subbase</td>
</tr>
<tr>
<td>$\mu_{s sl-sg}$</td>
<td>Coefficient of friction between the select subgrade layer and subgrade</td>
</tr>
<tr>
<td>$\mu_{sb-s sl}$</td>
<td>Coefficient of friction between the subbase and select subgrade layer</td>
</tr>
<tr>
<td>$\mu_{sb-sg}$</td>
<td>Coefficient of friction between the subbase and subgrade</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson's ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of concrete (kg/m$^3$), assumed to be 2400 kg/m$^3$ unless otherwise stated</td>
</tr>
<tr>
<td>$\sigma_b$</td>
<td>Allowable axial compressive stress in the concrete base from friction to prevent buckling</td>
</tr>
<tr>
<td>$\sigma_{conc}$</td>
<td>Stress in concrete</td>
</tr>
<tr>
<td>$\sigma_{matf, btm}$</td>
<td>Maximum allowable tensile stress in concrete from friction at bottom of base</td>
</tr>
<tr>
<td>$\sigma_{matf}$</td>
<td>Maximum allowable tensile stress in concrete from friction and defined as min($\sigma_{matf, btm}$, $\sigma_{matf, top}$)</td>
</tr>
<tr>
<td>$\sigma_{matf, top}$</td>
<td>Maximum allowable tensile stress in concrete from friction at top of base</td>
</tr>
<tr>
<td>$\sigma_{mb, dl}$</td>
<td>Maximum bending stress from settlement during the design life of pavement</td>
</tr>
<tr>
<td>$\sigma_{mb, ps}$</td>
<td>Maximum bending stress from settlement during the period of settlement and assumed to be equal to the tensile stress in the stress in the longitudinal steel in CRC</td>
</tr>
<tr>
<td>$\Phi_{cc,b}$</td>
<td>Basic concrete creep factor of base or subbase concrete. It is the ratio of ultimate creep strain to elastic strain for a specimen loaded at 28 days under a constant stress of $0.4 \times f'_c$. (Refer to AS 5100.5-2004, Bridge design - Concrete Code)</td>
</tr>
<tr>
<td>$\Phi_{cc}$</td>
<td>Basic concrete creep factor of base and defined as $\Phi_{cc} = k_2 k_3 \Phi_{cc,b}$</td>
</tr>
</tbody>
</table>
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APPENDICES
Appendix A  Allowable values for differential settlement

All concrete pavements are considered to have a concrete subbase and constructed to RMS specifications R82 and R83 (RMS, 2013b, 2013c). For the formation under the pavement and for traffic exceeding $10^6$ DESAs is to be constructed to RMS specification R44 (RMS, 2013a). Where asphalt is used, construct the AC layer to RMS specification R116 (RMS, 2012).

For special pavement Type 1 (refer to Table 1):

a) Short Slab JRC Base, then
   - Interlayer (50 to 100 mm AC or 150 to 200 mm non-erodible granular material)
   - Concrete subbase
   - Slip-moderately deformable granular subgrade layer (for settlement bowls > 150 m)
   - Upper subgrade is not bound

b) CRCP Base ($f_c \geq 60\text{ MPa}$, at first summer after start of settlement of CRCP base for settlement bowls > 150 m), then
   - Interlayer (50 to 100 mm AC or 150 to 200 mm non-erodible granular material)
   - Concrete subbase
   - Slip-moderately deformable granular subgrade layer (for settlement bowls > 150 m)
   - Upper subgrade is not bound

For special pavement Type 2 (refer to Table 1):

- AC base is a 175 mm in thickness
- CRCP subbase (250 mm for Table A5) ($f_c \geq 60\text{ MPa}$, at first summer after start of settlement of CRCP subbase for settlement bowls > 150 m)
- Erosion resistant lower subbase layer
- Slip-moderately deformable granular subgrade layer (for settlement bowls > 150 m)
- Upper subgrade is the Select Material Zone.

Tables A1 to A6 in this Appendix lists the following criteria with corresponding limitations:

- Minimum radius of curvature.
- Subbase and base concrete.
- Maximum horizontal movement of the upper subgrade.
- Maximum relative horizontal movement between concrete base and concrete subbase.
- Upper bound value for maximum horizontal tensile strain in the subgrade.
- Minimum $B_{fs}$ and $B_{st}$
Values in the tables are only a guide as they are based on certain assumptions, and so do not replace the need to consult the wider information in the Guide.
In some cases there may be some relaxation of limits (other than those for $R_{\text{min(local)}}$) for:

- low $\mu_{sb-sg}$ and low $\mu_{ssl-sg}$
- long shallow bowls.

Also modelling using finite element analysis may show there can be a relaxation for criteria other than $R_{\text{min(local)}}$.

Similar to the body of the Guide, light traffic is defined as less than $10^5$ DESA over the design life of the pavement.

A fast rate of settlement, such as occurs with underground mining, is where the majority of differential settlement, occurs within any two year period after paving, whereas typically a slow rate of settlement is where the maximum depth of differential settlement over any three year period since paving is no more than half the differential settlement over 40 years since start of settlement.

For PCP, PCP-R, PCP-D, JRCP and CRCP in Tables A1 to A3, the upper bound value for relative movement between concrete base and concrete subbase is assumed to be:

$$\frac{2.94 \times \mu_{sb-sd} \times T^2 \times \left[ t_{mb} + t_{msb} \right]}{(E_{sub}/CR_{sb}) \times t_{msb}} (mm)$$

That is:

$$T \leq \left( \text{upper bound value for relative movement between concrete base and concrete subbase} \times E_{sub} \times t_{msb} \right)^{0.5}$$

In Tables A4 and A5 the criteria and limits are listed for Type 1 pavement with short slab JRCP and CRCP bases respectively, and Table A6 is for Type 2 pavements. When using Table A6, use the following detailed notes in conjunction with the limits in the table:

a) Failure from buckling of the CRCP subbase is considered more critical than compression failure of the CRCP subbase from temperature and friction due to settlement and so no limit is given in the Table A6 for compressive failure for the CRCP subbase.

b) For the maximum allowable length of compression zone in the CRCP subbase, the relaxation of limits where the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m and is based on the assumption that the CRCP layer breaks down to 500 mm lengths in the tension zones under tensile stress from friction from settlement, traffic loading, temperature and shrinkage so that the maximum transverse crack opening in the CRCP subbase for 500 mm slabs = $0.6 \times 0.5 + 0.400 \times 0.25 \times 0.5 = 0.5$ mm. This is considered adequate to prevent corrosion of longitudinal steel and to provide sufficient shear transfer between slabs.

However, if the CRCP subbase is under 175 mm of asphalt, the concrete could break into regular 250 mm slabs in the tension zones, resulting in the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction being 1.6 mm/m, as the maximum transverse crack opening = $1.6 \times 0.25 + 0.400 \times 0.25 = 0.5$ mm. Alternatively, if the slabs are 500 mm in length between cracks rather than 250 mm where the maximum horizontal tensile strain of upper subgrade in the longitudinal direction is 1.6 mm/m, this allows the maximum transverse crack opening = $1.6 \times 0.5 +$
0.4 x 0.5 mm = 1.0 mm, which is considered too large to prevent corrosion of longitudinal steel and to give adequate shear transfer between slabs.

Also, not all the maximum unrestrained horizontal tensile strain of the upper subgrade in the longitudinal direction will be reflected in horizontal movement in the CRCP subbase, as there will be some slippage between the pavement and the subgrade, so a limit 0.6 mm/m for maximum horizontal tensile strain of the upper subgrade in the longitudinal direction may be more conservative than is appropriate.

Opening of the transverse joints/cracks in the CRCP subbase in the settlement crest region (ie in tension zones) may require the closing of gaps at transverse joints/cracks in the trough region (ie in the compression zone) and there is an upper limit on the average opening in transverse cracks in the tension zone due to geometrical considerations, and so correspondingly there is an upper limit on the maximum opening in a transverse crack in the middle of the tension zone.

c) For large horizontal movements of the subgrade in the longitudinal direction, say 100 to 150 mm, there must be at least 1000 mm of granular material below the slip-moderately deformable subgrade layer that can distort with horizontal movements.
### Table A1: Criteria and limits for PCP and PCP-R pavement types where limits for PCP-R vary from PCP (as noted).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum Radius of Curvature: ( R_{\text{min}} )</strong></td>
<td></td>
</tr>
<tr>
<td>To ensure there is:</td>
<td></td>
</tr>
<tr>
<td>• adequate rideability (longitudinal direction)</td>
<td></td>
</tr>
<tr>
<td>• adequate contact of the pavement with the subgrade (all directions)</td>
<td></td>
</tr>
<tr>
<td>• a certain degree of toughness (all directions)</td>
<td></td>
</tr>
<tr>
<td>For convex shape:</td>
<td></td>
</tr>
<tr>
<td>( R_{\text{min(local)}} ) = 10,000 m, for fast rate of settlement (all directions) for all traffic levels, or</td>
<td></td>
</tr>
<tr>
<td>( R_{\text{min(local)}} ) = 5,000 m, for slow rate of settlement (all directions) for all traffic levels</td>
<td></td>
</tr>
<tr>
<td>For concave shape:</td>
<td></td>
</tr>
<tr>
<td>( R_{\text{min(local)}} ) for slow rate of settlement and for light traffic = 1700 m (all directions)</td>
<td></td>
</tr>
<tr>
<td>(for PCP-R for slow rate of settlement for light traffic, ( R_{\text{min(local)}} ) = 850 m (all directions))</td>
<td></td>
</tr>
<tr>
<td>( R_{\text{min(local)}} ) for fast rate of settlement and for light traffic = 2500 m (all directions)</td>
<td></td>
</tr>
<tr>
<td>(For traffic less than ( 10^6 ) DESA over the design life of the pavement.)</td>
<td></td>
</tr>
<tr>
<td>(The ‘Thickness Design for Settlement Spreadsheet’ will determine whether a higher value of ( R_{\text{min(local)}} ) is needed for concave shape for higher traffic volumes)</td>
<td></td>
</tr>
<tr>
<td>To assess convex shape, ie crest regions of settlement bowls, a comprehensive design may need to be done. This will need to include an analysis of maximum negative temperature differentials throughout the life of the pavement and built-in curvature of the base concrete from construction. For convex shape, even an ( R_{\text{min(local)}} ) of 10,000 m, for fast rate of settlement, and an ( R_{\text{min(local)}} ) of 5,000 m, for slow rate of settlement, may be too low if there are relatively high negative temperature differentials throughout the life of the pavement and/or there is relatively large built-in concave curvature from construction, as this can lead to higher corner stresses.</td>
<td></td>
</tr>
<tr>
<td>For rates of settlement between fast and slow, it is considered conservative to adopt ( R_{\text{min(local)}} ) of 10,000 m. However, it may be appropriate to calculate a value for ( R_{\text{min(local)}} ) taking into account the maximum negative temperature differentials throughout the life of the pavement, the built-in concave curvature of the base concrete from construction, and the rate of settlement.</td>
<td></td>
</tr>
</tbody>
</table>

**Base Concrete:**

**Maximum Allowable Length of Compression Zone (T) to Avoid Buckling of Base**

Requires Special Analysis
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subbase Concrete: Maximum Allowable Length of Compression Zone (T) to Avoid Compression Failure and/or Buckling of Subbase</td>
<td>Requires Special Analysis</td>
</tr>
<tr>
<td>Maximum Horizontal Movement of the Upper Subgrade</td>
<td>Longitudinal Direction: 25 mm</td>
</tr>
<tr>
<td></td>
<td>Transverse Direction:</td>
</tr>
<tr>
<td></td>
<td>Summer Cast Concrete: No transverse movement (due to loss of aggregate interlock at transverse joints)</td>
</tr>
<tr>
<td></td>
<td>Winter Cast Concrete: maximum $D_{HH} = 0.628L_H^2/\left(W_H\pi^2\right)$ (mm)</td>
</tr>
<tr>
<td>Maximum Relative Horizontal Movement between Concrete Base and Concrete Subbase</td>
<td>1 mm (all directions)</td>
</tr>
<tr>
<td></td>
<td>(Using upper bound value for longitudinal direction, see relevant footnote)</td>
</tr>
<tr>
<td>Upper Bound Value for Maximum Horizontal Tensile Strain in the Subgrade (mm/m), in the middle region of settlement crest, to ensure adequate aggregate interlock. The allowable maximum horizontal tensile strain in the subgrade, in the longitudinal direction, will be further reduced by any rotation of the base concrete slabs, in the vertical plane, rather than bending of the slabs, to conform to the settlement profile.</td>
<td>for winter casting: $\frac{1.5}{\text{slab length (m)}} - 0.200$</td>
</tr>
<tr>
<td></td>
<td>for summer casting: $\frac{1.5}{\text{slab length (m)}} - 0.400$</td>
</tr>
<tr>
<td></td>
<td>For typical slab lengths this is negative, ie summer cast PCP cannot tolerate any settlement unless it is extremely small.</td>
</tr>
<tr>
<td>Minimum $B_{fs}$ and $B_{st}$</td>
<td>$B_{fs}$ and $B_{st}$ determined using 'Thickness Design for Settlement Spreadsheet', provided $R_{min lokal}$ is not too low</td>
</tr>
</tbody>
</table>
Table A2: Criteria and limits for JRCP and PCP–D bases where limits for PCP-D vary from JRCP (as noted).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
</table>
| Minimum Radius of Curvature: $R_{\text{min}}$ | for concave and convex shapes: 
  $R_{\text{min(local)}}$ for slow rate of settlement and for light traffic = 850 m (all directions) 
  (for PCP-D for slow rate of settlement for light traffic, $R_{\text{min(local)}} = 1700$ m (all directions)) 
  $R_{\text{min(local)}}$ for fast rate of settlement and for light traffic = 2500 m (all directions) 
  (For traffic less than $10^6$ DESA over the design life of the pavement.) 
  (The ‘Thickness Design for Settlement Spreadsheet’ will determine whether a higher value of $R_{\text{min(local)}}$ is needed for higher traffic volumes, for both concave and convex shapes.) |
| Base Concrete: 
  Maximum Allowable Length of Compression Zone (T) to Avoid Buckling of Base | Requires Special Analysis |
| Subbase Concrete: 
  Maximum Allowable Length of Compression Zone (T) to Avoid Compression Failure and/or Buckling of Subbase | Requires Special Analysis |
| Maximum Horizontal Movement of the Upper Subgrade | Longitudinal Direction: 
  25 mm for PCP-D and JRCP (where slab length is greater than 6.25 m) 
  50 mm for JRCP (where slab length is less than or equal to 6.25 m) in the longitudinal direction 
  Transverse Direction: 
  Summer Cast Concrete: maximum $D_{HH} = 1.7L_{HH} / (W_{HH} \pi^2)$ (mm) 
  Winter Cast Concrete: maximum $D_{HH} = 0.9L_{HH} / (W_{HH} \pi^2)$ (mm) |
| Maximum Relative Horizontal Movement between Concrete Base and Concrete Subbase | 7.5 mm (all directions) for JRCP 
  2 mm (all directions) for PCP-D |
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Bound Value for Maximum Horizontal Tensile Strain in the Subgrade (mm/m), in the middle region of crest, to prevent inadequate level of shear transfer of dowels</td>
<td>(Using upper bound value for longitudinal direction, see relevant footnote)</td>
</tr>
<tr>
<td>for winter casting:</td>
<td>$\frac{25}{\text{slab length (m)}} - 0.200$</td>
</tr>
<tr>
<td>for summer casting:</td>
<td>$\frac{25}{\text{slab length (m)}} - 0.400$</td>
</tr>
<tr>
<td>These are quite substantial and so may never be reached given the space taken up by all slabs in a settlement bowl. Where there is the possibility of reversals in horizontal strain, such as can occur with underground mining and in expansive soils, the limits may need to be much less, as JRCP and PCP-D are not expected to be able to tolerate large reversals in horizontal movement unless joint sealing of transverse joints is of such quality it prevents ingress of debris into joints.</td>
<td></td>
</tr>
<tr>
<td>Minimum $B_{fs}$ and $B_{st}$</td>
<td>$B_{fs}$ and $B_{st}$ determined using ‘Thickness Design for Settlement Spreadsheet’, provided $R_{\text{min}}$ is not too low.</td>
</tr>
</tbody>
</table>
### Table A3: Criteria and limits for CRCP base.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Radius of Curvature ( (R_{\text{min}}) )</td>
<td>for concave and convex shapes:</td>
</tr>
<tr>
<td>To ensure there is:</td>
<td>( R_{\text{min(lowal)}} ) for slow rate of settlement and for light traffic = 850 m (all directions)</td>
</tr>
<tr>
<td>- adequate rideability (longitudinal direction)</td>
<td>( R_{\text{min(lowal)}} ) for fast rate of settlement and for light traffic = 2500 m (all directions)</td>
</tr>
<tr>
<td>- adequate contact of the pavement with the subgrade (all directions)</td>
<td>(For traffic less than 10^5 DESA over the design life of the pavement.)</td>
</tr>
<tr>
<td>- a certain degree of toughness (all directions)</td>
<td>(The ‘Thickness Design for Settlement Spreadsheet’ will determine whether a higher value of ( R_{\text{min(lowal)}} ) is needed for higher traffic volumes.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Base Concrete: Maximum Allowable Length of Compression Zone (T) To Avoid Buckling of Base</th>
<th>Requires Special Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Concrete: Maximum Allowable Length of Tension Zone (T/2) To Avoid Excessive Cracking or Premature Fatigue Cracking of Base Concrete</td>
<td>Refer to Table C.4 for two ( f_c ) situations:</td>
</tr>
<tr>
<td>a) T/2 for ( f_c \leq 50 \text{ MPa} )</td>
<td>b) T/2 for ( f_c &gt; 50 \text{ MPa} )</td>
</tr>
<tr>
<td>Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis). Excessive cracking and/or premature fatigue cracking of the concrete base is not expected.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subbase Concrete: Maximum Allowable Length of Compression Zone (T) to Avoid Compression Failure and/or Buckling of Subbase</th>
<th>Requires Special Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Horizontal Movement of the Upper Subgrade</td>
<td></td>
</tr>
<tr>
<td><strong>Longitudinal Direction:</strong> 100 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Transverse Direction:</strong></td>
<td></td>
</tr>
<tr>
<td>Summer Cast Concrete: maximum ( D_H = 1.7L_H^2/(W_H \pi^2) ) (mm)</td>
<td></td>
</tr>
<tr>
<td>Winter Cast Concrete: maximum ( D_H = 0.9L_H^2/(W_H \pi^2) ) (mm)</td>
<td></td>
</tr>
</tbody>
</table>
### Criteria | Limit
---|---
Maximum Relative Horizontal Movement between Concrete Base and Concrete Subbase | 20 mm in the longitudinal direction 10 mm in the transverse direction (Using upper bound value for longitudinal direction, see relevant footnote)

Maximum Transverse Crack Opening in Base Concrete, In middle region of settlement crest to prevent corrosion of longitudinal steel and inadequate level of shear transfer | Refer to Table C4 Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), the transverse crack opening is tolerable.

Minimum Amount of Longitudinal Steel, $p$, in Base Concrete in middle region of settlement crest to prevent yielding of longitudinal steel | $p > \frac{(T/2) \times \mu_{b-sb}}{0.36 \times f_{sy}}$

Note: There is an upper limit of “$p$” to avoid poor compaction of the base concrete. This is particularly so for thicker bases as the quantity of longitudinal steel goes up linearly with the base thickness for the same value of $p$.

Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), excessive yielding of the longitudinal steel is not expected.

Minimum $B_{fr}$ and $B_{st}$ | $B_{fr}$ and $B_{st}$ determined using ‘ Thickness Design for Settlement Spreadsheet’, provided $R_{min(local)}$ is not too low
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Radius of Curvature ( R_{\text{min}} )</td>
<td>For concave and convex shapes:</td>
</tr>
<tr>
<td>To ensure there is:</td>
<td>( R_{\text{min,local}} ) for slow rate of settlement and for light traffic = 850 m (all directions)</td>
</tr>
<tr>
<td></td>
<td>(for PCP-D this limit for slow rate of settlement is 1700 m)( R_{\text{min,local}} ) for fast rate of settlement and for light traffic = 2500 m (all directions)</td>
</tr>
<tr>
<td></td>
<td>(For traffic less than ( 10^6 ) DESAs over the design life of the pavement.)( R_{\text{min,local}} ) is needed for higher traffic volumes)</td>
</tr>
<tr>
<td>Base Concrete:</td>
<td></td>
</tr>
<tr>
<td>Maximum Allowable Length of Compression Zone ((T)) to Avoid Buckling of Base</td>
<td>Requires Special Analysis</td>
</tr>
<tr>
<td>Subbase Concrete:</td>
<td></td>
</tr>
<tr>
<td>Maximum Allowable Length of Compression Zone ((T)) to Avoid Compression Failure and/or Buckling of Subbase</td>
<td>Requires Special Analysis</td>
</tr>
<tr>
<td>Maximum Horizontal Movement of the Upper Subgrade</td>
<td>Longitudinal Direction: 100 mm</td>
</tr>
<tr>
<td></td>
<td>Transverse Direction:</td>
</tr>
<tr>
<td></td>
<td>Summer Cast Concrete: maximum ( D_H = 1.7 \times \frac{L_H^2}{(W_H \times \pi^2)} )</td>
</tr>
<tr>
<td></td>
<td>Winter Cast Concrete: maximum ( D_H = 0.9 \times \frac{L_H^2}{(W_H \times \pi^2)} ) mm</td>
</tr>
<tr>
<td>Maximum Relative Horizontal Movement between Concrete Base and Concrete Subbase</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Upper Bound Value for Maximum Horizontal Tensile Strain in the Subgrade ((\text{mm/m})), in the middle region of settlement crest, to prevent</td>
<td>for winter casting:</td>
</tr>
<tr>
<td>Criteria</td>
<td>Limit</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| inadequate level of shear transfer of dowels | \[
\frac{25}{\text{slab length}} - 0.200
\]

  for summer casting:

\[
\frac{25}{\text{slab length (m)}} - 0.400
\]

These are quite substantial and so may never be reached given the space taken up by all slabs in a settlement bowl. Where there is the possibility of reversals in horizontal strain, such as can occur with underground mining and in expansive soils, the limits may need to be much less, as JRCP base is not expected to be able to tolerate large reversals in horizontal movement unless joint sealing of transverse joints is of such quality it prevents ingress of debris into joints.

| Minimum $B_{fs}$ and $B_{st}$           | $B_{fs}$ and $B_{st}$ determined using ‘Thickness Design for Settlement Spreadsheet’, provided $R_{min lokal}$ is not too low |
Table A5: Criteria and limits for Type 1 pavement type with CRCP base.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Radius of Curvature: ( R_{\text{min}} ): To ensure there is:</td>
<td>for concave and convex shapes:</td>
</tr>
<tr>
<td>• adequate rideability (longitudinal direction)</td>
<td>( R_{\text{min(local)}} ) for slow rate of settlement and for light traffic = 850 m (all directions)</td>
</tr>
<tr>
<td>• adequate contact of the pavement with the subgrade (all directions)</td>
<td>( R_{\text{min(local)}} ) for fast rate of settlement and for light traffic = 2500 m (all directions)</td>
</tr>
<tr>
<td>• a certain degree of toughness (all directions)</td>
<td>(For traffic less than 10^6 DESA over the design life of the pavement.)</td>
</tr>
<tr>
<td></td>
<td>(The 'Thickness Design for Settlement Spreadsheet' will determine whether a higher value of ( R_{\text{min(local)}} ) is</td>
</tr>
<tr>
<td></td>
<td>needed for higher traffic volumes.)</td>
</tr>
<tr>
<td>Base Concrete: Maximum Allowable Length of Compression Zone (T) To Avoid Buckling of Base</td>
<td>Requires Special Analysis</td>
</tr>
<tr>
<td>Base Concrete: Maximum Allowable Length of Tension Zone (T/2) To Avoid Excessive Cracking or Premature Fatigue Cracking of CRCP Base</td>
<td>Refer to Table C.4 for</td>
</tr>
<tr>
<td></td>
<td>a. ( T/2 ) for ( f'_c \leq 50 \text{ MPa} )</td>
</tr>
<tr>
<td></td>
<td>b. ( T/2 ) for ( f'_c &gt; 50 \text{ MPa} )</td>
</tr>
<tr>
<td></td>
<td>Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), excessive cracking and/or premature fatigue cracking of the concrete base is not expected.</td>
</tr>
<tr>
<td>Subbase Concrete: Maximum Allowable Length of Compression Zone (T) To Avoid Compression Failure and/or Buckling of Subbase</td>
<td>Requires Special Analysis</td>
</tr>
<tr>
<td>Maximum Horizontal Movement of the Upper Subgrade</td>
<td>Longitudinal Direction: 100 mm</td>
</tr>
<tr>
<td></td>
<td>Transverse Direction:</td>
</tr>
<tr>
<td></td>
<td>Summer Cast Concrete: maximum ( D_H = 1.7 \times L_H^2 / \left( W_H \times \pi^2 \right) ) mm</td>
</tr>
</tbody>
</table>
### Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Cast Concrete: maximum $D_{H} = 0.9 \times L_{H} / \left( W_{H} \times \pi^{2} \right)$ mm</td>
<td></td>
</tr>
<tr>
<td>Maximum Relative Horizontal Movement between Concrete Base and Concrete Subbase</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>
| Maximum Transverse Crack Opening in Base Concrete, in middle region of settlement crest to prevent corrosion of longitudinal steel and inadequate level of shear transfer | Refer to Table C4                                                                        

Alternatively, for long shallow bowls (ie large $T/2$ with relatively low $D$, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is $0.6$ mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), the transverse crack opening is tolerable.

Minimum Amount of Longitudinal Steel, $p$, in Base Concrete in middle region of crest to prevent yielding of longitudinal steel

Note: There is an upper limit of $p$ to avoid poor compaction of the base concrete. This is particularly so for thicker bases as the amount of longitudinal steel goes up linearly with the base thickness for the same value of $p$.

$$p > \frac{(T/2) m_{CRC\ Base–Interlayer}}{0.36 \times f_{cy}}$$

Alternatively, for long shallow bowls (ie large $T/2$ with relatively low $D$, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is $0.6$ mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), excessive yielding of the longitudinal steel is not expected.

Minimum $B_{ft}$ and $B_{st}$

$B_{ft}$ and $B_{st}$ determined using ‘Thickness Design for Settlement Spreadsheet’, provided $R_{min(local)}$ is not too low.
Table A6: Criteria and limits for Type 2 pavement type with CRCP subbase (refer to Table 1 for details).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Radius of Curvature: $R_{\text{min}}$:</td>
<td>For concave and convex shapes:</td>
</tr>
<tr>
<td>To ensure there is:</td>
<td>$R_{\text{min(local)}}$ for slow rate of settlement and for light traffic = 850 m (all directions)</td>
</tr>
<tr>
<td>• adequate rideability (longitudinal direction)</td>
<td>$R_{\text{min(local)}}$ for fast rate of settlement and for light traffic = 2500 m (all directions)</td>
</tr>
<tr>
<td>• adequate contact of the pavement with the subgrade (all directions)</td>
<td>(For traffic less than $10^6$ DESA over the design life of the pavement.)</td>
</tr>
<tr>
<td>• a certain degree of toughness (all directions)</td>
<td>(The ‘Thickness Design for Settlement Spreadsheet’ will determine whether a higher value of $R_{\text{min(local)}}$ is needed for higher traffic volumes)</td>
</tr>
<tr>
<td>CRCP Subbase:</td>
<td>Requires Special Analysis</td>
</tr>
<tr>
<td>Maximum Allowable Length of Compression Zone (T) To Avoid Buckling of</td>
<td></td>
</tr>
<tr>
<td>CRCP Subbase</td>
<td></td>
</tr>
<tr>
<td>CRCP Subbase Concrete:</td>
<td>Refer to Appendix C.3, making increase for tensile stresses from friction in the CRCP Subbase due to extra weight of the AC layer.</td>
</tr>
<tr>
<td>Maximum Allowable Length of Tension Zone (T/2) to Avoid Excessive</td>
<td>A conservative solution is to use:</td>
</tr>
<tr>
<td>Cracking or Premature Fatigue Cracking of CRCP Subbase</td>
<td>(the tolerable values for CRCP base in Table C4) x [minimum thickness of CRC/(mean thickness of AC + mean thickness of CRC)</td>
</tr>
<tr>
<td></td>
<td>Note: This is conservative as it assumes tensile stresses in the settlement crest at the top of CRCP Subbase from both friction and bending from settlement are both increased by the extra weight of the AC, when basically the extra weight of the AC only causes an increase in the tensile stress from friction from settlement in the CRCP Subbase. In fact the extra weight of the AC can be beneficial in ensuring better contact of the CRCP Subbase with its supporting layer. This meaning the constant stresses (from bending due to settlement from self-weight) are higher and so live stresses from traffic are reduced, which is beneficial for fatigue resistance. Also, the AC Base provides more insulation of the CRCP Subbase reducing tensile stresses from cold weather. Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), excessive cracking and/or premature fatigue cracking of the CRCP subbase is not expected.a</td>
</tr>
</tbody>
</table>

Note: This is conservative as it assumes tensile stresses in the settlement crest at the top of CRCP Subbase from both friction and bending from settlement are both increased by the extra weight of the AC, when basically the extra weight of the AC only causes an increase in the tensile stress from friction from settlement in the CRCP Subbase. In fact the extra weight of the AC can be beneficial in ensuring better contact of the CRCP Subbase with its supporting layer. This meaning the constant stresses (from bending due to settlement from self-weight) are higher and so live stresses from traffic are reduced, which is beneficial for fatigue resistance. Also, the AC Base provides more insulation of the CRCP Subbase reducing tensile stresses from cold weather. Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), excessive cracking and/or premature fatigue cracking of the CRCP subbase is not expected.
### Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
</table>
| **Maximum Horizontal Movement of the Upper Subgrade**                  | **Longitudinal Direction:** 150° mm  
**Transverse Direction:**  
Summer Cast Concrete: maximum \( D_H = 1.7 \times L_H^2 / \left( W_H \times \pi^2 \right) \) mm  
Winter Cast Concrete: maximum \( D_H = 0.9 \times L_H^2 / \left( W_H \times \pi^2 \right) \) mm   |
| **Maximum Relative Horizontal Movement between Concrete Base and Concrete Subbase** | Not Applicable                                                                                                                                  |
| **Maximum Transverse Crack Opening in CRCP Subbase, in middle region of settlement crest to prevent corrosion of longitudinal steel and inadequate level of shear transfer** | Refer to Table C4, and use the same procedure for CRCP subbase as used for CRCP base, but for the shortening of the compression zone due to friction from settlement on one side of settlement trough, use Shortening:  
\[
Q = 2.94 \mu_{CRC \text{subbase-erosion resistant lower subbase layer}} \times T^2 \times \left( t_{mb} + t_{msb} \right) \times \left( E_{mCRC \text{Subbase}} / CR_{sb} \right) \times t_{msb}
\]  
Where:  
- \( t_{mb} \) = mean thickness of AC  
- \( t_{msb} \) = mean thickness of CRCP subbase  
Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6 mm/m (unless a higher limit can be shown to be permissible by a finite element analysis), the transverse crack opening is tolerable.  
| **Minimum Amount of Longitudinal Steel, "p", in CRCP Subbase in middle region of settlement crest to prevent yielding of longitudinal steel** | \[
p > \frac{\left( T/2 \right) \times \mu_{CRC \text{subbase-erosion resistant lower subbase layer}} \times \left( \text{mean thickness of AC Base} + \text{mean thickness of CRC Subbase} \right)}{0.36 \times f_{yc} \times \left( \text{mean thickness of CRC Subbase} \right)}
\]  
Assuming thickness of CRCP subbase used for calculating the value of "p" is the mean thickness of CRCP subbase.  
Alternatively, for long shallow bowls (ie large T/2 with relatively low D, such as caused by large scale underground mining of coal where sufficient coal is left in place to create a shallow bowl), provided the maximum horizontal tensile strain of the upper subgrade in the longitudinal direction is 0.6mm/m (unless a
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>the CRCP subbase thickness for the same value of &quot;p&quot;.</td>
<td>higher limit can be shown to be permissible by a finite element analysis, excessive yielding of the longitudinal steel is not expected.</td>
</tr>
<tr>
<td>Minimum $B_{fs}$ and $B_{st}$</td>
<td>$B_{fs}$ and $B_{st}$ determined using 'Thickness Design for Settlement Spreadsheet', provided $R_{min(local)}$ is not too low</td>
</tr>
</tbody>
</table>
Appendix B  Coefficient of friction between pavement layers and subgrade

A number of the limiting values (for the design criteria associated with settlement) depend on the coefficient of friction between layers.

A range of values for the coefficient of friction for various pavement configurations is given in Table B1.

The values in Table B1 are a guide only, and actual values can vary quite markedly from those in the table due to such factors as the variability in surface texture and the effectiveness of the debonding treatments in filling any voids of the surface of the layer underneath.

For materials that have both cohesion and an internal friction angle, it is important to note that there are two components of shear force:

- the cohesion component is related to contact surface area (and so it is independent of thickness of pavement)
- the frictional component is related to the ‘normal force’ x ‘coefficient of friction’ (and so is related to the total mass per unit area of the overlying pavement and the coefficient of friction between the bottom layer of the overlying pavement and the layer immediately underneath)
Table B1: Coefficient of friction between a concrete and layer immediately underneath.

<table>
<thead>
<tr>
<th>Layer beneath the concrete</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Grained Soil</td>
<td>1.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sand</td>
<td>0.8&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Aggregate</td>
<td>1.4&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Polyethylene sheeting</td>
<td>0.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Sprayed seal on granular subbase where seal aggregate is:

<table>
<thead>
<tr>
<th>Layer beneath the concrete</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>2.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>5mm</td>
<td>2.3&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

 Lean-mix concrete surface:

<table>
<thead>
<tr>
<th>Curing:</th>
<th>Debonding:</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wax</td>
<td>Wax</td>
<td>1.5&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>HCR</td>
<td>Wax</td>
<td>1.7&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>WHCR</td>
<td>Wax</td>
<td>1.7&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wax</td>
<td>BSS</td>
<td>1.2&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wax</td>
<td>BE</td>
<td>1.5&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>SBR</td>
<td>Wax</td>
<td>1.7&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

 Stabilised gravel or rolled lean concrete:

<table>
<thead>
<tr>
<th>Curing:</th>
<th>Debonding:</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE</td>
<td>BE</td>
<td>2.5&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>BE</td>
<td>BSS</td>
<td>2.5&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

 Asphalt surface:

<table>
<thead>
<tr>
<th>Curing:</th>
<th>Debonding:</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Applicable</td>
<td>BE</td>
<td>3.0&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Notes:

a. Supplement to the AASHTO Guide, Table 14 Mean Peak Friction Coefficient (AASHTO, 1998).
c. Refer to paper by Ayton and Haber (Ayton, 1997).
d. Some of the values are expected to be temperature dependent.
e. The intention of the debonding treatment is to substantially fill all surface voids in the base to moderate the coefficient of friction and to minimise loss of pavement mortar. Spray application rates need to be designed accordingly.
f. Terms in table are:
   Wax = wax emulsion    HCR = hydrocarbon resin    WHCR = water-borne hydrocarbon resin
   BSS = bituminous sprayed seal with cover aggregate (5 or 7 mm)    SBR = styrene butadiene resin
   (water-borne)    BE = bitumen emulsion with a sand surfacing
g. Also refer to RMS specification R82 (RMS, 2013b)
Appendix C Design of concrete pavements for settlement

C1 Critical limits

The critical limits for concrete bases over concrete subbases are summarised in Appendix A. Where the critical limits are near or beyond the allowable values, it may be appropriate to carry out a more rigorous approach using finite element modelling. The following sections of Appendix C assist designers with developing an analysis procedure.

C2 Effect of bowl shape

Some of the critical limits depend on the shape of the settlement bowl and are described as:

- Depth of differential settlement and $R_{\text{min}}$
- Maximum horizontal displacement and relative horizontal movement between two points for a cosine curve
- Maximum slope of a cosine curve
- Localised effects and the value of $R_{\text{min}}$
- Shape and location of critical stresses
- Effect of skew

C2.1 Depth of Differential Settlement and $R_{\text{min}}$

Settlement bowls can be modelled using various types of curves. For a particular type of curve, the depth of differential settlement for a particular wavelength (or chord length for a circle or catenary) is related to the minimum radius of curvature, $R_{\text{min}}$, as follows:

For a cosine curve (see Figure C1):

$$R_{\text{min}} = 2 \times T^2 \left/ \left( \pi^2 \times D \right) \right.$$

and

$$D = 2 \times T^2 \left/ \left( \pi^2 \times R_{\text{min}} \right) \right.$$

where:

- $T =$ half wavelength (m),
- $D =$ the maximum depth (m) of differential settlement (ie. the depth in the middle of the trough)
- $R_{\text{min}} =$ the middle of the trough/crest (m)
Noting, that the radius of curvature (m) at a point along a settlement profile (where $s = D/2 \left[ 1 - \cos \left( x \times \pi / T \right) \right]$) is related to $D$ and $T$ by the following formula:

$$R = -2 \times T^2 \left[ D \times \pi^2 \times \cos \left( x \times \pi / T \right) \right],$$

where $R$, $D$, and $T$ are all in metres, as

$$R = \frac{1}{\left( d^2 s/dx^2 \right)} \times \left[ 1 + \left( ds/dx \right)^2 \right]^{1/2} \times \left| d^2 s/dx^2 \right|,$$

and $(ds/dx)^2$ is very small,

$$R = \frac{1}{\left( d^2 s/dx^2 \right)}$$

Therefore in the middle of a trough where $x = T$,

$$R = -2 \times T^2 \left[ D \times \pi^2 \times \cos \left( T \times \pi / T \right) \right]$$

$$= -2 \times T^2 \left[ D \times \pi^2 \times \cos \left( \pi \right) \right]$$

$$= -2 \times T^2 \left[ D \times \pi^2 \right]$$

$$= 2 \times T^2 \left[ D \times \pi^2 \right]$$

(ignoring signs)

For a catenary and a circle, where the ratio of the depth of differential settlement ($D$) to $T$ is small:

$$R_{\text{min}} = T^2 / (2 \times D)$$

Where:

- $T$ = half chord length (m),
- $D$ = the maximum depth (m) of differential settlement (depth in the middle of the curve), and
- $R_{\text{min}}$ = the middle of the trough of a catenary, whereas for a circle it is a constant over the whole arc (m)

Figure C2 shows differential settlement that follows an arc of a circle or catenary in the transverse direction. The sketches show relative change from original profile to profile after settlement, where the original profile refers to profile just after paving of the concrete base. Crossfalls are not shown, as what is relevant is the change in shape caused by settlement.
C2.2 Maximum horizontal displacement and relative horizontal movement between two points for a cosine curve

For a settlement bowl assuming the strain is sinusoidal over the tension zone, means that maximum horizontal movement which occurs at the junction of tension and compression zones, (where horizontal strains are zero) which also happens to be in the vicinity of the points of contraflexure of the settlement bowl.

For a sinusoidal strain over the tension zone, and say this maximum tensile strain = $k$ mm/m, then Maximum horizontal movement is:

\[
\int \text{strain over the tension zone} = \int k \times \sin\left(2 \times x \times \frac{\pi}{T}\right) \quad \text{where } x = \text{horizontal distance along the pavement}
\]
\[
= \int k\left(T/(2 \times \pi)\right)\left[-\cos\left(2 \times x \times \frac{\pi}{T}\right)\right]
\]
\[
= \int k\left(T/(2 \times \pi)\right)\left[-\cos\left(2 \times x \times \frac{\pi}{T}\right)\right] \text{ over } x = 0 \text{ to } x = T/2
\]
\[
= \int k\left(T/(2 \times \pi)\right)\left[-1 - (-1)\right]
\]
\[ k \times T / \pi \]

For example:
- \( 2T = 800 \text{m}, \ T = 400 \text{m} \) and \( T/2 = 200 \text{m} \)
- Maximum tensile strain = \( k = 2 \text{mm/m} \)

The maximum horizontal movement, which occurs at \( x = T/2 = 200 \text{m} = k \times T / \pi \) is:
- \( 2 \times 400 \text{m} / \pi \text{ mm} \)
- 255 mm

The relative movement between two points on either side of the trough, where the strain is sinusoidal over the compression zone can be estimated using the following approach. However, this analysis is hypothetical as the tensile and compressive strain equations are not the same equation, as the compression zone is twice the length of the tension zone for the same maximum strain.

Using the same properties as above, with two points being 50 m apart (ie. each is 25 m from the trough), then the maximum horizontal movement between two points either side of the trough is:

\[
\int \text{strain around center of trough} \quad \int k \times \sin\left(\frac{x \times \pi}{(2 \times T)}\right) \quad \int k \left(\frac{2 \times T}{\pi}\right) \left\{-\cos\left(\frac{375 \times \pi}{800}\right)\left(180 / \pi\right)\right\} - \cos\left(\frac{425 \times \pi}{800}\right)\left(180 / \pi\right)\right\} \\
= 2\left(\frac{800}{\pi}\right)\left\{-\cos\left(84.375 \text{ deg}\right) - \cos\left(95.624 \text{ deg}\right)\right\} \\
= 2\left(\frac{800}{\pi}\right)\left(-0.09802 - 0.09802\right) \text{ mm} \\
= -99.8 \text{ mm},
\]

which in absolute terms is 100 mm in contraction between the two points. Note that the average strain x 50 m is approximately the maximum strain x 50 m given that the strain is approximately constant over 25 m each side of this trough, and the maximum strain x 50 m = 2 mm/m x 50 m =100 mm, which for the purpose of this procedure equivalent to 99.8 mm.

### C2.3 Maximum slope of a cosine curve

Sometimes the maximum slope for settlement has been specified to keep settlement within acceptable limits. However this is not considered appropriate to assess the structural integrity of concrete pavements.

While changes in slope may have implications for non-structural aspects such as drainage and crossfalls, they do not affect the performance of the pavement. In fact where slopes are high the curvature \( \left(1 / R\right) \) may be very mild, eg for a settlement bowl of a cosine shape, maximum slope is where there is no curvature! So that at best maximum slope is only an indicator that something may be unacceptable somewhere.

The maximum slope of a cosine curve = \( T / \pi \times R_{\text{min}} \), so that the maximum slope of a settlement bowl is not just a function of \( R_{\text{min}} \) (ie. the minimum radius of a trough) but also \( T \) (where \( T \) is half the bowl length), so adopting a nominated \( R_{\text{min}} \) for a project would imply for cosine shapes:
• longer settlement bowls can tolerate higher maximum slopes
• shorter settlement bowls need flatter maximum slopes

So even if maximum slope is an indicator, it is a meaningless guide if it is not linked to the bowl length.

Hence this Guide uses $R_{\text{min}}$ rather than maximum slope. So to be conservative:

- for a given $D$ to ensure $R_{\text{min}}$ is tolerable, using a $T$ at least longer than the actual value is required to calculate the maximum tolerable slope, as maximum slope = $(\text{the given } D)\pi/(2T)$. Using a larger $T$ with the given $D$ ensures the maximum slope is smaller so the actual $R_{\text{min}}$ will be at least greater than the tolerable value of $R_{\text{min}}$.

- for given tolerable $R_{\text{min}}$, using a $T$ at least less than the actual value is required to calculate the allowable maximum slope, as maximum slope = $T/\pi$ (given tolerable $R_{\text{min}}$). Using a smaller $T$ with the given tolerable $R_{\text{min}}$ ensures the maximum slope is smaller so the actual $R_{\text{min}}$ will be at least greater than the given tolerable value of $R_{\text{min}}$.

Figure C3 shows relationships between a settlement bowl following a cosine shape and radius of curvature and slope.

The background to the relationship between maximum slope and $R_{\text{min}}$ for a cosine curve where the maximum slope is at the point of contraflexure is:

$$s = D/2 \left[1 - \cos(x \times \pi/T)\right]$$

where $s$ = differential settlement along a settlement profile.

Note that $s$ is mathematically a negative value, i.e.,

$$s = -D/2 \left[1 - \cos(x \times \pi/T)\right] = D/2 \left[\cos(x \times \pi/T - 1)\right]$$

and therefore differential settlement $= |s| = D/2 \left[\cos(x \times \pi/T - 1)\right]$.

and slope $= \frac{ds}{dx} = \left(\frac{D}{2}\right) \times \frac{\pi}{T} \times \sin\left(x \times \frac{\pi}{T}\right)$.

The maximum slope is: $D \times \pi/(2 \times T)$, ignoring signs, and occurs at $x = T/2$ and $3 \times T/2$ (the points of contraflexure). It is noted that the maximum slope, $D \times \pi/(2 \times T)$, is proportional to $D/T$. Hence, if the maximum slope is used for monitoring purposes for a given $D$, this requires a conservative $T$ to be used to determine allowable maximum slope. That is, a larger $T$ than the actual value is needed to calculate the maximum slope to ensure $R_{\text{min}}$ is tolerable. In addition, the average slope for one half of a cosine curve = $D/T$, and so the maximum slope = is $\left(\frac{T}{2}\right)$ x the average slope.

The maximum slope can be expressed in terms of $R_{\text{min}}$ and $T$ as follows:

$$= D \times \pi/(2 \times T), \text{ where } D = 2 \times T^2 \left(\pi^2 \times R_{\text{min}}\right)$$

and hence the maximum slope in terms of $R_{\text{min}}$ and $T$

$$= \left[2 \times T^2 \left(\pi^2 \times R_{\text{min}}\right)\right] \times \pi/(2 \times T)$$

$$= T/(\pi \times R_{\text{min}})$$
Figure C3: Differential settlement that follows a cosine curve: differential settlement (A), radius of curvature (B) and slope of a settlement bowl (C). (Sketch not to scale).
Therefore, for a given allowable $R_{\text{min}}$, the maximum allowable slope is proportional to $T$ (with $D$ changing in accordance with the given allowable $R_{\text{min}}$ and selected $\gamma$). Therefore, longer settlement bowls (and so greater $T$) can have larger maximum slopes for a given allowable $R_{\text{min}}$, or on the other hand, shorter bowls (and so smaller $T$) require lower maximum slopes for a given allowable $R_{\text{min}}$.

For example, if $T$ is halved, the maximum allowable slope is also halved, for a given allowable $R_{\text{min}}$.

Therefore, if maximum slope is to be used for monitoring purposes for a given tolerable $R_{\text{min}}$, this requires a conservative $T$ to be used to determine the allowable maximum slope, (a smaller $T$ than the actual value) is needed to calculate the maximum slope to ensure $R_{\text{min}}$ is not less than the tolerable $R_{\text{min}}$.

It is also important to consider local areas of a settlement bowl, ie. smaller bowls within the larger overall settlement bowl, noting shorter bowls require smaller maximum slopes to keep $R_{\text{min}}$ within a tolerable value. In other words, the maximum slope should reflect the localised bowl dimensions.

Now, the allowable maximum slope is also related to the time relative to the commencement of settlement, because as settlement progresses with time so also will the slope increase. Therefore the smaller the time interval from start of settlement, the lower is the allowable maximum slope.

For example where there is a small localised bowl, where $R_{\text{min(local)}}$ after long term settlement $= 1600$ m, and for the localised bowl, $2T' = 50$ m, ie. $T' = 25$ m, then

\[
D' = 2 \times T'^2 \left/ \left( \pi^2 R_{\text{min(local)}} \right) \right.
\]

\[
= 2 \times 25^2 \left/ \left( \pi^2 1600 \right) \right.
\]

\[
= 0.0791 \text{ m} \ (\approx 80 \text{ mm})
\]

This results in the maximum slope, after long-term settlement:

\[
= D' \pi / 2T' \text{ or } T' / (\pi R_{\text{min}})
\]

\[
= 0.00497
\]

\[
= 0.5 \% \text{ after long-term settlement, for } R_{\text{min(local)}} \text{ after long-term settlement of 1600 m.}
\]

Therefore, the maximum slope over the shorter term will need to be much less than 0.5 % so that $R_{\text{min}}$ is mild when stress relaxation is minimal. The actual value is related to the rate of settlement.

C2.4 Localised effects and the value of $R_{\text{min}}$

Even where settlement approximates a smooth curve, there can be local areas where the minimum radius of curvature can be much lower (refer to Figure C4). Therefore a reduction of the minimum radius of curvature from that of a smooth curve by an appropriate factor may be necessary.

As a very general guide, a factor of 0.5 is considered appropriate for $R_{\text{min(local)}} / R_{\text{min(overall)}}$, that is $R_{\text{min(overall)}} = 2 \times R_{\text{min(local)}}$.
For example, if the expected minimum radius of curvature to allow for localised effects is 1500 m, and adopting a factor of 0.5 for \( \frac{R_{\text{min(overall)}}}{R_{\text{min(local)}}} \), ie. \( R_{\text{min(overall)}} = 2 \times R_{\text{min(local)}} \), means \( R_{\text{min(overall)}} = 2 \times 1500 \text{ m} = 3000 \text{ m} \).

Each situation needs to be assessed. Some situations may require that greater allowance be made for localised effects.

- \[ R_{\text{min(overall)}} = 2 \times R_{\text{min(local)}} = 3000 \text{ m} \]

**C2.5 Shape and location of critical stresses**

The shape of the curve in the longitudinal direction is a general guide to the location and lengths of axial compression and axial tension. Whereas, it is the actual minimum radius of curvature that is critical for determining thickness (rather than the type of curve).

The shape of a settlement profile varies somewhat with the direction of the settlement, ie. whether it is longitudinal, transverse or skew. However, in all cases settlement shapes can be categorised into sections of convex and concave shape as shown in Figure C5.

- **Convex Shape**
- **Concave Shape**

**Figure C5: Convex and concave settlement**

In general, a cosine curve is often more appropriate to model settlement in the longitudinal direction, while a circular profile may be more appropriate for the transverse direction.

Longitudinal profiles have areas of convex settlement (at crests) and concave settlement (in...
troughs), whereas transverse cross sections may only have a convex or a concave shape, eg edge slumping of an embankment causes a convex shape, whereas subgrade compression may cause a concave shape. Note that in the case of subgrade compression, the use of flatter batters and/or berms may reduce differential settlement in the transverse direction.

In this Guide some of the particular limits were derived assuming that settlement, in the longitudinal direction, follows a cosine curve so that for settlement bowl of length $2T$, the compressive zone = $T$ and each tensile zone on either side of the compression zone = $T/2$. Therefore, for profiles different to those of a cosine curve, some of the critical limits will change.

It also needs to be noted that where there is a significant amount of settlement of a uniform nature in the middle of the settlement profile, the minimum radius of curvature may be much lower than if the settlement profile was a more like a cosine curve. Therefore, where there are sections of uniform settlement, the situation will be more critical than indicated by a cosine model and special care in design will be needed (see Figure C6.). In Figure C6 the cosine curve for the same maximum differential settlement is shown for comparison.

![Diagram of Settlement Bowl](image)

**Figure C6:** Settlement bowl with a section of uniform settlement, showing typical location of minimum radius of curvature of trough.

### C2.6 Effect of skew

Where settlement is on a skew (such as can occur with settlement over old river beds and with underground mining) then it is conservative for design to assume $R_{\text{min}}$ in the direction of skew is also the value of $R_{\text{min}}$ for both the longitudinal and transverse directions.

### C3 Minimum radius of curvature

Applicable to longitudinal, transverse and skew directions, for PCP, PCP-R, PCP-D, JRCP and CRCP.

The minimum radius of curvature is applicable to the longitudinal, transverse and skew directions, for all types of concrete pavement. A limit is placed on the radius of curvature to:

- Ensure adequate rideability
- Ensure adequate contact between the pavement and the subgrade (noting, that the
type of concrete base, the thickness of this base, and the stiffness of the subbase affect contact). Also refer to Appendix B of this Guide.

The tolerable radius of curvature for contact is also affected by the rate of settlement as this affects the modulus of elasticity of the concrete. The slower the rate of settlement the lower the radius of curvature that can be tolerable.

- Provide a certain minimum degree of toughness, so there is capacity for stresses other than those from bending due to settlement, and normal traffic loads, so that there is spare capacity for stresses from heavy loads in conjunction with stresses due to positive temperature differentials between top and bottom of the slab. (Note: where the minimum radius of curvature is satisfied, it is still necessary to determine appropriate values of $B_{f,s}$ and $B_{st}$, due to the extra stresses caused by settlement, see Appendix C5). The tolerable radius of curvature is also affected by the rate of settlement as this affects the amount of bending stress from settlement from self-weight of the concrete due to the influence of stress relaxation

- Prevent corner breaking in PCP and PCP-R.

Rideability only applies to the longitudinal direction, while the need to maintain adequate contact and a certain magnitude of toughness applies to longitudinal, transverse and skew directions.

A minimum value of $R = 850$ m, for PCP-D, JRCP (with short slabs) and CRCP is considered to be applicable to all directions to satisfy all three aspects, where the rates of settlement are slow and traffic is light. This is considered to apply to convex and concave shapes (though more work is needed on convex shapes in terms of contact and toughness requirements). However, all pavements are considered to need reinforcement for $R < 1700$ m, which then puts PCP-D into the category of JRCP unless $R \geq 1700$ m, whereas for PCP and PCP-R, an $R_{min}$ of 1700 m, for slow rate of settlement, is considered appropriate for concave settlement (longitudinal and transverse), but not for convex settlement (longitudinal and transverse) due to high corner and diagonal stresses (refer to AASHTO Guide 1998). With convex settlement, it is considered that $R_{min}$ will need to be 10,000 m for fast rates of settlement, and 5000 m for slow rates of settlement.

Where the rate of settlement is rapid, a higher minimum radius of curvature may be needed to ensure a satisfactory degree of toughness.

The ‘Thickness Design for Settlement Spreadsheet’, which is used for determining $B_{f,s}$ and $B_{st}$, using an appropriate change of settlement which is in proportion to $1/R_{min}$ with time, can be used to determine the minimum radius of curvature, $R_{min}$, at the end of the design life that is tolerable for higher traffic volumes.

For minor roads, and/or small lengths of settlement, where the rate of settlement is gradual, the limit of 850 m for JRCP and CRCP, and 1700 m for PCP-D may be able to be relaxed provided other criteria are met. Also, refer to the discussion in Appendix B and Appendix C5.

Delaying the construction of a pavement so that the minimum value for $R$, that the pavement will undergo, is not excessive may prevent or significantly delay the need for either an asphaltic concrete overlay to restore riding quality, or reconstruction.

Table C1 shows the maximum allowable depths of differential settlement for slow rate of settlement and light traffic for PCP-D, JRCP and CRCP for various lengths of settlement.
bowl for cosine curves, catenaries and circles, to satisfy a minimum \( R = 850 \) m. Also included, in brackets, are the maximum allowable depths of differential settlement where local effects cause the minimum radius of curvature to be half of that for a smooth settlement curve.

PCP and PCP-R have much stricter requirements for light traffic than those in Table C1. For higher traffic volumes the ‘Thickness Design for Settlement Spreadsheet’ shows whether an increase in \( B_{j} \) and/or \( B_{s} \) is needed to ensure adequate life under traffic and curvature. In some situations increasing base thickness may be required. However, it may not be possible or feasible to meet curvature criteria even with an increase in base thickness. A slow rate of settlement is where the depth of differential settlement after 3 years since paving is no more than half the settlement after 40 years since paving.

### Table C1: Maximum allowable depth of differential settlement (D) for PCP-D, JRCP and CRCP, for slow rate of settlement and light traffic (minimum radius of curvature of 850 m).

<table>
<thead>
<tr>
<th>Length of settlement bowl 2T (longitudinal, transverse or skew)</th>
<th>Maximum allowable depth of differential settlement after paving at the end of the design period: (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>For cosine curve</td>
</tr>
<tr>
<td>5 m</td>
<td>1.5 mm (0.7 mm)</td>
</tr>
<tr>
<td>10 m</td>
<td>6.0 mm (3.0 mm)</td>
</tr>
<tr>
<td>15 m</td>
<td>13.4 mm (6.7 mm)</td>
</tr>
<tr>
<td>20 m</td>
<td>23.8 mm (11.9 mm)</td>
</tr>
<tr>
<td>25 m</td>
<td>37.2 mm (18.6 mm)</td>
</tr>
<tr>
<td>50 m</td>
<td>149 mm (74.4 mm)</td>
</tr>
<tr>
<td>100 m</td>
<td>596 mm (298 mm)</td>
</tr>
<tr>
<td>100 m</td>
<td>&gt; 2000 mm (1100 mm)</td>
</tr>
<tr>
<td>200 m</td>
<td>&gt; 2000 mm (&gt; 2000 mm)</td>
</tr>
<tr>
<td>400 m</td>
<td>&gt; 2000 mm (&gt; 2000 mm)</td>
</tr>
</tbody>
</table>

Notes: The values not in brackets assumes a smooth bowl shape, whereas the values in brackets are for when local effects are such that the minimum radius of curvature is half that of a smooth curve.

In Table C1, D for the given T needs to be reduced by the same factor by which \( R_{\text{min(local)}} \) has been reduced from \( R_{\text{min(overall)}} \), as \( R_{\text{min}} \) is proportional to D for a given T. Alternatively, if D is not reduced, then the minimum allowable T needs to be increased by \( \left( R_{\text{min(overall)}} / R_{\text{min(local)}} \right)^{0.5} \), for designs based on \( R_{\text{min(local)}} \).

For a cosine curve \( D = 2T^2 / \left( \pi^2 R_{\text{min}} \right) \) and \( T = \pi \left( R_{\text{min}} D/2 \right)^{0.5} \) Therefore, allowing for local effects, where \( R_{\text{min}} \) (local) can be reduced by a factor of 2 from \( R_{\text{min}} \) (overall), making \( R_{\text{min(overall)}} = 2R_{\text{min(local)}} \). This indicates that
For a catenary and a circle, where the ratio of D to T is small: 

\[ D = \frac{T^2}{(2R_{\text{min}})} \]

where \( T \) = half chord length, and \( D, T \) and \( R_{\text{min}} \) are in metres. Therefore, allowing for local effects, where \( R_{\text{min}} \) (local) can be reduced by a factor of 2 from \( R_{\text{min}} \) (overall), gives:

\[ T = \left(4R_{\text{min(overall)}} \right)^{0.5} = 2\left( R_{\text{min(local)}} \right)^{0.5}, \text{ and } 2T = 4\left( R_{\text{min(local)}} \right)^{0.5} \]

2\( T = 4\left( R_{\text{min(local)}} \right)^{0.5} \), and if the length of the settlement bowl is increased by \( (2)^{0.5} = 1.414 \), that is it needs to be 1.414 \( \text{ longer than for a smooth catenary or circle for the same } D \), to allow for localised settlement effects.

Table C1 indicates:

- How concrete pavements are sensitive to small amounts of differential settlement over small lengths (ie short bowls, ie small values of 2\( T \)).
- That where there are likely to be localised areas of settlement with radius of curvature of lower than for a smooth curve, the maximum allowable depth of differential settlement will need to be reduced by the appropriate amount.

Where localised factors mean that the minimum radius of curvature will be half that of a smooth cosine curve, and where the overall settlement shape is a cosine curve, then \( R_{\text{min}} \) for localised effects \( R_{\text{min(local)}} = 0.5 \left( R_{\text{min(overall)}} \right) = 0.5 \times 2T / \left( \pi^2 D \right) = T / \left( \pi^2 D \right) \), where \( T \text{ and } D \) are for the overall settlement bowl.

### C4 Maximum length of tension zone of CRCP

This section covers the maximum length of the tension zone of CRCP to prevent excessive cracking and premature fatigue cracking of the CRCP base from friction due to settlement. This approach is to be applied to the crest regions of settlement bowls and applicable only to tension zones in the longitudinal direction. The critical pavement temperature is cold.

The following sub-sections cover the following stages towards the analysis of the potential cracking:

- Axial tensile stresses in CRCP from friction.
- Upper limit of axial tensile stress in concrete in CRCP from friction.
- Maximum allowable length of tension zone (\( T/2 \)) to prevent rupture of concrete in CRCP.
- Thick asphalt over CRCP subbase.

#### C4.1 Axial tensile stresses in CRCP from friction

The axial stress from friction due to settlement is generated externally on the concrete, which is different to stresses from temperature and shrinkage (which are internally generated). Therefore, while the tensile stresses in the concrete from shrinkage and temperature can be reduced in concrete by extra cracking, tensile stresses in the concrete caused by friction from settlement cannot be so relieved.
This means that CRCP can have significant internal tensile stresses from friction due to settlement in the tensile zone (i.e., crests) due to the long length of longitudinal steel which ties all the CRCP base slabs together. PCP, PCP-D or JRCP, due to their short length slabs, do not develop significant internal tensile stress from friction from settlement. Similarly subbase concrete will not have significant internal tensile stress from friction from settlement in tensile zones unless it is continuously reinforced.

Since tensile stresses within the CRCP concrete due to friction from settlement cannot be relaxed by extra cracking, such stresses must be kept below a reasonable upper limit to ensure adequate fatigue life of the concrete under traffic loading is maintained. The previous section discusses longitudinal steel requirements for CRCP bases to prevent yielding of the longitudinal steel in the crests.

C4.2 Upper limit of axial tensile stress in concrete in CRCP from friction

It is considered that the maximum allowable tensile stress from friction from settlement in the CRCP base $\sigma_{\text{matf}}$ is dependent on $f'_c$.

Different allowable values for $\sigma_{\text{matf}}$ are required for the top and bottom of CRCP base. This is because tensile stresses in CRCP base vary from the top to bottom of the base due to the effects of traffic loading, bending from settlement and temperature differentials between the top and bottom of the CRCP base.

The smaller of the value for $\sigma_{\text{matf}}$ for the top and bottom of the base needs to be satisfied for:

- $f'_c \leq 50$ MPa:
  
  \[
  \begin{align*}
  \text{at top of base: } & \sigma_{\text{matf, top}} = \left[0.30 \times MR_b - (0.60 \times \sigma_{\text{mbss, ps}})\times 1/1.2\right] \\
  \text{bottom of base: } & \sigma_{\text{matf, btm}} = \left[0.15 \times MR_b + (0.60 \times \sigma_{\text{mbss, ps}})\times 1/1.2\right]
  \end{align*}
  \]

- $f'_c > 50$ MPa:
  
  \[
  \begin{align*}
  \text{at top of base: } & \sigma_{\text{matf, top}} = \left[0.36 \times MR_b - (0.60 \times \sigma_{\text{mbss, ps}})\times 1/1.2\right] \\
  \text{bottom of base: } & \sigma_{\text{matf, btm}} = \left[0.21 \times MR_b + (0.60 \times \sigma_{\text{mbss, ps}})\times 1/1.2\right]
  \end{align*}
  \]

This shows that the magnitude of $\sigma_{\text{mbss, dl}}$ determines whether the top or bottom of the CRCP base is critical, where $\sigma_{\text{mbss, dl}}$ is at the critical time for tensile stresses from bending and friction from settlement.

While creep has only a small affect on the amount of tensile stress in concrete in CRCP from friction from settlement, stress relaxation has a very significant effect on reducing bending stresses in the concrete from settlement where the rate of settlement is slow. This has a positive benefit for the top of the base (as stress relaxation reduces tensile stresses from bending from settlement), resulting in longer tension zones. Alternatively, stress relaxation has a negative benefit for the bottom of the base, as this causes the compressive stresses from bending from settlement to be lower, resulting in shorter tension zones.
The effect of creep on the distribution of force from friction due to settlement, between longitudinal steel and concrete, can be ignored, as creep is found to only slightly reduce the force carried by the concrete in the central area of an individual slab.

The effect of stress relaxation on bending stresses from settlement is determined by the ‘Thickness Design for Settlement Spreadsheet’.

C4.3 Maximum allowable length of tension zone (T/2) to prevent rupture of concrete in CRCP

The maximum allowable length (m) of tension zone (T/2) to prevent rupture of the concrete in CRCP is as follows:

\[
<85 \times \sigma_{allow\ text\ stress\ in\ concrete\ from\ friction} \times \left[ 1 + \left( \frac{E_s}{E_b} \times \left( \frac{P}{100} \right) \right) \right] / \mu_{b-ab}
\]

where \( \sigma_{max} \) is the smaller value of the top and bottom of the base

Stresses from friction are additive to stresses from shrinkage, temperature, bending from settlement and traffic, noting that while stresses from temperature and shrinkage are reduced by extra cracking, they can still be significant. Therefore, variations in \( MR_b \) and \( t_b \) can affect the allowable length of tension zones of CRCP to prevent excessive cracking of the CRCP base.

The effect of variations in \( MR_b \) and/or \( t_b \) depends on whether the critical stress is on the top or bottom of the base concrete. Therefore, the impact of variations in \( MR_b \) and \( t_b \), on the maximum allowable length of tension zone (T/2), is affected by the type of settlement. Table C2 shows some of the basic differences between the two basic types of settlement (ie underground mining and volume changes in the subgrade).

Table C3 gives the maximum allowable lengths of tension zone of CRCP base for \( f_c \leq 50 \text{ MPa} \) (Table C3) and for \( f_c > 50 \text{ MPa} \) (Table C4).

In crests, substantial increases in \( MR_b \) are expected to have substantial benefits for critical tensile stresses from friction, whether they are in the top or bottom of a slab. With the improvement being more pronounced where the critical stress is at the top of a slab. However, increases in \( t_b \) may need to be kept small where tensile stresses are critical at the top of the base. Also, refer to Tables C2 to C4.

In summary:

i) For settlement due to underground mining where the critical stress can be at the top or bottom of the CRCP base (it is at the top where \( R_{min} \) is low to medium, and at the bottom for high \( R_{min} \)):
   - Increasing \( MR_b \) will increase the allowable length of a tension zone of CRCP concrete irrespective of whether the critical stress is at the top or bottom of the base concrete.
   - Increasing \( t_b \) by a small amount will cause a slight decrease in the allowable length of a tension zone where the critical tensile stress is at the top of the base (where \( R_{min} \) is low to medium), and a slight increase in the allowable length of a tension zone where the critical tensile stress is at the bottom of the base where \( R_{min} \) is high.
Table C2: Effect of friction due to settlement in the tension zone (ie crests) of CRCP for the two basic types of settlement.

<table>
<thead>
<tr>
<th>Type of settlement</th>
<th>Volume change in subgrade (where $R_{min}$ from bending from settlement is low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical location of critical tensile stress</td>
<td>Top or bottom of CRCP base (At top of the base for low to medium $R_{min}$; at bottom of the base for high $R_{min}$)</td>
</tr>
<tr>
<td>Underground mining</td>
<td>Top of CRCP base</td>
</tr>
<tr>
<td>Increase(^b) in $MR_b$</td>
<td>Significant increase in the allowable length of tension zone</td>
</tr>
<tr>
<td>Small increase(^b) in $t_b$</td>
<td>Slight decrease in the allowable length of tension zone for low-medium $R_{min}$ from bending from settlement (where critical stress is at the top of the base concrete) Slight increase in the allowable length of tension zone for high $R_{min}$ from bending from settlement (where critical stress is at the bottom of the base concrete)</td>
</tr>
<tr>
<td>Creep</td>
<td>Slight increase in the allowable length of tension zone</td>
</tr>
<tr>
<td>Slower rate of settlement</td>
<td>In general, not applicable to underground mining Large increase in allowable length of settlement bowl (as it reduces bending stresses from settlement)</td>
</tr>
</tbody>
</table>

Notes:

a. The descriptions in the table are only broad generalisations to show differences between the two basic types of settlement and therefore, this table does not replace the need for a full evaluation.

b. Increase in $t_b$ causes no change in tensile stress due to friction as the force from friction from settlement is proportional to the weight of the concrete base, which is proportional to thickness of the base, ie $t_b$, ie force ($F$) is proportional to $t_b$, but stress is proportional to $F/t_b$ so tensile stress is independent of $t_b$.

ii) For settlement due to volume change of the subgrade where bending stresses from settlement are high, (ie the $R_{min}$ is low where the critical stress is at top of the CRCP base):

- Increasing $MR_b$ will increase the maximum allowable length of a tension zone of CRCP in settlement.
- Increasing $t_b$ by a small amount will cause a slight reduction in the allowable length of tension zone.
Therefore, for all settlement types, CRCP can have longer lengths of tension zone (ie the crest region) without leading to excessive cracking and premature fatigue cracking with:

i) Higher $MR_b$ and/or higher $f'_c$. This means that where there is a delay in settlement, such as can occur with underground mining, and the cement of the base contains fly ash such that the tensile strength and $f'_c$ are high by the time that settlement commences, then longer lengths of tension zone are possible. This is because:

- The tensile force on the pavement from friction due to settlement is related to the density of the concrete and not the strength.
- Concrete with higher tensile strength (ie higher $f'_c$) can better resist rupturing of the concrete.
- Concrete with high $f'_c$ can tolerate closer spaced cracking which reduces tensile stress from shrinkage and cold temperature.

ii) Lower $\mu_{s-sb}$

iii) Lower $\mu_{s-sgl}$, noting that the tensile stress in the base from friction cannot exceed what it would be if there was full bonding between the base and subbase. Therefore $\mu_{b-s}$ cannot in effect be $> \mu_{s-sgl} \times (t_{mb} + t_{mub}) / B_c$. This takes into account the inability of the cracks in concrete subbase (which is unreinforced) to have any tensile capacity, by only using $B_c$ in the denominator as all tension is taken through the base cross section above cracks in the subbase.

iv) Lower $\mu_{s-sgl}$ may also be useful, noting that the tensile stress in the base from friction cannot exceed what it would be if there was full bonding between the base and subbase, and full bonding between the subbase and the select subgrade layer. Therefore $\mu_{b-s}$ cannot in effect be $> \mu_{s-sgl} \times (t_{mb} + t_{mub} + t_{mud}) / B_c$. This takes into account the inability of the cracks in concrete subbase (which is unreinforced) and the select subgrade layer to have any tensile capacity, by only using $B_c$ in the denominator.

When using Tables C3 and C4, take note of the following assumptions and notes:

i) While creep only has a small effect on the amount of tensile stress in concrete in CRCP from friction from settlement, stress relaxation has a very significant effect on reducing bending stresses in the concrete from settlement where the rate of settlement is slow. This has a positive benefit for the top of the base (as stress relaxation reduces tensile stresses from bending from settlement), resulting in longer tension zones. On the other hand, stress relaxation has a negative benefit for the bottom of the base, as this causes the compressive stresses from bending from settlement to be lower, resulting in shorter tension zones.

ii) T/2 has been rounded down to the nearest whole number in metres.

iii) Maximum allowable length of tension zone of CRCP,

$$T/2 = 85 \times \sigma_{mag} \times \left[1 + \left(\frac{E_s}{E_b}(p/100)\right)\right] / \mu_{s-sb}$$

iv) For bottom of base where in the early stages of settlement (say in the early years of settlement for concrete pavements over soft soils) where the frictional stresses may be significant but the offsetting compressive stresses from bending are low, it will be necessary to check that the length of a tension zone is not excessive. However, early on in settlement when bending stresses from settlement are low, there may not be sufficient horizontal movement to create significant tensile stresses from friction.

v) For a CRC base it is assumed that $E_b = 30,000$ or $36,000$ MPa, $E_s = 200,000$ MPa, $p = 0.67$, and $\mu_{s-sb} = 1.5$. 
vi) For these tables, \( MR_b \) is at the commencement of settlement, noting \( \sigma_{matf} \) is proportional to \( E_b \) and therefore \( MR_b \), assuming \( E_b \) and \( MR_b \) are both proportional to (compressive strength of concrete)\(^{0.5} \), which means \( \sigma \) maximum bending stress from settlement during the period of settlement is proportional to \( MR_b \) for a given \( t_b \), \( R \) and \( CR_b \) (assuming a simplified situation where stress relaxation can be modelled with a single value of \( CR_b \), and ignoring changes in \( CR_b \) with variations in \( f'_c \)). A more thorough analysis can be done using the 'Thickness Design for Settlement Spreadsheet' to assist in determining the critical time for stresses, and the equations:

for \( f'_c \leq 50 \) MPa:

\[
\sigma_{matf, top} = \left[ 0.30 \times MR_b - 0.60 \times \sigma_{mb, ps} \right] \times 1/1.2
\]

\[
\sigma_{matf, bm} = \left[ 0.15 \times MR_b + 0.60 \times \sigma_{mb, ps} \right] \times 1/1.2
\]

for \( f'_c > 50 \) MPa:

\[
\sigma_{matf, top} = \left[ 0.36 \times MR_b - 0.60 \times \sigma_{mb, ps} \right] \times 1/1.2
\]

\[
\sigma_{matf, bm} = \left[ 0.21 \times MR_b + 0.60 \times \sigma_{mb, ps} \right] \times 1/1.2
\]

where: \( T/2 = 85 \times \sigma_{matf} \times \left[ 1 + \left( E_s / E_b \right) \left( p / 100 \right) \right] / \mu_{s-b} \) and \( \mu_{s-b} \) cannot in effect be:

\[
> \mu_{s-bl} \times \left( t_{mb} + t_{msl} \right) / t_{bmcct}
\]

\[
> \mu_{s-bl} \times \left( t_{mb} + t_{msl} + t_{msl} \right) / t_{bmcct}
\]

Therefore a low \( \mu_{s-bl} \) and/or low \( \mu_{s-bl} \) can be advantageous.

vii) Where horizontal movements are only small compared to the length of settlement bowl, there may be a relaxation in the maximum allowable length of the tension zone of CRCP base.

viii) The thickness of the base (\( t_b \)) is a dependent variable in the table and so is not included as \( t_b \) is related to \( \sigma_{mb, ps} \).

ix) A more rigorous analysis using finite element analysis may show that the limits of Tables C3 and C4 can be relaxed.

Table C3 and C4 for CRCP base with \( f'_c \leq 50 \) MPa and with \( f'_c > 50 \) MPa respectively show the maximum allowable length of tensile zone (T/2) to prevent excessive cracking of the CRCP base (in the middle of the tension zone due to tensile stresses from friction due to settlement and cold temperature and shrinkage for a set of conditions. The maximum allowable tension zone, T/2, has been calculated for a pavement where \( E_a = 200,000 \) MPa, \( E_b = 30,000 \) MPa (for \( f'_c \leq 50 \) MPa), and \( E_b = 36,000 \) MPa (for \( f'_c > 50 \) MPa), \( p = 0.67 \) and \( \mu_{b-s} = 1.5 \) for variations in:

- \( \sigma_{mb, ps} \) in the CRCP base, and
- \( MR_b \)

Also, these tables highlight the sensitivity of \( T/2 \) to \( MR_b \) and the \( \sigma_{mb, ps} \) at the critical time for tensile stresses from bending and friction from settlement.

The 'Thickness Design for Settlement Spreadsheet' can be used to predict the \( \sigma_{mb, ps} \). However, early in the settlement phase for the bottom of base it will be necessary to check that the length of tension zone is not excessive where the offsetting compressive bending
stress from settlement is low, as Tables C3 and C4 indicate that there will be a relative low allowable length of tension zone (T/2) where frictional stresses are high, but where there is little relief from the compressive stresses from bending from settlement at the bottom of the base. An analysis of each year using the $\sigma_{mbss, ps}$ calculated using the ‘Thickness Design for Settlement Spreadsheet’ could be done so that the critical combination of friction and bending stresses during the life of the pavement can be analysed.

A more rigorous analysis using finite element analysis may show that the limits of Tables C3 and C4 can be relaxed early on in the early stages of settlement where bending stresses from settlement are low, as there may not be sufficient horizontal movement to create significant tensile stresses from friction due to settlement.

It is noted that Tables C3 and C4 indicates that the maximum allowable length of tension zone (T/2) occurs when both the top and bottom of the base are just critical, that is:

\[
\begin{align*}
T/2 & = \left[0.30 \times MR_b - (0.60 \times \sigma_{mbss, ps})\right] \times 1/1.2 \\
T/2 & = \left[0.15 \times MR_b + (0.60 \times \sigma_{mbss, ps})\right] \times 1/1.2
\end{align*}
\]

so that

\[0.15 \times MR_b = 1.20 \times \sigma_{mbss, ps}\]

and

\[\sigma_{mbss, ps} = 0.15 \times MR_b /1.20\]

\[= MR_b /8\]

Where the maximum horizontal tensile strain at the top of the subgrade is less than 0.6 mm/m then excessive cracking and premature fatigue cracking of CRCP in tension zones is not expected. This is a result because if the shrinkage and temperature strain is say 400 µm, which is 0.400 mm/m, assuming summer casting (the worst case scenario). The CRCP base then can be expected to have a maximum crack width from shrinkage and temperature strain in conjunction with the influence of upper subgrade tensile strain less than 0.5 mm for a crack spacing of 500 mm, as total strain per metre within the CRCP base = 0.6 + 0.4 mm/m = 1 mm/m, ie 0.5mm/500 mm. This is conservative as not all the horizontal movement of the upper subgrade will be transferred into the CRCP base and compression slabs may also limit the maximum transverse crack opening that is possible in tension zones.

This approach assumes the longitudinal steel in CRCP base at transverse cracks caused by settlement will extend, ie stretch, ‘releasing’ some of the tensile stresses in the concrete ‘slabs’, which is considered a reasonable approach for relative small horizontal movements.
Table C3: Maximum allowable length of tension zone of CRCP base for $f'_c \leq 50$ MPa

<table>
<thead>
<tr>
<th>$\sigma_{mbss, ps}$ (in the CRCP base) after taking into account stress relaxation of bending stresses from settlement</th>
<th>Top of base:</th>
<th>Bottom of base:</th>
<th>Location of Critical Tensile Stress and Amount of Maximum Allowable Tensile Stress in Concrete from Friction (ie $\sigma_{naff, bm}$; which is the lower of the allowable tensile stresses from friction at top and bottom of base)</th>
<th>Maximum allowable length of tension zone of CRCP base ($T/2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero (ie hypothetical)</td>
<td>$0.300MR_b x 1/1.2$</td>
<td>$0.150MR_b x 1/1.2$</td>
<td>Bottom of Base: $0.150MR_b x 1/1.2$</td>
<td>$25$ m $29$ m $33$ m $36$ m</td>
</tr>
<tr>
<td>$MR_b/20$</td>
<td>$0.270MR_b x 1/1.2$</td>
<td>$0.180MR_b x 1/1.2$</td>
<td>Bottom of Base: $0.180MR_b x 1/1.2$</td>
<td>$31$ m $35$ m $39$ m $44$ m</td>
</tr>
<tr>
<td>$MR_b/15$</td>
<td>$0.260MR_b x 1/1.2$</td>
<td>$0.190MR_b x 1/1.2$</td>
<td>Bottom of Base: $0.190MR_b x 1/1.2$</td>
<td>$32$ m $37$ m $42$ m $46$ m</td>
</tr>
<tr>
<td>$MR_b/10$</td>
<td>$0.240MR_b x 1/1.2$</td>
<td>$0.210MR_b x 1/1.2$</td>
<td>Bottom of Base: $0.210MR_b x 1/1.2$</td>
<td>$36$ m $41$ m $46$ m $51$ m</td>
</tr>
<tr>
<td>$MR_b/9$</td>
<td>$0.233MR_b x 1/1.2$</td>
<td>$0.217MR_b x 1/1.2$</td>
<td>Bottom of Base: $0.217MR_b x 1/1.2$</td>
<td>$37$ m $42$ m $48$ m $53$ m</td>
</tr>
</tbody>
</table>
### Table C3: Continued

<table>
<thead>
<tr>
<th>$MR_b/8$</th>
<th>$0.225MR_b \times \frac{1}{1.2}$</th>
<th>$0.225MR_b \times \frac{1}{1.2}$</th>
<th>Bottom/Top of Base: $0.225MR_b \times \frac{1}{1.2}$</th>
<th>38 m</th>
<th>44 m</th>
<th>49 m</th>
<th>55 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$MR_b/7$</td>
<td>$0.214MR_b \times \frac{1}{1.2}$</td>
<td>$0.236MR_b \times \frac{1}{1.2}$</td>
<td>Top of Base: $0.214MR_b \times \frac{1}{1.2}$</td>
<td>36 m</td>
<td>42 m</td>
<td>47 m</td>
<td>52 m</td>
</tr>
<tr>
<td>$MR_b/6$</td>
<td>$0.200MR_b \times \frac{1}{1.2}$</td>
<td>$0.250MR_b \times \frac{1}{1.2}$</td>
<td>Top of Base: $0.200MR_b \times \frac{1}{1.2}$</td>
<td>34 m</td>
<td>39 m</td>
<td>44 m</td>
<td>49 m</td>
</tr>
<tr>
<td>$MR_b/5$</td>
<td>$0.180MR_b \times \frac{1}{1.2}$</td>
<td>$0.270MR_b \times \frac{1}{1.2}$</td>
<td>Top of Base: $0.180MR_b \times \frac{1}{1.2}$</td>
<td>31 m</td>
<td>35 m</td>
<td>39 m</td>
<td>44 m</td>
</tr>
<tr>
<td>$MR_b/4$</td>
<td>$0.150MR_b \times \frac{1}{1.2}$</td>
<td>$0.300MR_b \times \frac{1}{1.2}$</td>
<td>Top of Base: $0.150MR_b \times \frac{1}{1.2}$</td>
<td>25 m</td>
<td>29 m</td>
<td>33 m</td>
<td>36 m</td>
</tr>
<tr>
<td>$MR_b/3$</td>
<td>$0.100MR_b \times \frac{1}{1.2}$</td>
<td>$0.350MR_b \times \frac{3}{4}$</td>
<td>Top of Base: $0.100MR_b \times \frac{1}{1.2}$</td>
<td>17 m</td>
<td>19 m</td>
<td>22 m</td>
<td>24 m</td>
</tr>
</tbody>
</table>
### Table C4: Maximum allowable length of tension zone of CRCP base for $f'_c > 50$ MPa

<table>
<thead>
<tr>
<th>Maximum bending stress from settlement during the period of settlement</th>
<th>Top of base: allowable tensile stress in concrete from friction at top of base</th>
<th>Bottom of base: $\sigma_{\text{mutf, btm}} = [0.21MR_b + 0.6\sigma_{\text{mbxs, ps}}] \times 1/1.2$ (At the critical time for tensile stresses from bending and friction from settlement, noting that for early stages of settlement the expected benefit from bending creating compression at bottom of the base may not be fully realised)</th>
<th>Location of Critical Tensile Stress and Amount of Maximum Allowable Tensile Stress in Concrete From Friction (i.e. $\sigma_{\text{mutf}}$; which is the lower of the allowable tensile stresses from friction at top and bottom of base)</th>
<th>Maximum allowable length of tension zone of CRCP base ($T/2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero (i.e. hypothetical)</td>
<td>$0.360MR_b \times 1/1.2$</td>
<td>$0.210MR_b \times 1/1.2$</td>
<td>Bottom of Base: $0.210MR_b \times 1/1.2$</td>
<td>56 m</td>
</tr>
<tr>
<td>$MR_b / 20$</td>
<td>$0.330MR_b \times 1/1.2$</td>
<td>$0.240MR_b \times 1/1.2$</td>
<td>Bottom of Base: $0.240MR_b \times 1/1.2$</td>
<td>64 m</td>
</tr>
<tr>
<td>$MR_b / 15$</td>
<td>$0.320MR_b \times 1/1.2$</td>
<td>$0.250MR_b \times 1/1.2$</td>
<td>Bottom of Base: $0.250MR_b \times 1/1.2$</td>
<td>67 m</td>
</tr>
<tr>
<td>$MR_b / 10$</td>
<td>$0.300MR_b \times 1/1.2$</td>
<td>$0.270MR_b \times 1/1.2$</td>
<td>Bottom of Base: $0.270MR_b \times 1/1.2$</td>
<td>72 m</td>
</tr>
</tbody>
</table>

MR$_b = 5.5$ MPa
MR$_b = 6.0$ MPa
### Table C4: Continued

<table>
<thead>
<tr>
<th>$MR_b/9$</th>
<th>$0.293MR_b \times 1/1.2$</th>
<th>$0.277MR_b \times 1/1.2$</th>
<th>Bottom of Base: $0.277MR_b \times 1/1.2$</th>
<th>74 m</th>
<th>81 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$MR_b/8$</td>
<td>$0.285MR_b \times 1/1.2$</td>
<td>$0.285MR_b \times 1/1.2$</td>
<td>Bottom/Top of Base: $0.285MR_b \times 1/1.2$</td>
<td>76 m</td>
<td>83 m</td>
</tr>
<tr>
<td>$MR_b/7$</td>
<td>$0.274MR_b \times 1/1.2$</td>
<td>$0.296MR_b \times 1/1.2$</td>
<td>Top of Base: $0.274MR_b \times 1/1.2$</td>
<td>73 m</td>
<td>80 m</td>
</tr>
<tr>
<td>$MR_b/6$</td>
<td>$0.260MR_b \times 1/1.2$</td>
<td>$0.310MR_b \times 1/1.2$</td>
<td>Top of Base: $0.260MR_b \times 1/1.2$</td>
<td>70 m</td>
<td>76 m</td>
</tr>
<tr>
<td>$MR_b/5$</td>
<td>$0.240MR_b \times 1/1.2$</td>
<td>$0.330MR_b \times 1/1.2$</td>
<td>Top of Base: $0.240MR_b \times 1/1.2$</td>
<td>64 m</td>
<td>70 m</td>
</tr>
<tr>
<td>$MR_b/4$</td>
<td>$0.210MR_b \times 1/1.2$</td>
<td>$0.360MR_b \times 1/1.2$</td>
<td>Top of Base: $0.210MR_b \times 1/1.2$</td>
<td>56 m</td>
<td>61 m</td>
</tr>
<tr>
<td>$MR_b/3$</td>
<td>$0.160MR_b \times 1/1.2$</td>
<td>$0.410MR_b \times 1/1.2$</td>
<td>Top of Base: $0.160MR_b \times 1/1.2$</td>
<td>43 m</td>
<td>47 m</td>
</tr>
</tbody>
</table>
C4.4 Thick asphalt over CRCP subbase

The use of thick asphalt over CRCP subbases will increase stresses due to friction by the ratio:

\[
\frac{\text{mean mass of asphallic concrete}}{\text{meter width}} + \frac{\text{mean mass of CRC}}{\text{meter width}} = \frac{\text{mean thickness of AC} \times \text{density of AC} + \text{mean thickness of CRC} \times \text{density of CRC}}{\text{minimum thickness of CRC} \times \text{density of CRC}}
\]

Therefore, for thick AC over CRCP base, the maximum allowable length of the tension zone, \(T/2\), needs to be multiplied by

\[
\frac{\text{minimum thickness of CRC} \times \text{density of CRC}}{\text{mean thickness of AC} \times \text{density of AC} + \text{mean thickness of CRC} \times \text{density of CRC}}
\]

This reduces \(T/2\) by a conservative amount as it assumes the minimum thickness of the CRCP occurs at the middle of the tension zone and ignores the effect of bending stresses in the CRCP by the influence of the AC, as only the frictional stresses are increased in the above calculations.

The above equations indicate a substantial reduction in allowable length of tension zone, \(T/2\), with AC bases; however, pavements with bases of AC over subbases of CRCP have several advantages, which are:

- Lower tensile stress in CRCP from cold temperature due to thermal insulation of AC.
- Tensile stresses from drying shrinkage are also expected to be reduced as the CRCP is expected to have higher moisture content due to the ‘moisture’ insulation of the AC.
- Less risk of punch-out failures than do pavements with CRCP bases.
- The friction between a CRCP subbase and its supporting layer may be able to be made low by use of material with low coefficient of friction (and low cohesion), because of less stringent erosion requirements of this supporting layer due to the thick AC base, in which case, the allowable length of the tension zone may be higher. An analysis would need to be carried out to confirm this condition.
- Increasing the thickness of CRCP relative to AC is also helpful within the constraints of the need for a certain minimum thicknesses of AC to resist erosion.

Therefore, AC-CRCP subbase pavements where there are substantial thicknesses of AC, say 175 mm, may be able to tolerate more cracking of CRCP subbase than that for CRCP base.

What becomes more critical in this case is:

- No excessive transverse crack openings so that CRCP subbase still gives structural integrity. This will be the case if maximum tensile strain of the upper subgrade is less than or equal to 0.6 mm/m. Higher strains than 0.6 mm/m may also be tolerable as 0.6 mm/m ignores any slippage between the CRCP subbase and the select subgrade layer. A finite element analysis may show the higher value can be tolerated.
- Ensuring the longitudinal steel in the CRCP subbase does not yield or if it does then it is only of a minor nature, so that the CRCP subbase effectively operates with the advantage of CRC. This may require using a higher \(p\) and/or higher \(f_{sy}\) for the longitudinal steel.
C5  Maximum transverse crack opening of CRCP

Critical temperature is cold for transverse crack openings in CRCP layers.

To prevent loss of shear transfer and corrosion of longitudinal steel in CRCP, a limit needs to be placed on the maximum transverse crack opening, after settlement. This limit will vary depending on factors such as the closeness of the pavement to a marine environment, susceptibility to corrosion, and on the required design life of the pavement before any reconstruction.

No limit for corrosion is normally needed for PCP-D, and JRCP, as the large diameter of the dowels is considered normally sufficient to resist corrosion.

Where it is expected that a pavement will need to be reconstructed before the typical design life of a concrete pavement is reached of say 40 years, due to non-structural factors (such as inadequate drainage, sight distance, or rideability), then a wider transverse crack opening may be able to be tolerated. This is because there is less time for corrosion or problems associated with the loss of shear transfer to develop. This will depend on the desired residual value of the pavement.

The size of the transverse crack opening after settlement depends on a range of factors, the main ones being:

- length of the settlement bowl
- depth of the differential settlement
- shape of the settlement profile
- $\mu_{b-sb}$
- $\mu_{w}$ and $CR_v$
- season when the concrete base was constructed
- number and the spacing of transverse cracks, before and after settlement.

It is difficult to calculate precisely the maximum transverse crack opening in CRCP with settlement. This is a result of CRCP acting somewhat independently of the subgrade because of the longitudinal reinforcing steel that ties the CRCP base together. Therefore a model was developed which is discussed below.

The model has a number of conservative aspects, including:

- all longitudinal movement of the CRCP is assumed to be taken up at the cracks (ie all expansion of the actual concrete in the slabs in the tensile zone, due to friction from settlement is ignored).
- it ignores the capacity of CRCP to drag in surrounding pavement into the settlement profile.
- it assumes the CRCP will have full closure of all cracks in the compression zone.
- the longitudinal steel across the transverse cracks offers no resistance to closing or opening of the cracks when in fact the longitudinal steel in the compression zone offers resistance and so transverse crack closing may be less than when all transverse cracks in the compression zone are assumed to be closed.

However, the use of the model assumes some non-conservative aspects such as the slabs bend rather than remaining straight and rotating to conform to the settlement profile. Bending slabs have lower openings at mid-slab. Therefore, if slabs remain straight and rotate this may mean compressive slabs take up more space reducing space available for
transverse crack opening in tension zones.

On balance, the model is considered to be conservative.

The critical location for transverse crack opening is in the middle of the crest, with the critical temperature being cold.

The model uses the maximum displacement of the base along the profile at the end of the tension zone at its junction with the compression zone. The maximum displacement of the:

\[
\text{base} = \text{the net lengthening of half the settlement bowl} + \text{shortening of base in the compression zone on one side of trough from friction due to settlement} + \text{sum of the closure of all transverse cracks in the base in the compression zone on one side of the settlement trough for the critical case, ie minimum winter temperatures.}
\]

A number of possible scenarios need to be considered. In all of these the maximum allowable transverse crack opening, in the middle of the tension zone (ie middle of the crest), after settlement, needs to be specified.

These scenarios are where settlement causes:

- no increase in transverse cracking in CRCP
- an increase in number of transverse cracks in CRCP.

In the first condition where there is no extra transverse cracking as a result of settlement:

\[
\text{maximum transverse crack opening after settlement} = \text{maximum transverse crack opening prior to settlement} + \left\{\left[\frac{\pi}{2}\right] \times \left(\frac{\text{maximum displacement of the base along the profile (mm)}}{\text{original number of transverse cracks in the tension zone}}\right)\right\}
\]

When using this equation the original number of transverse cracks in the tension zone = (T/2)/(transverse crack spacing prior to settlement).

The affect of season of casting and the minimum pavement temperature is taken into account with the parameter: "the maximum transverse crack opening prior to settlement".

In the second condition where settlement causes an increase in number of transverse cracks in CRCP, the CRCP pavements have the capacity to form more transverse cracks in areas of high tensile stress. This increase in cracking can be incorporated into the formula (given above) by multiplying by:

\[
\text{new transverse cracking spacing in the critical area after settlement, ie in the middle of the tension zone} \times \frac{\text{old transverse crack spacing, prior to settlement}}{	ext{(new transverse crack spacing in the critical area, ie in the middle of the tension zone after settlement)/(old transverse crack spacing in the tension zone prior to settlement)}}
\]

This makes the maximum transverse crack opening after settlement

\[
= \left\{\left[\left(shrinkage and thermal strain\right) \times \text{original crack spacing (m)} + \left(\frac{\pi}{2}\right) \times \left(\frac{\text{maximum displacement of the base along the settlement profile (mm)}}{\text{number of transverse cracks in the tension zone prior to settlement}}\right)\right]\right\} \times \left(\frac{\text{new transverse crack spacing in the critical area, ie in the middle of the tension zone after settlement}}{\text{old transverse crack spacing, prior to settlement}}\right)
\]
in the middle of the tension zone after settlement)/(old transverse crack spacing in the tension zone prior to settlement)}

In the above equation the number of transverse cracks in the tension zone prior to settlement = \((T/2)/(\text{old transverse crack spacing})\)

\[= \left\{\left[(\text{shrinkage and thermal strain}) \ (\text{mm/m})\right] + \left[(\pi/2) \times (\text{maximum displacement of the base along the settlement profile (mm)})/(T/2)\right]\right\} \times \left\{\left[(new \ transverse \ crack \ spacing \ (m)\ in \ the \ critical \ area,) \ ie \ in \ the \ middle \ of \ the \ tension \ zone \ after \ settlement\right]\right\} \times \left\{\left[(\text{shrinkage and thermal strain}) \ (\text{mm/m})\right] + \left[(\pi/T) \times (\text{maximum displacement of the base along the settlement profile (mm)})\right]\right\} \times \left\{\left[(new \ transverse \ crack \ spacing \ (m)\ in \ the \ critical \ area,) \ ie \ in \ the \ middle \ of \ the \ tension \ zone \ after \ settlement\right]\right\}

Therefore, the maximum transverse crack opening after settlement

\[= \left\{\left[(\text{shrinkage and thermal strain}) \ (\text{mm/m})\right] + \left[(\pi/T) \times (\text{maximum displacement of the base along the settlement profile (mm)})\right]\right\} \times \left\{\left[new \ transverse \ crack \ spacing \ (m) \ in \ the \ critical \ area,) \ ie \ in \ the \ middle \ of \ the \ tension \ zone \ after \ settlement\right]\right\}\]

where the maximum displacement of the base along the settlement profile

\[= \text{net lengthening of half the settlement bowl + shortening on one side of trough, due to compression from friction + shortening, on one side of trough, due to crack closure in the compression zone during cold conditions} \]

It is noted that there is an upper allowable limit to the extra transverse cracking, to avoid punch out failures in the CRCP and a limit on the new transverse crack spacing, following settlement, needs to be specified.

Therefore, the following values need to be specified, for the middle of the tension zone (ie the crest area):

- maximum allowable transverse crack opening
- tolerable new transverse crack spacing, following settlement, in the critical area, ie in the middle of the tension zone

The tensile zone of CRCP base is expected to be longer than T/2 as the expansion of the tension zone has to equal the contraction of the compression zone at the interface of the two zones. The tensile zone of CRCP base is expected to lie between 0.5T and 0.59T.

Assuming the tension zone of T/2 for CRCP is expected to be conservative in analysing crack opening.

The following two examples cover the settlement of CRCP due to soft soil and underground mining.

Example 1: CRCP subject to normal settlement

In this example the following parameters are chosen:

- The length of the settlement bowl (2T) = 400 m, ie T = 200 m (half the settlement bowl) and length of tensile zone = T/2 = 100 m
- D = 500 mm (depth of differential settlement)
- the settlement follows a cosine curve
- \(E_{mb}/CR_b = 10,000 \text{ MPa}\)
- \(\mu_{b-ib} = 1.5\)
- crack spacing of 1.0 m prior to settlement, and assuming 0.5 m is tolerable transverse
crack opening after settlement (which will occur in the middle of the tensile zone)

- maximum allowable transverse crack opening of 0.50 mm.
- shrinkage and thermal strain is:
  - 200 µm for winter casting = 0.2 mm/m
  - transverse crack opening prior to settlement for winter casting for 1.0 m for crack spacing = 0.2 mm
  - 400 µm for non-winter casting = 0.4 mm/m
  - transverse crack opening prior to settlement for winter casting for 1.0 m for crack spacing = 0.4 mm

Using the approach outlined in this Section, the five steps are as follows:

A. Net lengthening of half the settlement bowl (for T = 200 m and D = 500 mm) = 0.8 mm for all cases

B. Shortening on one side of trough, due to compression from friction:

\[
\frac{\mu_{b}\times b_{m}}{E_{w}} \times \frac{2.94 \times T^2}{CR_{b}}
\]

\[
= \frac{1.5 \times 2.94 \times 200^2}{10,000} = 17.6 \text{ mm}
\]

(this assumes full mobilisation of friction between the base and subbase)

C. Shortening, on one side of trough, due to crack closure in the compression zone during cold conditions:

- for winter casting = 0.2 x T/2 = 0.200 x 100 = 20 mm
- for non-winter casting = 0.4 x T/2 = 0.400 x 100 = 40 mm

Note that the shortening on one side of the trough, due to compression from friction and crack closure in the compression zone, cannot be greater than the maximum horizontal movement of the subgrade.

D. Winter casting (with a crack spacing, prior to the effects of settlement, of 1.0 m)

maximum transverse crack opening, after settlement for winter casting

\[
= [0.200 \text{ mm/m} + \frac{\pi/2 \times (0.8 + 17.6 + 20) \text{ (mm)/(100 (m))}}{100 (m)}] \times 0.5 \text{ m} = 0.40 \text{ mm}, \text{ which is acceptable as it is less than maximum allowable transverse crack opening of 0.50 mm}
\]

E. Non-winter casting (with a crack spacing, prior to the effects of settlement, of 1.0 m)

maximum transverse crack opening, after settlement for non-winter casting

\[
= [0.400 \text{ mm/m} + \frac{\pi/2 \times (0.8 + 17.6 + 40) \text{ (mm)/(100 (m))}}{100 (m)}] \times 0.5 \text{ m} = 0.66 \text{ mm which is unacceptable.}
\]

Given that the maximum allowable transverse crack opening was given as 0.50 mm, then for this example only the base concrete cast in winter has an acceptable maximum transverse crack opening, after settlement, in the middle of the tension zone, for a new crack spacing of 500 mm.
Example 2: CRCP subjected to underground mining

In this example the following parameters are chosen:

- The length of the settlement bowl (2T) = 1,000 m, ie T = 500 m (half the settlement bowl) and length of tensile zone = T/2 = 250 m
- D = 1.500 mm, maximum depth of differential settlement
- the settlement follows a cosine curve
- \( \frac{E_{mb}}{CR_{base}} = 10,000 \text{ MPa} \). Creep is taken into account as considering the pavement will still contract in the compression zone, and expand in the tension zone under the stress created from settlement even after settlement, which is fast, ceases. However the figure of 10,000 MPa is probably too conservative.
- \( \mu_{b-sb} = 1.5 \)
- transverse crack spacing of 1.0 m prior to settlement, and assuming 0.5 m is tolerable transverse crack opening after settlement (which will occur in the middle of the tensile zone)
- maximum allowable transverse crack opening of 0.50 mm
- shrinkage and thermal strain is:
  - 200 µm for winter casting = 0.2 mm/m, and
  - transverse crack opening prior to settlement for winter casting for 1.0 m for crack spacing = 0.200 mm
  - 400 µm for non-winter casting = 0.4 mm/m
  - transverse crack opening prior to settlement for winter casting for 1.0 m for crack spacing = 0.400 mm

Using the approach outlined in this Section, the five steps are as follows:

A. Net lengthening of half the settlement bowl (for T = 500 m and D = 1.500 mm) = 2.8 mm for all cases.

B. Shortening on one side of trough, due to compression from friction:

\[
\frac{\mu_{b-sb} \times 2.94 \times T^2}{E_{mb} / CR} = \frac{1.5 \times 2.94 \times 500^2}{10,000} = 110.3 \text{ mm}
\]

(this assumes full mobilisation of friction between the base and subbase)

C. Shortening, on one side of trough, due to crack closure in the compression zone during cold conditions:

- for winter casting = \( 0.2 \times \frac{T}{2} = 0.200 \times 250 = 50 \text{ mm} \)
- for non-winter casting = \( 0.4 \times \frac{T}{2} = 0.400 \times 250 = 100 \text{ mm} \)

Note that the shortening on one side of the trough, due to compression from friction and crack closure in the compression zone, cannot be greater than the maximum horizontal movement of the subgrade.
D. Winter casting (with a crack spacing, prior to the effects of settlement, of 1.0 m)
maximum transverse crack opening, after settlement for winter casting

\[
\begin{align*}
0.200\frac{mm}{m} + \left(\frac{\pi}{2}\right) \times \left(2.8 + 110.3 + 50\right)\frac{mm}{(250(m))} \times 0.5m &= 0.61 m
\end{align*}
\]

E. Non-winter casting (with a crack spacing, prior to the effects of settlement, of 1.0 m)
maximum transverse crack opening, after settlement for non-winter casting

\[
\begin{align*}
0.400\frac{mm}{m} + \left(\frac{\pi}{2}\right) \times (2.8 + 73.5 + 50)\frac{mm}{(250(m))} \times 0.5 = 0.71 mm
\end{align*}
\]

Given that the maximum allowable transverse crack opening was given as 0.50 mm, then for this example the base concrete has an unacceptable maximum transverse crack opening after settlement, whatever the time of casting, in the middle of the tension zone, for a new crack spacing of 500 mm.

In the above example if the allowance for creep using \( E_{mb}/CR_{base} = 10,000 \) MPa is too conservative, and say 15,000 MPa is considered more appropriate, then the shortening on one side of trough, due to compression from friction:

\[
\begin{align*}
\frac{\mu_{b-sh} \times 2.94 \times T^2}{E_{mb}/CR_b} &= \frac{1.5 \times 2.94 \times 500^2}{15,000} \\
&= 73.5 mm
\end{align*}
\]

The above value assumes the full mobilisation of friction between the base and subbase, and this results in the maximum transverse crack opening, after settlement for winter casting

\[
\begin{align*}
\left[0.200\frac{mm}{m} + \left(\frac{\pi}{2}\right) \times (2.8 + 73.5 + 50)\frac{mm}{(250(m))}\right] \times 0.5m = 0.497 mm
\end{align*}
\]

which is acceptable.

Therefore if \( E_{mb}/CR_{base} = 15,000 \) MPa is appropriate for the base concrete and maximum allowable transverse crack opening is 0.50 mm, for Example 2 the base concrete cast in winter has an acceptable maximum transverse crack opening, after settlement, in the middle of the tension zone, for a new crack spacing of 500 mm.

There may be some relaxation in the predicted transverse crack opening for long shallow bowls.

C6 Minimum base thickness

C6.1 Introduction

This section considers the minimum base thickness for traffic, radius of curvature from settlement and temperature differentials and is applicable for both longitudinal and transverse directions.
Due to settlement, the base thickness may need to be increased. In general, the amount of increase, if any, depends on:

- $MR_b$
- The size of $B_f$ compared to $B_e$. (The smaller the $B_f$ relative to the $B_e$, the greater the buffer for stresses from settlement).
- The change in curvature ($1/R_{\min}$) over time, at the critical locations for stress. All directions (i.e., longitudinal, transverse, and skew) and both concave and convex shape need to be considered.
- Stress relaxation properties of the base concrete.
- The degree of any uneven support created by excessive relative horizontal movement between the base and subbase, and excessive relative horizontal movement between subbase and subgrade. This requires selecting an appropriate type of concrete pavement. Even when the requirements of Sections 9 and C2.5 are satisfied, there may need to be an increase in the base thickness due to uneven support. This increase in base thickness for uneven support is additional to that determined in this section.
- Temperature differentials. (Negative temperature differentials in the case of convex settlement; and positive temperature differentials in the case of concave settlement).

The thickness design method assumes that erosion is not affected by settlement.

The critical tensile stress from traffic is calculated at the bottom of the slab in the middle of a slab along the edge in the longitudinal direction, using Austroads pavement design method (Austroads, 2012).

In developing a design procedure for settlement, the base thickness must be such that it can withstand the combined effect of settlement stress caused by:

- the pavement conforming to the settlement profile due to self-weight
- traffic loading
- temperature differentials between the top and bottom of the concrete base.

An increase in pavement thickness will actually increase stress due to settlement for a particular settlement profile. This is because for a given R from settlement, the stress from bending from settlement is proportional to the thickness of the base. However, as the pavement thickness is increased the tensile stresses due to traffic and temperature differentials will be reduced. The reduction in traffic stress with increasing base thickness is shown in Austroads pavement design method (Austroads, 2012).

The effect of thicker bases on temperature differentials can be demonstrated as follows:

- $R$ from maximum temperature differentials $\propto$ base thickness $/\text{maximum temperature differential (°C)}$
- stress from maximum temperature differentials $\propto \left[\frac{1}{R \text{\ from maximum temperature differentials}}\right] \times \text{basethickness}$
  and for a given concrete (i.e., where concrete properties, including $E_b$, Poisson’s Ratio, and Coefficient of Thermal Expansion per °C, are unchanged), then
- stress from maximum temperature differentials $\propto$ maximum temperature differentials $\times \left[\frac{1}{\text{base thickness}}\right] \times \text{(base thickness)}$
  stress from maximum temperature differential (°C) $\times$ maximum temperature differential (°C)
and is independent of base thickness. As the maximum temperature differential is reduced with increase in base thickness where the initial base thickness is substantial such as those typically used in pavements, the accompanying stress from temperature differentials is reduced.

C6.2 Design thickness

The design thickness is the greatest of the following:

- $B_e$ (for erosion without settlement)
- $B_{fs}$ (to satisfy fatigue under traffic after including the effect of settlement)
- $B_{st}$ (to ensure there is sufficient capacity for stresses due to a heavy load with settlement and positive temperature differentials)

(besides any increase in thickness needed due to uneven support, created by settlement)

$B_{fs}$ and $B_{st}$ are all calculated using the ‘Thickness Design for Settlement Spreadsheet’.

Assuming no increase in thickness is needed due to uneven support, the maximum of $B_e$, $B_{fs}$, and $B_{st}$ is the design thickness. This value becomes the minimum construction thickness of the base concrete, $B_e$.

C6.3 Determining critical conditions for $B_{fs}$ and $B_{st}$:

The worst curvature situation, that is smallest $R$, is used to determine $B_{fs}$ and $B_{st}$ using the ‘Thickness Design for Settlement Spreadsheet’ whatever its direction (i.e. longitudinal, transverse or skew), and irrespective of whether it is convex or concave (see Figure C7 for these two shapes) as this is conservative. It is noted that further research work is needed to refine pavement design methods to distinguish between convex and concave settlement.

The traffic stresses are determined using the Austroads pavement design method (Austroads, 2012). These bottom tensile stresses are calculated for the edge of a middle slab in the longitudinal direction. This implies that only in the concave shape are the tensile stresses from traffic, settlement and positive temperature differentials are additive.

![Concave Shape](image1)

![Convex Shape](image2)

Figure C7: Deformation shapes of base concrete subject to differential settlement
Since the Austroads design method calculates the tensile stress in the longitudinal direction at the bottom of the slab and because the 'Thickness Design for Settlement Spreadsheet' uses this stress and the smallest \( R \) whatever its direction (ie longitudinal, transverse or skew) and whatever its shape (irrespective of whether it is convex or concave to calculate tensile stresses from bending from settlement) when determining \( B_{f,i} \), means the method is conservative for \( B_{f,i} \) for:

- convex settlement shape, all directions (ie longitudinal, transverse and skew)
- concave settlement shape, in the transverse direction.

Therefore, for a base thickness of \( B_{f,i} \), determined using the spreadsheet, any convex settlement (all directions) and any concave settlement (transverse direction) will have some 'spare capacity' for stresses from settlement, assuming the Austroads approach is always suitable. However, it is difficult to determine the actual magnitude of this 'spare capacity' and the designer would be required to carry out a rigorous finite element analysis of the stresses if the determination of the 'spare capacity' is required. It also needs to be noted that the stress state of concrete pavements is more complex than assumed in the Austroads method. For example, stresses due to multi-axle wheels over slabs distorted by temperature differentials and/or moisture are not considered and this 'spare capacity' may to some extent not be realised.

Temperature differentials in conjunction with traffic stress from an isolated heavy vehicle and differential settlement can create a critical situation for the stress level in concrete pavements. These critical situations are (shown in Figure C8):

- convex settlement with negative temperature differentials
- concave settlement with positive temperature differentials

Figure C8 is considered simplistic as it does not show the effect of the self-weight on a concrete slab, nor does it show the effect of creep/stress relaxation on the shape. For example, with a concave settlement with positive temperature differentials there is a sag superimposed on the drawn shape of the slab. The sag is from self-weight and effects of creep/stress relaxation of bending stresses/strains from settlement. The influence of stress relaxation/creep is complex to analyse due to the changing shape of the slab with temperature and moisture changes.
Concave settlement with traffic, settlement and positive temperature differentials, is more critical than convex settlement with traffic, settlement and negative temperature differentials (see Figure C8) for a given curvature. To be conservative the ‘Thickness Design for Settlement Spreadsheet’ calculates $B_{st}$, using the smallest $R$ from settlement (to calculate tensile stresses from bending from settlement) whatever its direction, the maximum positive temperature differential (to calculate tensile stresses from positive temperature differentials) and tensile stress from traffic loading calculated using Austroads.

It is noted that the above approach only examines tensile stresses in the middle of a slab. Therefore, with PCP and PCP-R, there is also a possibility of corner breaking and diagonal cracking with negative temperature differentials between the top and bottom of the slab (AASHTO, 1998). Such stresses are made even more critical with convex settlement.

For convenience, the references to shape in this Guide are to the change in shape, rather than the actual final shape, unless otherwise indicated, as bending stresses due to settlement depend on the change in shape of the profile caused by settlement from the original profile. For instance, the original profile may be convex because of road geometry, but the change due to settlement may be concave, with the combined effect still being convex, ie crest shape. What is critical for stresses is the change in shape, that is the concave shape that has been superimposed on the original shape as the shape due to the original profile is not ‘felt’ by the concrete as this was the setting shape.

**C6.4 Thickness design for radius of curvature from settlement**

**C6.4.1 Determining $B_{st}$**

The determination of the base concrete thickness to satisfy fatigue distress from traffic stress and stress due to settlement is covered in this Section. The thickness design method for $B_{st}$ is applied for all types of concrete pavements. It is based on the tensile stress from bending from settlement (ie the settlement stress) and the tensile stress from traffic.

The settlement stress at any one time depends on the settlement history up to this point, and the stress relaxation. This is taken into account with the ‘Design Thickness for Settlement Spreadsheet’ which analyses the effects of the changing of the radius of curvature with time and stress relaxation.

A range of possible settlement scenarios can be analysed using the spreadsheet.

To give some appreciation of what is involved in the calculations, a simple case of a one-off settlement will now be discussed.

If there is a one-off settlement, then the value of the bending stress due to settlement at a particular time can be calculated, as for this situation the effect of stress relaxation at a particular time after the settlement, will be one value for $C_{R2}$ (determined from the time since settlement).
This 'settlement stress', at this particular time is:

\[ t_b \times E_b = \frac{t_b \times E_b}{2 \times R \times (1 - \mu^2) \times CR_b} \]

The base thickness, \( t_b \) must be such that for each axle group:

\[
\text{Settlement Stress} = \text{Modulus of Rupture}
\]

has a magnitude for each axle group at its standard loading, for the \( t_b \) less than, or equal to:

\[
\text{the reduction in Traffic Stress} = \text{Modulus of Rupture}
\]

due to the increase in thickness from \( B_f \) to \( t_b \).

This takes into account the impact of constant stress conditions (as caused by bending from settlement) have less impact than variable stress (as caused by traffic).

To determine the minimum value of \( t_b \) to satisfy the above, an iterative trial and error procedure is required and it is illustrated in Figure C9. Figure C9 shows the stress state for a base with settlement for increasing base thickness, for a particular axle group at a standard loading. For this diagram the only constant stress is from bending from settlement.

Also, in Figure C9 the point \( A_1 \) is the stress state before any settlement for base thickness of \( B_f \), ie traffic stress = \( S_s \) (for the particular axle group and standard load) and point \( B_1 \) is the stress state for \( B_f \) after including bending stresses from settlement. As \( t_b \) is increased by an increment of thickness from \( B_f \), \( A_2 \) is the new stress state without settlement for the axle group with the standard load, and \( B_2 \) is the new stress state for this increased thickness after settlement. Similarly a further increment in thickness leads to \( A_3 \) and \( B_3 \), and then a further increment in thickness leads to \( A_4 \) and \( B_4 \), and finally \( A_5 \) to \( B_5 \). At this last thickness Figure C9 shows the stress state of point \( B_5 \) has the same fatigue life as \( B_f \) without settlement as it is on the original fatigue curve of \( N = 10^6 \). This implies the thickness to cause \( A_5 \) and \( B_5 \) is \( B_f \).

Note that the increments in thickness going from \( A_1 \) to \( A_2 \), and \( A_2 \) to \( A_3 \), and \( A_3 \) to \( A_4 \), and \( A_4 \) to \( A_5 \) will not be the same, as for this illustration, the increment for each step is that which reduces the variable stress/MR, i.e. the traffic stress/MR by approximately one quarter of the total reduction required, which requires the actual increment in thickness in going from \( A_1 \) to \( A_2 \), and then \( A_2 \) to \( A_3 \), and then \( A_3 \) to \( A_4 \), and finally from \( A_4 \) to \( A_5 \), to be higher each time.

Figure C9 shows that the settlement stress/MR, which is a constant stress, increases as the base thickness increases, noting that the length of \( A_1 \) to \( B_1 \), \( A_2 \) to \( B_2 \), \( A_3 \) to \( B_3 \), \( A_4 \) to \( B_4 \). This is because bending stress from settlement, which is caused by self-weight of the concrete base, is proportional to the base thickness, provided the radius of curvature of the settlement profile is within tolerable values for concrete pavements which ensures a concrete pavement conforms to a settlement profile due to self-weight of concrete.
Figure C9: The effect of increasing concrete base thickness on the stress state due to a nominated traffic load and settlement situation (at a particular time)

\[
\frac{\text{Variable Stress}}{MR_b} = \frac{\text{Traffic Stress due to Nominated Traffic Load}}{MR_b}
\]

\[
\frac{\text{Constant Stress}}{MR_b} = \frac{\text{Bending Stress at a particular point in time, from settlement due to self – weight of concrete}}{MR_b}
\]

The fatigue lines and stress levels are only illustrative and so they cannot be used as a true indication of fatigue life. This assumes an infinite fatigue life of concrete for variable stress (ie stress from traffic loading less than \(0.4 \times MR_b\) where there is no constant stress).

For the purposes of an example, the Tepfers and Kutti equation has been used to determine the intercept of the fatigue contours on the vertical axis.

For a particular axle group, the used up fatigue life for a trial \(t_b\) (ie trial \(B_c\)) can be determined by the calculation of an equivalent \(S_a\) for this trial \(B_c\) for the standard loading for this axle group. This is called \(S_{\text{equive}-a}\).
For the particular axle group and standard loading for this axle group the $S_{\text{equiv-c}}$ gives the same fatigue life for the trial $B_c$ for no settlement stress, as does the trial $B_c$ with the actual $S_c$ together with the settlement stress. The equation for $S_{\text{equiv-c}}$ is as follows:

$$S_{\text{equiv-c}} = S_c \text{ for } t_b \left( 1 - \mu_{\text{settlement}} \text{ for trial } B_c / MR_h \right)$$

The used up fatigue life for this particular axle group for its axle load distribution is calculated using Miner’s Law.

This is the approach used in the ‘Thickness Design for Settlement Spreadsheet’ where the used-up fatigue life of all axle groups with their respective axle load distribution is calculated using Miner’s Law.

When the trial $B_c$ has a total fatigue life for all axle groups and their respective axle load distribution equal to (or greater) than $B_f$ for no settlement, then this particular trial $B_c$ is $B_{sf}$. Note that if the settlement is too large, the settlement stress for base thickness of $B_f$ will be large, and no increase in thickness will be able to be determined to satisfy the required fatigue life, as settlement stress just becomes increasingly excessive with each increase in trial $B_c$.

As discussed earlier in this Section, the method for determining $B_{sf}$ is conservative for convex settlement and where the convex settlement is more severe than concave settlement, more analysis may show a lower base thickness can be used than determined assuming concave settlement. Such analysis would need to include a study of:

- the interaction of traffic, negative temperature differentials and convex settlement
- the nature of contact of base slabs on subbase for convex settlement profiles

Note that while convex settlement can be beneficial for PCP-D, JRCP and CRCP, it is detrimental to PCP and PCP-R as for these two pavements convex settlement results in corner cracking.

C6.4.2 Determining $B_{st}$

Determining the base concrete thickness is needed to ensure the base after experiencing settlement stresses maintains the same capacity for stresses from heavy axle loads in conjunction with positive temperature differentials, that it had prior to settlement. For a pavement to have the same ability to withstand an isolated heavy load, after settlement as before, requires that consideration be given to the tensile stresses from positive temperature differentials in the slab as this is typically the critical temperature differential for traffic loading. This requires that the base thickness be increased above $B_f$ (that needed for fatigue without settlement). This requirement is more significant for pavements designed for lighter traffic than for heavy traffic, as thinner bases have less capacity for isolated heavy loads.

To determine $B_{st}$, the ‘Thickness Design for Settlement Spreadsheet’ can be used. This allows for the effect of change in curvature due to self-weight of the concrete from settlement over time, and the associated change in bending stresses from stress relaxation over time.
This spreadsheet uses the AASHTO (1998) formula for tensile stresses caused by positive temperature differentials. These are assumed to be unaffected by stress relaxation because of their cyclical nature (ie short duration).

The design approach is to provide a base concrete thickness which, after taking into account of bending due to self-weight of the concrete due to settlement and stresses due to positive temperature differentials, has the same capacity for isolated heavy vehicles as $B_f$ has without settlement. So the method is to ensure the sum of stresses for a single overload is less than rupture stress rather than being an issue of fatigue due to multiple passes for a certain design stress.

For $B_f$ without settlement the available capacity for traffic stresses after taking account of stresses due to positive temperature differentials = $1 - \left( Z \text{ for } B_f / MR_b \right)$, where $Z$ = tensile stress due to positive temperature differential, and so the capacity for traffic stresses from a heavy vehicle compared to a particular axle group at its standard load used for determining $S_e$ for this particular axle group = $\left[ 1 - \left( Z \text{ for } B_f / MR_b \right) \right] / \left[ S_e \text{ for } \right]$. Therefore to determine the thickness ($B_{st}$) needed for isolated heavy vehicles after taking into account settlement stresses and stress due to positive temperature differentials requires finding the minimum $B_{st}$, for each axle group at its standard loading, to satisfy the following equation:

$$\frac{1 - \left( Z \text{ for } B_{st} / MR_b \right) - \left( \text{Settlement Stress} / MR_b \right)}{S_e \text{ for } B_{st} / MR_b} \geq \frac{1 - \left( Z \text{ for } B_f / MR_b \right)}{S_e \text{ for } B_f / MR_b}$$

So

$$\left[ 1 - \left( Z \text{ for } B_{st} / MR_b \right) - \left( \text{Settlement Stress} / MR_b \right) \right] \left[ S_e \text{ for } B_f / MR_b \right] \geq 1$$

where the settlement stress is the stress after taking into account stress relaxation.

Once the minimum possible value of $B_{st}$ is obtained for each axle group, the larger of these values is the $B_{st}$.

So as long as each year uses less than 100% of fatigue capacity then the pavement is considered satisfactory for heavy loads in conjunction with positive temperature differentials, where the value for $B_f$ for each year is determined on the basis of the traffic for that year. If the $B_f$ were to be calculated on the basis of the total traffic over the design period, it would be larger, and this would mean the calculated $B_{st}$ would be too conservative.

To illustrate the procedure, a simplistic case will be examined where settlement is a one off event and where only one year is examined, so that $R$ is constant throughout the life of a pavement, and stress relaxation in one year has a given $CR_b$.

In this case where the settlement is just a one off, and where only one particular year is examined, the value of $B_{st}$ would simply need to satisfy:

$$\frac{1 - \left( Z \text{ for } B_{st} / MR_b \right) - \left( \text{Settlement Stress} / MR_b \right)}{\left[ S_e \text{ for } B_{st} / MR_b \right] \left[ 1 - \left( Z \text{ for } B_f / MR_b \right) \right]} \geq 1$$
\[
\frac{1 - (Z \text{ for } B_f / MR_b) - \left[ \left( B_{st} \times E_b \right) / \left( 2 \times R_{min} \times MR_b \times (1 - \nu^2) \times CR_b \right) \right] \left( S_e \text{ for } B_f / MR_b \right)}{(S_e \text{ for } B_f / MR_b) (1 - Z \text{ for } B_f / MR_b)} \geq 1
\]

for each axle group, where \( B_f \) is based on the traffic for the year being examined and \( Z \) = tensile stress due to positive temperature differentials, using a nominated value, or using a formula related to base thickness, and other parameters, such as the AASHTO (1998) formula.

C6.4.3 Choosing an appropriate LSF

An appropriate Load Safety Factor (LSF) for the area of differential settlement needs to be determined. Some designers may consider that it is appropriate to use a lower value for the LSF for the settlement area because only part of the pavement will be in the most critical area, and so not all the settlement area will have the minimum radius of curvature. Therefore, not all the pavement needs to be thickened by the same amount.

Another approach for using a lower LSF for the settlement area is considered as follows.

The thickness for the critical area should be simply the thickness for the overall project using the LSF for the overall project. This in effect is using a lower LSF for the area of settlement design. This will prevent most of the pavement being over designed and only leave the settlement area being under designed. Therefore, only the settlement area will have less reliability than normally required.

If this approach is adopted, any cost savings in construction, will need to be offset against the likelihood of early intervention in the settlement area. There may also be extra repercussions if a section of base concrete needs to be removed and replaced in the trough area, as the removal process may cause compressive failure in the subbase concrete, due to the transfer of frictional forces back from the base to the subbase.

Also it needs to be noted that differential settlement causes the base, subbase and subgrade to move horizontally, but by different amounts. This creates some degree of uneven support within the pavement. The larger the relative horizontal movement between the base and the subbase, and between the subbase and the subgrade, the thicker the base will need to be, to keep stresses to within tolerable values. Therefore, where the relative horizontal movements are significant, it is considered unwise to reduce the \( LSF \).
If the settlement profile basically follows a cosine shape, the maximum horizontal movement of the pavement and subgrade occurs in the region of the point of contraflexure, which is well away from either the middle of the trough or crest. At the place of maximum horizontal movement, the bending stresses from settlement are expected to be zero or minor ignoring any high curvatures (ie low $R_c$) due to localised effects. Whereas at troughs and crests, where bending stresses are a maximum, the horizontal movements of the top of subgrade are minor or zero. In which case, the extra base thickness provided to withstand the bending expected at the trough or crest, in a settlement bowl, will help prevent excessive stress being created by uneven support in the region of the point of contraflexure, where horizontal movements of the top of the subgrade are the largest.

It is noted that in the case of underground mining, horizontal movements can be relatively large, even though the minimum radii of curvatures for the troughs and crests may be mild. Therefore, where horizontal movements are large there can be grounds for increasing the LSF.

Therefore $MR_b$ is:

- Where the maximum horizontal movement of the top of subgrade is significant and/or the areas of pavement which have a low radius of curvature is significant, it is considered that the LSF should not be decreased and there may be a valid case for it to be increased where settlement is likely to occur.
- When maximum horizontal movement of the top of subgrade is small and the areas with a low radius of curvature are also small, then a lower LSF may be considered, ie $LSF_{settlement}$ can be less than $LSF_{no\ settlement}$ provided $B_{fs}$ calculated using $LSF_{settlement}$ is not less than $B_f$ (the thickness for fatigue with no settlement calculated using $LSF_{no\ settlement}$).

One approach, worthy of consideration is to keep the same LSF but to increase the cement (and/or fly ash) content in the concrete for the critical locations. This increases the LSF for the critical locations, which reduces the value of $B_f$ and therefore reduces the value for $B_{fs}$ and $B_{st}$ for these locations. It may be that the value for $B_{fs}$ and $B_{st}$ needed for the critical area of settlement, using the higher cement (and/or fly ash content), may be no greater than that needed for the $B_f$ for the remainder of the project, using the basic cement content.

For strategic roads, it is generally considered that the LSF used for settlement should be the same as that used for determining the thickness without settlement (ie $LSF_{settlement} = LSF_{no\ settlement}$) even where the horizontal movement of the top of the subgrade is small.

However, when non-structural criteria for the settlement area, such as rideability, drainage considerations, or sight distance, are expected to be more critical than structural considerations, it may be appropriate to adopt a lower value of LSF for assessing the potential settlement area. As in this situation, the pavement in the settlement area may need reconstruction or a substantial overlay, to restore these non-structural values to the appropriate standard, before the pavement ever reaches its fatigue life. This assumes of course that it is still feasible to use the proposed pavement.
Appendix D Design spreadsheet for the design of concrete pavements in areas of settlement – User’s Guide

D1 Introduction

Concrete pavements can be used in areas of differential settlement only when they meet the relevant criteria. The design spreadsheet allows a range of possible settlement scenarios to be analysed to determine whether or not criteria related to curvature are satisfied and shows whether an increase in $B_{fr}$ and/or $B_{st}$ is needed to ensure adequate life under traffic and curvature. In some situations increasing base thickness may be required and in some situations it may not be possible or feasible to meet curvature criteria even with an increase in base thickness.

For the curvature analysis of PCP and PCP-R bases, there is only a need to assess thickness requirements for curvature for concave shape in transverse direction where traffic is greater than $10^6$ DESA (refer to Table 10).

Due to settlement, the base thickness may need to be increased. In general, the amount of increase, if any, depends on:

- Modulus of Rupture of the base ($MR_b$)
- The size of $B_f$ compared to $B_c$. The smaller the $B_f$ relative to $B_c$, the greater the buffer for stresses from settlement.
- The change in curvature ($1/R_{min}$) over time, at the critical locations for stress. All directions (i.e. longitudinal, transverse, and skew) and both concave and convex shape need to be considered.
- Stress relaxation properties of the base concrete.
- The degree of any uneven support created by excessive relative horizontal movement between the base and subbase, and excessive relative horizontal movement between subbase and subgrade.
- Temperature gradient. For instance, negative temperature gradient in the case of convex settlement; and positive temperature gradient in the case of concave settlement.

The thickness design method assumes that erosion is not affected by settlement. It is also assumed that RMS design practices as outlined in the pavement design supplement (RMS, 2011) and use of RMS specifications R44, R82, R84 and R116 are applied to the contractor to achieve high standards of materials and construction to meet 40 year design lives.

The critical tensile stress from traffic is calculated at the bottom of a middle slab along the edge in the longitudinal direction, using current pavement design techniques (Austroads, 2012).

In developing a design procedure for settlement, the base thickness must be such that it can withstand the combined effect of settlement stress caused by:

- the pavement conforming to the settlement profile due to self-weight,
- traffic loading, and
- temperature gradient between the top and bottom of the concrete base.
Over time not only does bending stresses from settlement increase from the self-weight of concrete, so does traffic volumes (where there may also be an increase in load per axle group). This indicates that where the performance of a pavement is considered to be satisfactory after 15 to 20 years, this may give sufficient indication of the performance of the same pavement over the next decade or two. Therefore, it is important to analyse a concrete pavement over the whole design period of say 30 to 40 years using the 'Thickness Design for Settlement Spreadsheet', rather than simply relying on seemingly good experience based on say 10 to 20 year old pavements.

**D2 Effects of increasing pavement thickness**

As the pavement thickness increases:
- The stress due to settlement for a particular settlement profile will increase. This is because for a given R from settlement, the stress from bending as a result of settlement is proportional to the thickness of the base.
- The tensile stresses due to traffic and temperature gradient will decrease.

The effect of thicker bases on temperature gradient can be demonstrated as follows:

\[
R_{\text{from maximum temperature differentials}} \propto \frac{\text{base thickness}}{\text{maximum temperature differential}\left(\degree\text{C}\right)}
\]

and

\[
\sigma_{\text{from maximum temperature differentials}} \propto \frac{1}{R_{\text{from maximum temperature differentials}}} \times \text{base thickness}
\]

and for a given concrete (i.e. where concrete properties, including \(E_b\), Poisson’s Ratio, and Coefficient of Thermal Expansion per °C, are unchanged), then

\[
\sigma_{\text{from maximum temperature differentials}} \propto \text{maximum temperature differentials} \times \frac{1}{\text{base thickness}} \times \text{base thickness}
\]

and so

\[
\sigma_{\text{from maximum temperature differentials}} \propto \text{maximum temperature differentials}
\]

and is independent of base thickness.

Since the maximum temperature differential is reduced with increase in base thickness where the initial base thickness is substantial such as those typically used in pavements, the accompanying stress from temperature gradient is reduced.

**D3 Structure and use of the design spreadsheet**

The structure of the design spreadsheet file consists of the following sheets in order of appearance (ie left most tab to the right):

- Summary
- Creep
- k2 Factor
- Settlement
Figure D1 shows the front page of the spreadsheet and additional screen captures are shown in Figures D2 to D14.

In summary, the design spreadsheet is used to:

- Determine $B_{fi}$ and $B_{st}$
- Determine the necessity and/or benefit of delaying the time of paving.
- Indicate a concrete pavement may be able to withstand a particular settlement rate; it is also necessary to ensure $R_{min,(local)}$ at the end of the design period is not below the minimum tolerable value to ensure adequate rideability (longitudinal direction), adequate contact in all directions of the pavement with the subgrade, and adequate toughness (all directions). These properties are a function of type of concrete pavement and rate of settlement.
- Analyse different rates of settlement to determine the effect of stress relaxation of bending stresses from settlement on the pavement.
- Determine whether a higher value of $R_{min,(local)}$ is needed for concave shape for high traffic volumes.
- In the case of concave settlement, the critical situation is when positive temperature gradient occurs causing the critical stress to form in the mid-slab area (which is the same for JRCP and CRCP). These stresses can be analysed.
- Even where settlement is not delayed (eg settlement associated with soft soils) there can still be considerable advantage gained by using cements with high fly ash
contents, as settlement keeps increasing with time and traffic loadings both in quantity and even in axle loads keep increasing. So there can be very significant reductions in base thickness needed where the concrete has a high long-term strength. The spreadsheet can be used to calculate this effect.

- Calculates the settlement stress for a particular time period, after taking into account stress relaxation, due to the changes in time of $\Phi_{cc,b}$, $k_2$, and $k_3$ as a result of increases in strength over time of the concrete.

The spreadsheet is used to determine the stress-state and its effect on life, after taking into account the rate of settlement and the stress relaxation properties of the base concrete. The stress relaxation properties are based on the model adopted in the Austroads Bridge Design Code, 1992).

As concrete gains strength, both the $E_b$, and the $MR_b$ increase. However, the increase in strength means that the values of $k_3$ and $\Phi_{cc,b}$ are both lower. Where there is delayed settlement and increasing strength of concrete, there will be less stress relaxation. Alternatively, by the time of commencement of the settlement, any increase in $MR_b$ of the concrete over time will result in the thickness needed for traffic stresses, $B_f$, will be lower. Therefore, it is considered that the pavement will be better able to tolerate stress where the concrete gains strength with time. The net effect of this can be determined using the 'Thickness Design for Settlement Spreadsheet'.

**D4 Design thickness**

The design thickness is the greatest of the following:

- $B_e$ (for erosion without settlement)
- $B_{fi}$ (to satisfy fatigue analysis after including the effect of differential settlement)
- $B_{st}$ (to ensure there is sufficient capacity for stresses due to load fatigue in conjunction with differential settlement and the effect of a positive temperature gradient, including any increase in thickness needed due to uneven support, created by settlement)

Assuming no increase in thickness is needed due to uneven support, the maximum of $B_e$, $B_{fi}$, and $B_{st}$ is the design thickness. This value becomes the minimum construction thickness of the base concrete, $B_c$.

**D5 Data entry requirements**

As noted in Appendix D3, the designer is required to enter various site specific inputs in order for the analysis to take place. The following section of the Guide summarises the input data required and the screen captures are displayed to assist the user at each step.

**Summary Sheet**: (refer to Figures D1 and D2)

Single input:

- Project name
- Comments
- % of HVAG in Design Lane (%)
- Effective subgrade CBR (%)
- Characteristic Base Flexural Strength at 28 days ($MR_{b28}$) (MPa)
- Load Safety Factor
- Adjustment for traffic loading (Yes/No)
- Characteristic Modulus of base at 28 days ($E_{b28}$) (MPa)
- Minimum construction base thickness ($B_c$) (mm)
- Poisson’s Ratio of base layer ($\nu$)
- Concrete Shoulders (Yes/No)
- Dowelled/CRCP (Yes/No)
- Fatigue Adjustment Factor
- Variation in $\Phi_{l,c}$
- MR growth reduction factor in fatigue formula
- $k_2$ series type
- Settlement type
- Joint spacing (L) (m)
- Subbase modulus ($E_{st}$) (MPa)
- Base/subbase friction coefficient ($\mu_{b-st}$)
- Subbase thickness ($T_{st}$) (mm)
- Effective elastic modulus of subgrade support ($k$) (kPa/mm)
- Edge support adjustment factor ($ES$)
- Mean annual wind speed (WIND) km/h
- Mean annual temperature (TEMP) (Deg.C)
- Mean annual precipitation (PRECIP) (mm)

![Figure D2: The lower half of the front page of the spreadsheet when the file is opened in Microsoft Excel.](image-url)
Annual input (Columns B to U and Rows 33, 37, 43, 57, 59 and 61 – and repeated in Rows 66 to 94) consists of:

- Phi.cc.b ($\Phi_{cc.b}$) at start of period
- Creep coefficient $k_3$ at start of period
- Traffic load distribution type
- MRbp ($MR_{bp}$) at start of period (MPa) (for fatigue calculations)
- Ebp ($E_{bp}$) at start of period (MPa)
- Extra tensile stress (MPa)

The majority of the project information is entered on this sheet. If needed the following equation can be used for an estimation of the characteristic modulus of the base at 28 days $E_{b28}$.

$$MR_b = K \left( f'_c \right)^{0.5}$$

Hence

$$f'_c = \left( \frac{MR_b}{K} \right)^{2}$$

$$E_b = \rho_c^{1.5} \times 0.043 \left( f'_c \right)^{0.5}$$

Choosing an appropriate Load Safety Factor (LSF) may be based on experience or refer to a detailed discussion on the selection of load safety factors can be found in Appendix C6.4.3.

For important roads, it is generally considered that the LSF used for settlement should be the same as that used for determining the thickness without settlement, i.e. $LSF_{settlement} = LSF_{no settlement}$, even where the horizontal movement of the top of the subgrade is small. However, when non-structural criteria for the settlement area, such as rideability, drainage considerations, or sight distance, are expected to be more critical than structural considerations, it may be appropriate to adopt a lower value of LSF for assessing the potential settlement area.

Creep Ratio ($CR$) refers to the effective change in strain due to creep, with the Effective Modulus of the concrete base $= E_b / CR_b$, and the Effective Modulus of the concrete subbase $= E_{sb} / CR_{sb}$. It also refers to the change in bending stress of the concrete base (or concrete subbase) for a particular increment of bending strain or for a constant curvature, caused by settlement, due to stress relaxation for concrete. See also under stress relaxation.

$$CR = 1 + k_2 k_3 \Phi_{cc.b} \left( 1 + \text{variation in } \Phi_{cc} \right)$$

where,

- $CR_b =$ Creep Ratio of the concrete subbase
- $CR_{b(n-i)} =$ for the strain increment that occurs during the “i”th period, i.e. $\varepsilon_i - \varepsilon_{i-1}$, is determined using $k_2$ and $k_3$ values (as per Austroads Bridge Design Code, 1992) for a time equal to (n–i) periods, and an appropriate value for $\Phi_{cc,b}$, noting:
\[ k_2, k_3 = \text{coefficients used for calculating the Creep Ratio (CR), where } k_2 \text{ depends on the environment and the period under constant strain (ie the conditions for stress relaxation) or constant stress (ie the conditions for creep), and } k_3 \text{ is a maturity coefficient.} \]

\[ k_3 \text{ (the maturity coefficient)} = 1.0 \text{ for concrete with a Coefficient of Variation (CV) of about 12\%.} \]

\[ k_3 \text{ depends on the strength ratio of } f_{cm}/f'_{c}, \text{ see Austroads Bridge Design Code, 1992, Figure 5.6.1.8 (B)); noting } f_{cm} \text{ is the mean value of the compressive strength of the concrete at the relevant age and } f'_{c} \text{ is the characteristic compressive strength at 28 days; and when } f_{cm}/f'_{c} \text{ is about 1.2, and } f_{cm} \text{ is at 28 days, this corresponds to a CV of 0.20/1.645 = 0.12, i.e. 12 \% and so } k_3 = 1.0, \text{ see Table 1.8 in the main body of the Guide.} \]

\[ 1000/R = 1000 \times \text{curvature} \]

\[ \text{Strain } \varepsilon = \frac{t_b}{2R(1-v^2)} \]

The amount of stress relaxation is calculated by dividing the period of settlement into time periods. Now the strain at the end of Period 1 has the most time for stress relaxation. If stress relaxation is analysed using yearly periods, and if settlement over 40 years is considered, the strain at end of year 1 is assumed to have stress relaxation for 39 years. Likewise the strain at the end of year 2 minus the strain at the end of year 1 has stress relaxation for 38 years, and so on.

Therefore, the stress at the end of \( n \) years is as follows:

\[
\sigma_n = \left[ \frac{\varepsilon_i}{CR_{b(n-1)}} \right] E_b + \left[ \frac{\varepsilon_2 - \varepsilon_1}{CR_{b(n-2)}} \right] E_b + \left[ \frac{\varepsilon_3 - \varepsilon_2}{CR_{b(n-3)}} \right] E_b + \ldots + \left[ \frac{\varepsilon_n - \varepsilon_{n-1}}{CR_{b(0)}} \right] E_b
\]

Where:

\[ \varepsilon_i = \text{strain at the end of the } i^{th} \text{ period} = \frac{t_b}{2R(1-v^2)} \]

\[ R_i = \text{radius of curvature at end of the } i^{th} \text{ period, and} \]

\[ CR_{b(n-1)} = \text{the Creep Ratio of the base concrete for an increment of strain which will be experienced by the base for 'n-1' periods.} \]

\[ n = \text{time at which stress from bending from settlement, due to self-weight of the base concrete, is calculated.} \]

A particular increase in bending strain over a particular time period undergoes stress relaxation over the later time periods. The spreadsheet assumes the stress relaxation for a given increment of strain which occurred at a given time is a function not only of the elapsed time since the particular increment of strain was sustained (which is taken account of by \( k_2 \)) but is also a function of the properties of the concrete at that time. Therefore, the stress
relaxation for a given increment of strain uses the current values of $k$ and $\Phi_{cc,b}$ i.e. values for the age of the concrete when the increment of strain occurs.

The total bending stress from settlement at a given time sums the contributions to stress of each increment of strain. This means the values of $k$ versus time are shifted by one cell to the right.

**Creep Sheet:**

No data entry required on this sheet (refer to Figure D3).

---

**Figure D3:** The Creep Sheet of the spreadsheet.
**k2 Factor Sheet:**
A user specified $k_2$ at start of each period in needed (refer to Figure D4).

![k2 Factor Sheet](image)

**Figure D4:** A view of the k2 Factor sheet of the spreadsheet.

**Settlement Sheet:**
The rate of settlement may be entered as logarithmic, uniform or user defined for each year (refer to Figure D5).

For the logarithmic rate of settlement:
- $R$ at $x$ years after start of secondary creep settlement ($R_x$) (m)
- Time to reach $R_x$ since start of secondary creep settlement (years)
- Time of paving ($t_0$), relative to start of secondary creep settlement (years)

$$R_x = R \text{ at } x \text{ years after start of secondary creep settlement}$$
\( t_{R_x} = \text{time to reach } R_x \text{ since start of secondary creep settlement} \)

\( t_o = \text{time of paving relative to start of secondary creep settlement} \)

The curvature (x 1000) due to settlement at time \( i \) since the start of settlement is given by:

\[
= \frac{1000}{R_x} \times \frac{1}{\log(t_{R_x})} \times \log(t_i)
\]

The curvature (x 1000) at the time of pavement due to settlement is given by:

\[
= \frac{1000}{R_x} \times \% \text{ of } \frac{1000}{R_x \text{ at } t_0}
\]

\[
= \frac{1000}{R_x} \times \frac{1}{\log(t_{R_x})} \times \log(t_0)
\]

The curvature (x 1000) due to settlement at time \( i \) since the start of pavement is given by

\[
\frac{1000}{R_i(m-1)} = \frac{1000}{R_x} \times \frac{1}{\log(t_{R_x})} \log(t_{i+t_0}) - \frac{1000}{R_x} \times \frac{1}{\log(t_{R_x})} \times \log(t_0)
\]

where \( R_i \) is change in \( R \) since paving.

If a value for \( k_2 \) is selected based on the total time from the start of settlement of the concrete layer to the end of the design period, this will overestimate the stress relaxation of stresses from bending from settlement. This is because latter increments of bending strain from the increasing settlement will not experience the same amount of time for stress relaxation. Therefore, the true solution lies between that determined for \( CR_h = 1.0 \) and that using a \( CR_h \) based on \( k_2 \) from the start of settlement of the concrete layer to the end of the design period. For more precision, with regard to calculating stresses from bending, an incremental analysis has been used in the spreadsheet. Alternatively, a \( CR_h = 1.0 \) can be adopted for calculating bending stresses, realising this may be far too conservative. On the other hand, if \( CR_h = 1.0 \) is used for calculating the shortening of a layer, this will underestimate the actual shortening.)

Table D1 shows values that have been derived from Austroads Bridge Design Code, 1992, using Figure 5.6.1.8 (A), with \( h_b = 400 \) (i.e. thickness of base concrete = 200 mm) and Table 5.6.1.8 (A). For thicknesses of base concrete greater than 200 mm but less than
250 mm, there will be a slight reduction in $k_2$, but this is considered only to be minor and so can be ignored.

Values of $k_2$ are independent of $f_c$.

For a uniform rate of settlement:

- $R_{\text{final}}$ (m)
- Time to reach $R_{\text{final}}$ (years)

The final settlement radius (m) and time required for settlement to reach this radius is entered. The curvature for each yearly period is then determined by the piecewise function:

$$\left(\frac{1000}{R}\right)_i = \begin{cases} 
\frac{1000}{R_{\text{final}}} & \text{if } i < t_{R_i} \\
\frac{1000}{R_i} & \text{if } i \geq t_{R_i}
\end{cases}$$

If a user defined settlement is applied, $1000/R$ (m-1) for each time period. A user defined curvature at the end of each period can be entered if desired. Additionally, these cells are utilised by the VBA and set to zero.

The spreadsheet uses $1000/R$ as the curvature of the settlement bowl. As we are dealing with relatively large radii, and hence small curvatures, a factor of 1000 has been introduced to reduce rounding errors.

**Workings Sheet:**

A trial design base thickness is selected and the total fatigue and erosion damage is calculated for the entire traffic volume and composition during the 40 year design period. If either the fatigue or erosion damage exceeds 100%, then the trial thickness needs to be increased for the current pavement type and service conditions (refer to Figure D6). Determining Critical Conditions for $B_{fc}$ and $B_{et}$ is discussed in Appendix C5.

![Figure D6: A view of the Workings sheet of the spreadsheet.](image-url)
### Table D1: Value of Creep Coefficient, $k_2$ for concrete bases between 200 mm and 250 mm

<table>
<thead>
<tr>
<th>Time for a particular increment of strain (n-i)</th>
<th>$k_2$ (at start of period) for tropical &amp; near coastal environment (Approx RH 70%)</th>
<th>$k_2$ (at start of period) for temperate inland environment (Approx RH 60%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 yrs (i.e. 0 - 1 yr)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 yr (i.e. 1 – 2 yrs)</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>2 yr (i.e. 2 – 3 yrs)</td>
<td>0.30</td>
<td>0.36</td>
</tr>
<tr>
<td>3 yrs (i.e. 3 – 4 yrs)</td>
<td>0.36</td>
<td>0.43</td>
</tr>
<tr>
<td>4 yrs (i.e. 4 – 5 yrs)</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>5 yrs (i.e. 5 – 6 yrs)</td>
<td>0.39</td>
<td>0.47</td>
</tr>
<tr>
<td>6 yrs (i.e. 6 – 7 yrs)</td>
<td>0.41</td>
<td>0.49</td>
</tr>
<tr>
<td>7 yrs (i.e. 7 – 8 yrs)</td>
<td>0.42</td>
<td>0.51</td>
</tr>
<tr>
<td>8 yrs (i.e. 8 – 9 yrs)</td>
<td>0.44</td>
<td>0.53</td>
</tr>
<tr>
<td>9 yrs (i.e. 9 – 10 yrs)</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>10 yrs (i.e. 10 – 11 yrs)</td>
<td>0.47</td>
<td>0.57</td>
</tr>
<tr>
<td>11 yrs (i.e. 11 – 12 yrs)</td>
<td>0.47</td>
<td>0.57</td>
</tr>
<tr>
<td>12 yrs (i.e. 12 – 13 yrs)</td>
<td>0.47</td>
<td>0.57</td>
</tr>
<tr>
<td>13 yrs (i.e. 13 – 14 yrs)</td>
<td>0.47</td>
<td>0.57</td>
</tr>
<tr>
<td>14 yrs (i.e. 14 – 15 yrs)</td>
<td>0.47</td>
<td>0.57</td>
</tr>
<tr>
<td>15 yrs (i.e. 15 – 16 yrs)</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>16 yrs (i.e. 16 – 17 yrs)</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>17 yrs (i.e. 17 – 18 yrs)</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>18 yrs (i.e. 18 – 19 yrs)</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>19 yrs (i.e. 19 – 20 yrs)</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>20 yrs (i.e. 20 – 21 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>21 yrs (i.e. 21 – 22 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>22 yrs (i.e. 22 – 23 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>23 yrs (i.e. 23 – 24 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>24 yrs (i.e. 24 – 25 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>25 yrs (i.e. 25 – 26 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>26 yrs (i.e. 26 – 27 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>27 yrs (i.e. 27 – 28 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>28 yrs (i.e. 28 – 29 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>29 yrs (i.e. 29 – 30 yrs)</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>30 yrs (i.e. 30 – 31 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>31 yrs (i.e. 31 – 32 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>32 yrs (i.e. 32 – 33 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>33 yrs (i.e. 33 – 34 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>34 yrs (i.e. 34 – 35 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>35 yrs (i.e. 35 – 36 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>36 yrs (i.e. 36 – 37 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>37 yrs (i.e. 37 – 38 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>38 yrs (i.e. 38 – 39 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>39 yrs (i.e. 39– 40 yrs)</td>
<td>0.50</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Graphs Sheet:
No data entry required on this sheet (refer to Figure D7).

Figure D7: A view of the Graphs sheet of the spreadsheet.
Varying Bc Sheet:
No data entry required on this sheet (refer to Figure D8).

Bc for log stimnt Sheet:
The two data entry values required on this sheet are (refer to Figure D9):

- Number of \( B_c \)
- Number of paving periods

Figure D8: A view of the Varying Bc Sheet of the spreadsheet.

Figure D9: A view of the Bc for log stimnt sheet of the spreadsheet.
Bfs & Bst Life Sheet:
No data entry required on this sheet (refer to Figure D10).

Figure D10: A view of the Bfs & Bst Life sheet of the spreadsheet.

Traffic Sheet:
The data entry values required on this sheet are (refer to Figure D11):

- Traffic growth type
  - 1 = geometric growth
  - 2 = linear growth
  - 3 = user specified
- Total traffic for carriageway in first timer period (Type 1 & 2) (HVAG)
- Annual geometric growth rate (Type 1) (%)
- Annual increment relative to first year (Type 2) (%)
- Axle group proportions for SAST, SADT, TAST, TADT, TRDT and QADT
- Axle group/axle group load distributions
Figure D11: A view of Traffic sheet of the spreadsheet.

Stage 2 Sheet:
The two data entry values required on this sheet are (refer to Figure D12):

- Number of $B_c$
- Number of MR

Figure D12: A view of Stage 2 sheet of the spreadsheet.

Stage 3 Sheet:
The two data entry values required on this sheet are (refer to Figure D13):

- Number of $B_c$
- Number of effective subgrades
Stage 4 Sheet:
The two data entry values required on this sheet are (refer to Figure D14):

- Number of $B_c$
- Number of effective subgrades

Factors Sheet:
No data entry required on this sheet.
D6 Procedure

Table D1 lists the procedure to be undertaken for the calculation of $B_c$ from Austroads pavement design method for rigid pavement in Chapter 9 (Austroads, 2012).

Table D2  A description of the nine steps in the use of the spreadsheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Calculate the expected load repetitions of each axle group load of each axle group type.</td>
</tr>
<tr>
<td>B</td>
<td>From the project Traffic Load Distribution, obtain the highest axle load for the SAST axle group and determine the allowable repetitions in terms of fatigue from Equation 26 and Equation 27.10 Calculate the ratio of the expected fatigue repetitions (Step 8) to the allowable repetitions (Step 9). Multiply by 100 to determine the percentage fatigue.</td>
</tr>
<tr>
<td>C</td>
<td>Determine from Equation 29 the allowable number of repetitions for erosion for the highest axle load for the SAST axle group.</td>
</tr>
<tr>
<td>D</td>
<td>Calculate the ratio of the expected erosion repetitions (Step 8) to the allowable repetitions (Step 11). Multiply by 100 to determine the percentage erosion damage.</td>
</tr>
<tr>
<td>E</td>
<td>Repeat steps 9 to 12 for each axle group load up to a load level where the allowable load repetitions exceed 1011, at which point further load repetitions are not deemed to contribute to pavement distress.</td>
</tr>
<tr>
<td>F</td>
<td>Sum the percentage fatigue for all relevant loads of this axle group type; similarly, sum the percentage erosion for all relevant loads of this axle group type.</td>
</tr>
<tr>
<td>G</td>
<td>Repeat steps 9 to 14 for each axle group type (i.e. SADT, TAST, TADT, TRDT and QADT).</td>
</tr>
<tr>
<td>H</td>
<td>Sum the total fatigue and total erosion damage for all axle group types.</td>
</tr>
<tr>
<td>I</td>
<td>Steps 9 to 16 inclusive are repeated until the least thickness that has a total fatigue less than or equal to 100% and also, a total erosion damage less than or equal to 100% is determined. This is the design base thickness.</td>
</tr>
</tbody>
</table>

D7 Discussion on workbook Sheet

D7.1 General

The following subsections provide discussion towards the use of the spreadsheet the in the areas of:

- Adequacy for Bfs
- Fatigue distress mode
- Adequacy for Bst
- Adequacy for Be
- Graphs
- Traffic
- Stages 2 to 4
D7.2 Adequacy for Bfs

This theory is discussed in detail in Appendix C5.4. 

\[ B_f = \text{base concrete thickness to satisfy distress from traffic and bending stresses (from self-weight) due to settlement.} \] 

It is based on the tensile stress from bending as a result of settlement (i.e. the settlement stress) and the tensile stress from traffic.

The settlement stress at any one time depends on the settlement history up to this point, and the stress relaxation. The spreadsheet takes this into account by analysing the effects of the changing of the radius of curvature with time and stress relaxation.

If there is a one-off settlement, then the value of the bending stress due to settlement at a particular time can be calculated, as for this situation the effect of stress relaxation at a particular time after the settlement, will be one value for \( CR_b \) (determined from the time since settlement).

This 'settlement stress', at this particular time is:

\[
S_s = \frac{t_b E_b}{2R(1-\nu^2)CR_b}
\]

The base thickness, \( t_b \) must be such that for each axle group:

\[ \frac{\text{Settlement Stress}}{\text{Modulus of Rupture}} \]

And has a magnitude for each axle group at its standard loading, for the \( t_b \) less than, or equal to:

\[ \frac{\text{Reduction in Traffic Stress}}{\text{Modulus of Rupture}} \]

due to the increase in thickness from \( B_f \) to \( t_b \).

To determine the minimum value of \( t_b \) to satisfy the above, an iterative trial and error procedure is required. This is illustrated in Figure D15 and shows the stress state for a base with settlement for increasing base thickness, for a particular axle group at a standard loading. For this figure the only constant stress is from bending as a result of settlement.

In Figure D15 the following is noted:

- Point A\(_1\) is the stress state before any settlement for base thickness of \( B_f \), that is traffic stress = \( S_e \) (for the particular axle group and standard load) and point B\(_1\) is the stress state for \( B_f \) after including bending stresses from settlement.
- As \( t_b \) is increased by an increment of thickness from \( B_f \), \( A_2 \) is the new stress state without settlement for the axle group with the standard load, and \( B_2 \) is the new stress state for this increased thickness after settlement.
• Similarly a further increment in thickness leads to $A_3$ and $B_3$, and then a further increment in thickness leads to $A_4$ and $B_4$, and finally $A_5$ to $B_5$.

• At this last thickness Figure D15 shows the stress state of point $B_5$ has the same fatigue life as $B_f$ without settlement as it is on the original fatigue curve of $N = 10^8$. This means the thickness to cause $A_5$ and $B_5$ is $B_f$. Note that the increments in thickness going from $A_1$ to $A_2$, and $A_2$ to $A_3$, and $A_3$ to $A_4$, and $A_4$ to $A_5$ will not be the same, as for this illustration, the increment for each step is that which reduces the variable stress/$MR_b$, i.e. the traffic stress/$MR_b$ by approximately one quarter of the total reduction required, which requires the actual increment in thickness in going from $A_1$ to $A_2$, and then $A_2$ to $A_3$, and then $A_3$ to $A_4$, and finally from $A_5$ to $A_6$, to be higher each time.

Figure D15 shows that the 'settlement stress/$MR_b$', which is a constant stress, increases as the base thickness increases, noting that the length of $A1 > A2 > A3 > A4$ to $B4$. This is a results to the bending stress from settlement, which is caused by self-weight of the concrete base, is proportional to the base thickness, provided the radius of curvature of the settlement profile is within tolerable values for concrete pavements which ensures a concrete pavement conforms to a settlement profile due to self-weight of concrete.

![Diagram](https://via.placeholder.com/150)

Figure D15: The effect of increasing concrete base thickness on the stress state due to a nominated traffic load and settlement situation (at a particular time)

\[
\frac{\text{Variable Stress}}{MR_b} = \frac{\text{Traffic Stress due to Nominated Traffic Load}}{MR_b}
\]
The fatigue lines and stress levels are only illustrative and so they cannot be used as a true indication of fatigue life.

This assumes an infinite fatigue life of concrete for variable stress, i.e. stress from traffic loading, less than $0.4MR_b$ where there is no constant stress.

For the purposes of illustration the Tepfers and Kutti equation has been used to determine the intercept of the fatigue contours on the vertical axis.

For a particular axle group, the used up fatigue life for a trial $t_b$, i.e. trial $B_c$, can be determined by the calculation of an equivalent $S_v$ for this trial $B_c$ for the standard loading for this axle group. This is called $S_{equiv-c}$. For the particular axle group and standard loading for this axle group the $S_{equiv-c}$ gives the same fatigue life for the trial $B_c$ for no settlement stress, as does the trial $B_c$ with the actual $S_v$ together with the settlement stress. The equation for $S_{equiv-c}$ is as follows:

$S_{equiv-c} = \frac{S_v \text{ for } t_b}{1 - \left(\sigma_{settlemnt} \text{ for trial } B_c / MR_b\right)}$

The used up fatigue life for this particular axle group for its axle load distribution is calculated using Miner’s Law.

When the trial $B_c$ has a total fatigue life for all axle groups and their respective axle load distribution equal to (or greater) than $B_f$ for no settlement, then this particular trial $B_c$ is $B_{fs}$.

Note that if the settlement is too large, then settlement stress for base thickness of $B_f$ will be large, and no increase in thickness will be able to be found to satisfy the required fatigue life, as settlement stress just becomes increasingly excessive with each increase in trial $B_c$.

The method for determining $B_{fs}$ is conservative for convex settlement. Therefore where convex settlement is more severe than concave settlement, more work may show a lower base thickness can be used than determined assuming concave settlement. Such work would need to include a study of:

- the interaction of traffic, negative temperature gradient and convex settlement
- the nature of contact of base slabs on subbase for convex settlement profiles

While convex settlement can be beneficial for PCP-D, JRCP and CRCP, it is detrimental to PCP and PCP-R as for these two pavements convex settlement results in corner cracking.)
D7.3 Fatigue distress mode

Fatigue damage is determined by Miner’s rule. Miner’s rule states that, for mixed traffic loading, fatigue failure will occur when:

\[ \sum_i \frac{n_i}{N_i} \]

Reaches a value of 1, where:

- \( n_i \) = the number of passages (within the mixed traffic loading) of type \( i \), and
- \( N_i \) = the number of passages of loading type \( i \) which will cause fatigue failure when loading type ‘\( i \)’ is the ONLY loading applied.

The summation is taken over all loading types present in the mixed traffic. For each axle group load and load type the expected repetitions is calculated by:

\[ \text{ExpReps} = \text{Design Lane Traffic in the Period (HVAG)} \times \text{Axle Group Proportion} \times \text{Axle Group Load Proportion} \]

Design Lane Traffic in the period (HVAG) = Total Period Traffic for Carriageway (HVAG) \times \%HVAG in the Design Lane

The fatigue is then calculated for each axle group load and axle group type combination. The allowable repetitions for each axle group load and axle group type combination are then determined based on (Axle Group Type) ES, (Axle Group Type) Reps and load type.

\[ S_{r1} = \frac{1}{\frac{1}{MR} \times f_{cf}} \]

\[ S_{r2} = \left( \frac{S_r \times \text{Fatigue AdjFactor} \times P}{4.45F_t} \right)^{0.94} \left( \frac{1}{\frac{\text{Settlement Stress} + \text{Extra Tensile Stress}}{\text{Flex Strength}}} \right) \]

\[ S_r = S_{r1}S_{r2} \]

\[ \text{ExpReps} = \text{ExpReps} \times (\text{Axle Group}) \text{Reps} \]

If \( S_r > 0.55 \)

\[ \text{AllowReps} = 10^{\left( \frac{0.9719 - S_r}{0.0828} \right)} \]

If \( 0.45 \leq S_r \leq 0.55 \)

\[ \text{AllowReps} = \left( \frac{4.258}{S_r - 0.4325} \right)^{3.268} \]

The fatigue life of all axle groups with their respective axle load distribution is calculated using Miner’s Law.

\[ \text{Fatigue} = \frac{\text{ExpReps}}{\text{AllowReps}} \]

\[ \text{FatigueSum}_i = \text{FatigueSum}_{i-1} + \text{Fatigue}_i \]
These calculations are completed for each axle group type and axle group load with the summation of all fatigues. According to Miner’s rule the resulting summation represents the total fatigue experienced by the pavement during the current time period.

D7.5 Adequacy for Bst

The adequacy for Bst is also discussed in Appendix C6.4.2.

For a pavement to have the same ability to withstand an isolated heavy load, after settlement has occurred, the tensile stresses from positive temperature gradient in the slab need to be assessed. This is typically the critical temperature differential for traffic loading. As a result the base thickness needs to be increased above $B_f$, which is needed for fatigue without settlement.

The spreadsheet allows for the effect of a change in curvature due to self-weight of the concrete from settlement over time, and the associated change in bending stresses from stress relaxation over time to be calculated.

The philosophy is to provide a base concrete thickness which, after taking into account bending due to self-weight of the concrete as a result of settlement, and stresses due to positive temperature gradient, has the same capacity for isolated heavy vehicles as $B_f$ has without settlement.

As a result the calculation ensures the sum of stresses for a single overload is less than rupture stress, rather than being an issue of fatigue due to multiple passes for a certain design stress.

For $B_f$ without settlement the available capacity for traffic stresses after taking account of stresses due to positive temperature gradient $= 1 - \left( \frac{Z_{B_f}}{MR_{B_f}} \right)$, where $Z$ = tensile stress due to positive temperature differential, and so the capacity for traffic stresses from a heavy vehicle compared to a particular axle group at its standard load used for determining $S_e$ for this particular axle group $= \left[ 1 - \left( \frac{Z_{B_f}}{MR_{B_f}} \right) \right] / \left[ S_e \right]$, where $M_{B_f}$.

Therefore, to determine the thickness ($B_{st}$) needed for isolated heavy vehicles after taking into account settlement stresses and stress due to positive temperature gradient requires finding the minimum $B_{st}$, for each axle group at its standard loading, to satisfy the following equation:

$$\left( 1 - \frac{Z_{st}}{MR_{st}} \right) \frac{S_e \text{ for } B_{st}}{MR_{st}} \geq \left( 1 - \frac{Z_{B_f}}{MR_{B_f}} \right) \frac{S_e \text{ for } B_f}{MR_{B_f}}$$

where ‘Settlement Stress’ is the stress after taking into account stress relaxation.

Once the minimum possible value of $B_{st}$ is obtained for each axle group, the larger of these
values adopted as $B_{st}$.

So as long as each year uses less than 100% of fatigue capacity then the pavement is considered satisfactory for heavy loads in conjunction with positive temperature gradient, where the value for $B_f$ for each year is determined on the basis of the traffic for that year. If the $B_f$ were to be calculated on the basis of the total traffic over the design period, it would be larger, and this would mean the calculated $B_{st}$ would be too conservative.

$B_f$ is based on the traffic for the year being examined

$Z = \text{tensile stress due to positive temperature gradient, using a nominated value, or using a formula related to base thickness, and other parameters, such as the AASHTO (1998) formula.}$

$B_{st}$ is subjected to the same fatigue distress mode calculations as $B_f$. However firstly the minimum, maximum $B_f$ for SS, SD, TAD or TRD must be determined. Once determined the minimum of max $B_f$ for all axle groups is selected as the concrete base thickness for the fatigue calculations.

$B_c = \text{minimum construction thickness of the base concrete}$

$B_e = \text{base concrete thickness to satisfy the erosion distress from traffic}$

$B_f = \text{base concrete thickness to satisfy the fatigue distress from traffic}$

$B_{st} = \text{base concrete thickness to ensure the base after experiencing bending stress (from self-weight) due to settlement, maintains the same capacity for stresses from a heavy load in conjunction with positive temperature gradient, that it had prior to settlement.}$

$Z = \text{tensile stress due to positive temperature gradient}$

### D7.6 Calculating the stress in the base due to a positive temperature difference

**StressFromTD:**

This spreadsheet uses the AASHTO (1998) formula for tensile stresses caused by positive temperature gradient. These are assumed to be unaffected by stress relaxation because of their cyclical nature, that is their short duration. Where possible the US terms for pavement layers of pavement and base has been replaced with the equivalent Austroads layers base and subbase respectively.

I psi = 6.89 kPa

$$l = \frac{E_cD^3}{12(1-\mu^2)k}$$

Equation 45 (supplement to the AASHTO Guide for Design of Pavement Structures V2R4)

$\mu = \text{Poisson's ratio for concrete}$

$k = \text{effective elastic modulus of subgrade support, (psi/in)}$
\[ E_c = \text{modulus of elasticity for concert base, psi} \]
\[ E_b = \text{modulus of elasticity of subbase, psi} \]
\[ D = \text{concrete base thickness, inches} \]
\[
\log(b) = -1.944 + 2.279 \frac{D}{l} + 0.0917 \frac{L}{l} - 433,080 \frac{D^3}{kl^4} + \left( \frac{0.0614}{l} \right) \left( \frac{E_b H_b^{15}}{1.4k} \right)^{0.5} - 438.642 \frac{D^2}{kl^2} - 498,240 \frac{D^3 L}{kl^6} 
\]

Equation 47 (supplement to the AASHTO Guide for Design of Pavement Structures V2R4)

\[ L = \text{joint spacing (inch)} \]
\[ TD = \text{effective positive temperature differential, top to bottom of base (deg.F)} \]

Effective Positive \( TD = 0.962 - \frac{52.181}{D} + 0.341 \times \text{WIND} + 0.184 \times \text{TEMP} - 0.00836 \times \text{PRECIP} \]

Eq 48 (supplement to the AASHTO Guide for Design of Pavement Structures V2R4)

\[ D = \text{concrete base thickness, inches} \]
\[ \text{WIND} = \text{mean annual wind speed, mph} \]
\[ \text{TEMP} = \text{mean annual temperature, deg.F} \]
\[ \text{PRECIP} = \text{mean annual precipitation, inches} \]

\[ F = 1.177 - 4.3 \times 10^{-8} DE_b - 0.01155542 D + 6.27 \times 10^{-7} E_b - 0.000315 f \]

Equation 46 (supplement to the AASHTO Guide for Design of Pavement Structures V2R4)

\[ f = \text{friction coefficient between base and subbase (refer to Table D3).} \]

Table D3: Value of Friction Coefficient for concrete bases between 200 mm and 250 mm

<table>
<thead>
<tr>
<th>Base type of interface treatment</th>
<th>Modulus of Elasticity (psi)</th>
<th>Peak Friction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Fine-grained soil</td>
<td>3,000 – 40,000</td>
<td>0.5</td>
</tr>
<tr>
<td>Sand</td>
<td>10,000 – 25,000</td>
<td>0.5</td>
</tr>
<tr>
<td>Aggregate</td>
<td>15,00 – 45,000</td>
<td>0.7</td>
</tr>
<tr>
<td>Polyethylene sheeting</td>
<td>NA</td>
<td>0.5</td>
</tr>
<tr>
<td>Lime-stabilised clay</td>
<td>20,000 – 70,000</td>
<td>3.0</td>
</tr>
<tr>
<td>Cement-treated gravel</td>
<td>(500 + CS) * 1000</td>
<td>8.0</td>
</tr>
<tr>
<td>Asphalt-treated gravel</td>
<td>300,000 – 600,000</td>
<td>3.7</td>
</tr>
<tr>
<td>Lean concrete without compounding</td>
<td>(500 + CS) * 1000</td>
<td>&gt;36</td>
</tr>
<tr>
<td>Lean concrete with single or double wax curing compound</td>
<td>500 + CS) * 1000</td>
<td>3.5</td>
</tr>
</tbody>
</table>

NOTE: CS = compressive strength in psi.

\[
\sigma_t = \frac{18,000}{D^2} \left[ 4.227 - 2.381 \left( \frac{180}{l} \right)^{0.2} - 0.0015 \left( \frac{E_b H_b}{1.4k} \right)^{0.5} - 0.155 \left( \frac{H_b}{E_c} \right)^{0.75} \right]^{0.4} 
\]

Equation 44 (supplement to the AASHTO Guide for Design of Pavement Structures V2R4)

\[ E_b = \text{modulus of elasticity of the concrete slab (psi)} \]
\[ E_c = \text{modulus of elasticity of the base (psi)} \]
\[ \sigma'_i = \sigma_i EF \left[ 1.0 + 10^{\log(b)} \right] T_D \]

Equation 43 (supplement to the AASHTO Guide for Design of Pavement Structures V2R4)

\( \sigma'_i \) = midslab tensile stress due to load and temperature from equation 43 with inputs from new pavement design

\( \sigma_i \) = midslab tensile stress due to load only, from equation 44

\( E \) = edge support adjustment factor

\( = 1.0 \) for conventional 3.66 m wide traffic lane

\( = 0.94 \) for conventional 3.66 m wide traffic lane plus tied concrete shoulder

\( = 0.92 \) for 0.6m widened slab with conventional 3.66 m lane width

\( F \) = ratio between base stress at a given coefficient of friction \( f \) between the base and subbase stress at full friction from equation 46

Stress from TD = \( \sigma'_i - \sigma_i \)

**Function Bf_for_AG2:**

If \( Z_{Bc} = 0 \), then the Bf_for_AG = Bc, this is because, if there is no tensile stress due to positive temperature gradient, then no reduction in Bc (thus forming Bf) is needed such that the pavement.

**Adequacy for \( B_{st} \):**

Starting at \( B_f = B_c \), \( B_f \) is iterated by reducing it by 1 mm at a time until Test 1 >= Test 2.

Reduces \( B_f \) by 1 until Test 1 >= Test 2 becomes true, hence finding the maximum \( B_f \) for a particular AG (Axle Group). Or until \( B_f = 125 \) mm.

\[ \text{Test } 1 = \left( 1 - \frac{Z_{Bc}}{MR_{bp}} - \frac{S_t}{MR_{b28}} \right) / S_E \left( \text{for } B_f \right) \]

**Function Bf_for_AG2:**

\[ \text{Test 2} = \left( 1 - \frac{Z_{Bc}}{MR_{bp}} \right) / S_E \left( \text{for } B_c \right) \]

\( \text{Test } 1 = \text{Test 2} \)

\( B_f := B_f - 1 \)

This is repeated for each AG and then the minimum of the maximum \( B_f \) for each axle group is selected as this represents the worst case scenario.

The smaller the \( B_f \) relative to \( B_e \) the greater the buffer for stresses from settlement

**D7.7 Adequacy for Be**

The procedure for the determination of the total erosion follows the same procedure as for the \( B_{st} \) fatigue distress mode, without the interactions of base thickness as required for \( B_{st} \).

The allowable load repetitions for \( (N_e) \) for a given axle load is given by equation 29 (Austroads)
\[
\log(F_2 N_e) = 14.524 - 6.777 \max \left( 0, \left( \frac{PL_{SF}}{4.45 F_4} \right)^2 \frac{10 F_3}{41.35} - 9.0 \right)^{0.103}
\]

\[F_2 = \text{adjustment factor for slab edge effects}\]
\[= 0.06 \text{ for base with no concrete shoulder}\]
\[= 0.94 \text{ for base with concrete shoulder}\]

\[F_3 = \text{erosion factor}\]
\[F_4 = \text{load adjustment factor for erosion due to axle group}\]
\[= 9 \text{ for SAT}\]
\[= 18 \text{ for SADT}\]
\[= 18 \text{ for TAST}\]
\[= 36 \text{ for TADT}\]
\[= 54 \text{ for TRDT}\]
\[= 54 \text{ for QADT}\]

\[\text{Factor} = \left( \frac{PL_{SF}}{4.45 F_4} \right)^2 \frac{10 F_3}{41.35} - 9.0\]

If Factor >0, then

\[\text{AllowReps} = 10^{(14.524 - 6.777 \times \text{Factor})^{0.103}} \times \text{shoulderFactor}\]

\[\text{Erosion} = \text{ExpReps} / \text{AllowReps}\]
\[\text{ErosionSum}_i = \text{ErosionSum}_{i-1} + \text{Erosion}_i\]

Applicable to longitudinal and transverse directions.

**D7.8 Graphs**

Graphs of the following are automatically generated with respect to the time period:

- 1000/R (since paving) at end of time period
- Used up capacity for $R_e$ (per year)
- Settlement Stress $/MR^5_{328}$
- Used up capacity for $B_e$ (per year)
- Used up capacity for $B_{fe}$ (per year)
- Used up capacity for $B_{st}$ (per year)

**D7.9 Varying Bc**

Generates graphs for:

- Used up capacity for $B_{fe}$
- Used up capacity for $B_{st}$ (for worst period)
Used up capacity for $B_c$

Over ten user defined minimum base thicknesses with a default from 220 to 265 mm in increments of 5 mm.

**D7.10 Bc for log stlmnt**

Generates a sensitivity analysis of used up capacity for $B_f$ and capacity for $B_B$ (for words period) with respect to variations in time of paving relative to start of secondary creep settlement and minimum construction base thickness $B_c$.

**D7.11 Bfs & Bst Life**

Graphs the expected pavement life for $B_f$ and $B_B$ for varying time of pavement relative to the start of secondary creep settlement.

**D7.12 Traffic**

Four different traffic load distributions can be entered, each with different axle group proportions and axle load distributions.

Total traffic for the carriageway for the first time period (HVAG) is also entered, then whether geometric or linear growth can be specified. Alternatively a user specified HVAG can be entered for each time period.

The equation used for annual geometric growth is

$$HVAG_{t+1} = HVAG_t \times (1 + r)$$

The equation used for annual incremental growth is:

$$HVAG_{t+1} = HVAG_t + HVAG_0 \times r$$

**D7.13 Stage 2**

When using, the user has to manually reset the design parameters before starting on the next stage as the last set of trial parameters remain on the sheet.

Generates a sensitivity analysis with respect to $B_c$ and Modulus of Rupture (MPa) for the following pavement properties:

- Life for $B_f$ (years)
- Life for $B_c$ (years)
- Minimum Life for $B_f$ and $B_c$ (years)
- Life for $B_f$ (HVAG)
- Life for $B_c$ (HVAG)
- Minimum Life for $B_f$ and $B_c$ (HVAG)
D7.14 Stage 3

When using, the user must manually reset the design parameters before starting on the next stage as the last set of trial parameters remain on the sheet.

Generates a sensitivity analysis with respect to $B_c$ and Effective subgrade CBR (%) for the following pavement properties:

- Life for $B_f$ (years)
- Life for $B_e$ (years)
- Minimum Life for $B_f$ and $B_e$ (years)
- Life for $B_f$ (HVAG)
- Life for $B_e$ (HVAG)
- Minimum Life for $B_f$ and $B_e$ (HVAG)

D7.15 Stage 4

When using, the user must manually reset the design parameters before starting on the next stage as the last set of trial parameters remain on the sheet.

Generates a sensitivity analysis with respect to Modulus of Rupture (MPa) and Effective subgrade CBR (%) for the following pavement properties:

- Life for $B_f$ (years)
- Life for $B_e$ (years)
- Minimum Life for $B_f$ and $B_e$ (years)
- Life for $B_f$ (HVAG)
- Life for $B_e$ (HVAG)
- Minimum Life for $B_f$ and $B_e$ (HVAG)

D7.16 Factors

Contains the tables coefficients for prediction of equivalent stresses, production of erosion factors for undowelled bases and for prediction of erosion factors for dowelled or CRCP bases.