Structural Design of Pavements

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1. INTRODUCTION

In many countries concrete pavement structures are becoming increasingly popular due to competitive investment costs and lower maintenance costs (in comparison with asphalt pavements) and due to an increasing confidence in a good long term pavement behavior (caused by more reliable design methods and better construction techniques).
This course intends to explain the principles of the structural design of the two most widely applied types of concrete pavement, which are plain (unreinforced) concrete pavements and continuously reinforced concrete pavements.

In chapter 2 the materials usually applied in the various layers of (un)reinforced concrete pavements are described in general terms. Furthermore (indicative) values for the most important material properties are given.
Chapter 3 explains the usually applied theories for the calculation of the flexural tensile stresses (and the vertical displacements) within the concrete top layer due to the most important (external) loadings. These are not only the traffic loadings but also the temperature gradients and unequal subgrade settlements. Next the principles of the fatigue analysis, to take into account the repeated traffic loadings together with the temperature gradient loadings, are discussed. Furthermore, the applicability of the finite element method with respect to the structural design of concrete pavements is reviewed in general terms.
In chapter 4 first some existing empirical concrete pavement design methods and the flowchart of some analytical design methods are briefly described, and a critical review about the applicability of these two types of design method is presented.
Finally, in chapter 5 the Dutch analytical structural design method for concrete pavements is discussed. The original method (developed in the eighties) as well as the (in the nineties) revised method, both only valid for plain concrete pavements, are briefly discussed. Emphasis is laid on the current method, released early 2005 as the software program VENCON2.0, that covers both plain and reinforced concrete pavements.

2. CONCRETE PAVEMENT STRUCTURE

2.1 General

The top layer of a concrete pavement structure consists of cement concrete that exhibits an elastic behavior until the moment of failure (cracking). Cement concrete has a very high Young's modulus of elasticity, which results in a great load spreading in the top layer and hence in low stresses in the underlying substructure (base plus sub-base plus subgrade).

There are three possibilities to prevent uncontrolled cracking of the top layer due to shrinkage of the concrete, which occurs during the hardening process and in hardened concrete due to a decrease of temperature:

- in plain (unreinforced) concrete pavements every 3 to 6 m a transverse joint is made, and in wide pavements also longitudinal joints are made; this means that the pavement is divided into concrete slabs;
- in reinforced concrete pavements such an amount of longitudinal reinforcement (0.6 to 0.75%) is applied, that every 1.5 to 3 m a very narrow crack occurs;
- in prestressed concrete pavements by prestressing such compressive stresses are introduced that the (flexural) tensile stresses due to shrinkage, temperature and traffic loadings stay within acceptable values.

Prestressed concrete pavements are such a specialized (and costly) type of concrete pavement structure, that they are only applied at some airport-platforms (for instance at Amsterdam Airport Schiphol), where 'zero maintenance' is very important. In this lecture note no further attention will be given to prestressed concrete pavements.

The thickness of the (un)reinforced concrete top layer is 150 to 450 mm, dependent on the traffic loadings, the climate, the concrete quality, the type of concrete pavement and the properties of the substructure materials.

Considering the great load spreading in the concrete top layer, for reasons of strength a base is not (always) necessary. Nevertheless, generally a base (with a high resistance to erosion) is applied to prevent as much as possible the loss of support of the concrete top layer, which could result in unevenness and/or early cracking of the concrete. Both cement-bound materials and unbound materials can be applied in the base. Generally, the base thickness is 150 to 300 mm.

A sub-base can be necessary to realize an embankment, to prevent damage due to frost action (in cold climates) or to strengthen the concrete pavement structure. However, especially on weak subgrades an important reason for application of a sub-base is that in this way a stable platform is created to construct the overlying base and/or concrete top layer.

2.2 Subgrade

The Young's modulus of elasticity of the concrete top layer is much higher than that of the underlying layers, which means that the top layer takes the main part of the traffic loading. This implies that the bearing capacity of the subgrade has only a small effect on the stresses in the concrete layer due to a traffic loading.

Due to this small effect, it is common use in the design of concrete pavement structures to simply schematize the subgrade as a Winkler-foundation, so into a system of independent vertical linear-elastic springs with stiffness k_o, the so-called 'modulus of subgrade reaction' (see 3.2).
The bearing capacity of the subgrade (modulus of subgrade reaction k_o) does have a great effect on the vertical displacements (deflections) of a concrete pavement structure due to a traffic loading.
Because of the characteristic behavior of a concrete pavement structure and the high repair costs in case of failure, it is important to use in the design of the concrete pavement structure a relative low modulus of subgrade reaction, for instance the value that has a 95% probability of exceeding.

Besides the bearing capacity also the settlement behavior of the subgrade is important.
Except the connection to bridges, founded on piles, equal settlements of the subgrade generally are not a problem.
However, by unequal subgrade settlements extra flexural stresses are introduced in the concrete pavement structure. The magnitude of these stresses is dependent on the wavelength and amplitude of the settlement pattern (related to the dimensions of the concrete pavement) and on the velocity of the settlement process (because of stress relaxation in the cement concrete) (see 3.5).

2.3 Sub-base

The thickness of the sub-base is dependent on the designed height level of the road surface, the frost penetration depth (in cold climates), the permeability and bearing capacity of the subgrade, the traffic loadings (especially during the construction of the road) and the properties of the sub-base material.
Generally, an unbound granular material (like gravel, crusher run, blast furnace slags, sand etc.) is applied for the sub-base. The grading should meet the filter laws to the subgrade material and eventually to the unbound base material.

Similar to the subgrade, also the bearing capacity of the sub-base has a limited effect on the stresses in the concrete layer due to a traffic loading and a considerable effect on the deflections of the concrete pavement structure due to a traffic loading.
In the design of concrete pavement structures the effect of a sub-base generally is taken into account by means of a certain increase (dependent on the thickness and Young's modulus of elasticity of the sub-base) of the modulus of subgrade reaction k_o (see 3.2).

In cold climates the sub-base may be within the frost penetration depth. In such cases the sub-base material should not be frost-susceptible.

In case of a good quality subgrade (sand or better) a sub-base in concrete pavement structures may not be necessary.

2.4 Base

2.4.1 General

For reasons of strength a base is not absolutely necessary in a concrete pavement structure because (similar to the subgrade and the sub-base) it has only a limited effect on the stresses in the concrete layer due to a traffic loading. However, there are other reasons why in concrete pavement structures nowadays nearly always a base is applied, such as:

- below the concrete top layer there has to be a layer with a high resistance to erosion, to ensure a good support of the concrete layer and to prevent ‘pumping’ of fine material through joints and cracks;
- by applying a base, the deflection of the concrete pavement structure due to a traffic loading is considerably reduced, which is very favorable with respect to the long-term pavement behavior (especially the evenness around joints in plain concrete pavements);
- the construction traffic and the construction equipment (slipformpaver) for the concrete layer require an even surface with sufficient bearing capacity; in general, the sub-base and especially the subgrade cannot fulfill these requirements.

At each side of the road the base has to be at least 0.5 m wider than the concrete layer, to give sufficient support to the slipformpaver.
To obtain an equal thickness of the concrete top layer, the surface of the base has to be rather even, for instance a maximum deviation of 15 mm over a distance of 3 m.
In cold climates the base is within the frost penetration depth and therefore has to be frost-resistant.

As base materials in concrete pavement structures especially unbound materials and cement-bound materials are applied.

2.4.2 Unbound base

An unbound base material has to fulfill the following requirements:

- a good permeability to remove as soon as possible (to the sub-base or subgrade) the rainwater that entered the concrete pavement structure;
- a good resistance to crushing to prevent frost-susceptibility and to prevent loss of support of the concrete top layer due to erosion;
- a good resistance to permanent deformation to prevent as much as possible loss of support of the concrete top layer due to the repeated traffic loadings.

Well graded crusher run, (high quality) gravel etc. can be used as unbound base materials in concrete pavement structures.
The thickness of the unbound base is dependent on the traffic loadings (also construction traffic), the bearing capacity of the underlying layers (sub-base, if any, and subgrade) and the properties of the base material. In general, in road pavements the thickness of an unbound base is 200 to 300 mm.

Similar to the sub-base (see 2.3), in the design of concrete pavement structures the effect of an unbound base generally is taken into account by means of a further increase (dependent on the thickness and Young's modulus of elasticity of the base) of the 'modulus of subgrade reaction' of the subgrade plus the sub-base (see 3.2).

Generally, an unbound base is mainly applied for lightly loaded concrete pavement structures. However, in the USA high quality, permeable unbound base materials are also preferred for heavily loaded concrete pavement structures (high resistance against erosion, lower temperature stresses in the concrete top layer). In other countries a cement-bound base is used in heavily loaded concrete pavements for motorways, airport platforms, container yards, etc.

2.4.3 Cement-bound base

Like cement concrete also a cement-bound base material is subjected to shrinkage of the concrete, which occurs during the hardening process and in the hardened cement-bound base due to a decrease of temperature. Due to the friction with the underlying layer this shrinkage results in cracking. The more cement in the base material, the wider cracks will occur at greater mutual distance.
Without measures there will grow an uncontrolled crack pattern in the cement-bound base, with variable crack distances and crack widths. The major cracks give the risk of reflection cracking, which means the growth of cracks from the base into the concrete top layer.
There are some measures to prevent this reflection cracking:

1. Preventing the adhesion between the cement-bound base and the concrete top layer by the application of a 'frictionless' layer (plastic foil) on top of the base. For plain concrete pavements this measure has however the great disadvantage that only a very limited number of the joints actually will crack and these few joints then exhibit a very great width, with the risk of penetration of rainwater and subsequent erosion of the base, reduced driving comfort etc. In reinforced concrete pavements instead of the desired crack pattern (every 1.5 to 3 m a fine crack) only a few wide cracks at great mutual distance may easily grow with similar consequences as for plain concrete pavements. A 'frictionless' layer is therefore hardly ever applied between a cement-bound base and the concrete top layer.
2. Not preventing the adhesion between the cement-bound base and the concrete top layer, but controlling the cracking in the base by means of:
    a. distribution of the construction traffic for the concrete top layer, in such a way that there will grow a regular pattern of fine cracks in the cement-