INTRODUCTION TO CONCRETE PAVEMENTS

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February 2013

Abstract

This paper describes the experiences and design methodologies for concrete pavements in Australia. It is based on the selection and adoption of World’s best practices for design and construction of heavy duty pavements. It differentiates between rigid and flexible pavements.

The paper briefly describes the characteristics and profiles of the various pavements used with an overview of the four (main) concrete pavement types, i.e. the Plain Concrete Pavement (PCP), Jointed Reinforced Concrete Pavement (JRCP), Continuously Reinforced Concrete Pavement (CRCP) and Steel Fibre Reinforced Concrete (SFCP) Pavement. It explains the behaviour of rigid pavements under repeated external loads and internally developed stresses.

To illustrate the differences with flexible pavements, a schedule of the design Elastic Moduli of various pavement materials is provided. The unique method of determining the equivalent subgrade strength over 1 m thickness is explained and demonstrated. The use of the Lean Mix Concrete subbase is peculiar to concrete pavements and its role is explained.

1 Purpose

The purpose of this paper is to provide a summary overview and a general introduction to the types and performance characteristics of concrete pavements. It is not intended as a design guide for practitioners but an introduction to the principles of design methodology, requirements and the benefits of concrete pavements.

2 Elements of a Concrete Pavement

A concrete pavement is a structure comprising of a layer of Portland cement concrete (base) which is usually supported by a subbase layer on the subgrade. The terminology used in Australia is illustrated in Figure1. Concrete pavements may be either unreinforced (plain) or reinforced depending on how the designer prefers to control shrinkage cracking, which will occur in the pavements.
Figure 1 – Concrete Road Pavement Structure

The high modulus of elasticity and rigidity of concrete compared to other road making materials provides a concrete pavement with a reasonable degree of flexural or “beam” strength. This property leads to externally applied wheel loads being widely distributed. This in turn limits the pressures applied to the subgrade as illustrated in Figure 2. The major portion of the load carrying capacity of a concrete pavement is therefore provided by the concrete layer alone. Its thickness is primarily determined by the flexural strength of the concrete and by the magnitude of the wheel or axle loads.

Figure 2 – Distribution of Wheel Loads under Concrete Pavements

Subbases do not make a significant structural contribution to concrete pavements. The purpose of the subbase is to provide uniform support to the base concrete layer and to provide sufficient resistance to erosion of the subbase material under traffic and environmental conditions. Only lean mix concrete or bound subbases are recommended in the design guides, but in Australia 150 mm of the former is adopted as a norm.

By contrast, a flexible pavement is a structure comprising a number of layers of bound or unbound materials which can have a variety of surface treatments and in which the intensity of stresses from traffic loads requires a lot more depth to diminish as illustrated in Figure 3. Both the base and subbase layers in flexible pavements contribute significantly to the structural properties of the pavement.
Although the strength of the subgrade does not significantly affect the thickness of the concrete pavement, unlike the situation with flexible pavements where the thickness is more sensitive to variations in the subgrade strength, the proper design and construction of the subgrade and subbase is still important to the performance and long term serviceability of a concrete pavement.

Table 1 compares the large and very significant variations of the Elastic Moduli between concrete and flexible pavement materials. For identical loading, it is obvious that the performance of concrete pavements would be greatly superior.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of Elasticity MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural material CBR 10%</td>
<td>100 (150 absolute max)</td>
</tr>
<tr>
<td>Unbound dense graded gravel</td>
<td>500</td>
</tr>
<tr>
<td>2% cement modified dense graded gravel</td>
<td>2,000</td>
</tr>
<tr>
<td>5% cement stabilised material</td>
<td>5,000</td>
</tr>
<tr>
<td>Dense Graded Asphalt</td>
<td>Av 3,500</td>
</tr>
<tr>
<td>Open Graded Asphalt</td>
<td>No design strength</td>
</tr>
<tr>
<td>5 MPa Lean Mix Concrete</td>
<td>10,000</td>
</tr>
<tr>
<td>35 MPa concrete</td>
<td>30,000</td>
</tr>
</tbody>
</table>

Table 1 – Comparison of Moduli of Elasticity

Where provided, steel reinforcement is used for the control of cracking resulting from drying shrinkage and subsequent temperature changes within the pavement. It is important to note that this reinforcement is not for crack prevention nor to increase the flexural strength of the concrete base.

3 Types of Concrete Pavements

As there are differences in the definitions of “flexible” and “rigid”, in Australia only cementitious concrete pavements are regarded as rigid, with all other types classified as flexible. The types of concrete pavements are:
1 Jointed Plain (unreinforced) Concrete Pavement – PCP
2 Jointed Reinforced Concrete Pavement – JRCP
3 Continuously Reinforced Concrete Pavement – CRCP
4 Steel Fibre Reinforced Concrete Pavement – SFCP

A fifth type is the Prestressed Concrete Pavement, but this has not been used in Australia.

For bases, 35 MPa compressive strength (4.5 MPa flexural strength) concrete is used. For heavy duty (highway) pavements its specified that the minimum thickness is 230 mm for CRCP and 250 mm for PCP. The lean mix concrete subbase has a characteristic 28 day compressive strength of 5 MPa and is designed with a low shrinkage characteristic of less than 450 µm.

3.1 Jointed Plain Concrete Pavement – PCP

- PCPs contain no reinforcement, except at special situations where irregularly shaped slabs or mismatching joints are involved
- PCP is the most common pavement for highways Worldwide
- 80% of the concrete pavement inventory in New South Wales (State) in Australia has PCP (the rest are mainly CRCP)
- Transverse contraction joints are induced by saw cuts and their spacing is determined by limiting the maximum shrinkage movement in the joint to 2 mm. This results in an average spacing of about 4.2 m (For longer lengths of up to 5 m, dowels have to be used).
- Longitudinal joints are either induced by saw cuts or formed. These have a maximum spacing of 4.3 m and are held together by suitably spaced 12 mm Ø deformed tiebars.

3.2 Reinforced Concrete Pavement – JRCP

- JRCPs are typically reinforced with welded steel fabric, usually F82 (8mm Ø bars at 200 mm centres)
- Transverse contraction joints are induced by saw cuts providing slab lengths of 8 m – 12 m. (Slab lengths are varied depending on the length of the mesh sheets available)
- JRCP joints are always dowelled.
- The criteria for longitudinal joints is the same as for PCP
3.3 Continuously Reinforced Concrete Pavement – CRCP

- CRCP has continuous longitudinal reinforcement of N16 Ø deformed bars to induce transverse cracking at random spaces of 0.5 – 2.5
- Nowadays the preferred location is central
- No contraction joints are provided
- Transverse reinforcement bars are provided to support the longitudinal steel and as a means of holding together any unplanned longitudinal cracks
- The criteria for longitudinal joints are the same as for PCP.
- Worldwide there is no universal agreement on the percentage of the longitudinal steel required. In Australia 0.65% of the cross sectional area of the slab is recommended, compared with 0.6% by FHWA, Texas 0.42% or US Corps of Engineers at 0.32%. In Belgium they have pavements with up to 0.8%.

3.4 Steel Fibre Concrete Pavement – SFCP

- SFCP is used in situations where there is a need to provide increased resistance to cracking in both odd shaped and acute cornered slabs and is ideally suited for areas with high proportion of slabs of irregular shape, e.g. roundabouts.
- Transverse and longitudinal contraction joints in SFCPs are undowelled and at a maximum spacing of 6 m
- Steel fibre is usually mixed at ~70 kg/m³ and the characteristic compressive strength of concrete is 40 – 45 MPa, giving a flexural strength of 5 MPa.
- Slabs are generally thinner than those of conventional concrete and have a minimum thickness of 180 mm.

3.5 Prestressed Concrete Pavement - PSCP

- PSCP is generally used for prefabrication of base slabs for replacement of damaged slabs in all types of concrete pavements
- This method has not been used in Australia

4 Lean Mix Concrete (LMC) Subbase

- LMC subbases are constructed as mass concrete without transverse or longitudinal joints and therefore will develop cracks.
• Limiting both the upper strength of the concrete and shrinkage will control cracking.
• It is intended to achieve a pattern of relatively closely spaced and narrow cracks that will also provide a degree of load transfer and which in conjunction with the debonding layer will not reflect or effect the structural base.
• Even though LMC is non-structural in design, it has an important role to perform:
  - to provide a working platform
  - to resist erosion of the subgrade and limit the likelihood of “pumping” at joints and slab ends
  - to provide uniform support for the base slab
  - to reduce deflections at joints
  - to enhance load transfer across the joints
  - to assist controlling swell/shrinkage of high-volume-change soils in the subgrade
  - to provide accurate levels for the base

5 Principles of Pavement Design

The Australian design methodology is based on the USA Portland Cement Association (PCA 1984, Packard 1984) method with a number of revisions developed from practical experience and to suit local conditions. Broadly, it is based on the assessment of the:
• predicted traffic volume and composition of Heavy Vehicle spectrum over the design period;
• strength of the subgrade in terms of the California Bearing Ratio (CBR), and
• flexural strength of the base concrete.

Rather than using a bound subbase, in Australia it has become the norm to provide a lean mix concrete (LMC) subbase. The reasons for this are listed in section 4. As already mentioned, the LMC subbase is not a structural layer.

5.1 Subgrade Strength Evaluation

• The strength of the subgrade is assessed in terms of the California Bearing Ratio (CBR).
• For the benefit of designers who use the Modulus of Subgrade Reaction (k), the relationship with CBR is approximately:

<table>
<thead>
<tr>
<th>CBR %</th>
<th>k (kPa/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 2 – Equivalencies of CBR and Modulus of Subgrade Reaction
In concrete pavement design, all materials within one metre below the subbase are assessed for the determination of the average design subgrade CBR. It is not permissible to adopt the CBR of just the (thin) layer immediately below the subbase.

It is also normal to provide 300 mm of selected subgrade material of CBR >5% (preferably 10+ %), if the subgrade has a CBR <5%.

The depth of the selected subgrade material below the subbase is increased to 600 mm if expansive clays are encountered.

With this information the Equivalent Subgrade strength is calculated using the Japan Road Association equivalency formula:

$$CBR_{eq} = \left[\frac{\Sigma h_i CBR_i^{0.333}}{\Sigma h_i}\right]^3$$

where: $CBR_i$ is the CBR value of $i^{th}$ layer

$h_i$ is the thickness of $i^{th}$ layer (m)

$\Sigma h_i$ is taken to a depth of 1.0 m

For example, assuming that there are only two layers of 300 mm of CBR 15% and 700 mm of CBR 2%, then:

$$CBR_{eq} = \left[0.3 \times 15^{0.333} + 0.7 \times 2^{0.333}\right]^3 = 4.3$$

As the 150 mm of LMC subbase is non-structural, it also forms part of the “subgrade” and hence the Effective Subgrade strength can be calculated, e.g.:

<table>
<thead>
<tr>
<th>CBR\text{equivalent} (%)</th>
<th>CBR\text{effective} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3 – Equivalent vs Effective Subgrade Strength

This means that for Equivalent CBR values of >5% there is no change in the design CBR value.

5.2 Base Thickness Design

There are two distress modes considered in the design procedure:
- Flexural fatigue cracking, which mainly applies to CRCP and dowelled pavements, and
- Subgrade/subbase erosion arising from repeated deflections at joints and planned cracks. This mainly applies to jointed unreinforced pavements.
• The predicted repetitions of the Heavy Vehicle Axle Group (HVAG) loading spectrum are one of the main inputs to the calculations.
• A trial base thickness is selected and the total fatigue and erosion damage is calculated for the entire traffic volume and composition during the design period. The damage is based on the proportions of the predicted and allowable repetitions for each HVAG combination.
• The Effective subgrade strength is used for the calculation for the support available for the base slab.
• If either fatigue or erosion damage exceeds 100%, then the trial base thickness is increased and the design process repeated.

6 Concrete Pavements

6.1 Benefits

The beneficial attributes of concrete pavements can be summarised as:

1. Longer lasting – 40 year Design Life (some States in US ale already using 50 years and even this may increase in the future).
2. Heavy duty Pavements have generally the lowest cost.
3. Pavement maintenance costs are up to 10 times cheaper than the same for flexible pavements.
4. Minimum maintenance requirements result in less traffic disruption, minimum congestion time and as a result Work zone safety.
5. Lowest Life Cycle Cost of all Heavy Duty pavements and highest salvage value.
6. Can be constructed over poor subgrades.
7. Thinner overall pavement thickness = lower consumption of raw materials.
8. Resistant to abrasion from turning actions.
9. Not susceptible to high or low temperatures.
10. No affected by weather, inert to spills and fire.
11. Completely recyclable.
12. High abrasion durability.
13. Profile durability.
14. Safer because it maintains its shape, no deformation, resistance to rutting and potholes and excellent skid resistance.
15. High sustainability rating through use of local materials.
16. Use of waste products like flyash and slag.
17. Riding quality does not deteriorate.
18. Can be slipformed up to 13 m.
19. Saving of fuel costs of at least 1.1% over asphalt (VTI Sweden – 1.1% 2008, NRC Canada – 0.8 to 6.9%).
20. Light colour enhances night visibility.
21. Less energy for street lighting (up to 30%).
22. Less heatsink effect (av 8°C lower than asphalt = less air conditioning energy in urban areas.
23. Longitudinal diamond grinding, called Next Generation Concrete Surfacing (NGCS) now provides quieter surface than for example Open Graded Asphalt overlay.
6.2 Negatives

- To provide economics and quality, it requires larger projects.
- Set-up costs are significant.
- On-site batch plant is essential for slipforming.
- Slipforming requires minimum 200 m runs.
- Concrete must achieve a certain strength before it can be placed under traffic (in Australia 20 MPa, in US ~10 MPa).
- Repairs take longer = traffic disruption and work site safety.
- Unless longitudinal grooving is used, tyre/road noise can become a nuisance issue in urban areas after 80/90 km/h speeds. (Transverse texturing creates higher frequency noise that is objectionable to some: concrete = 1100 Hz vs asphalt = 800Hz).

References

2. Green Highways, American Concrete Pavement Association, Baton Rouge, Louisiana - April 2008
3. Doolan C. Concrete Pavements. Main Roads Western Australia - August 2010
5. RTA Specification R82 – Lean Mix Concrete Subbase
6. RTA Specification R83 – Plain Concrete Pavement
7. RTA Specification R84 – Continuously Reinforced Concrete Pavement
13. Tinni A. Reasons and Effect of Cracking in Lean Mix Concrete Subbases.