PCA Thickness Design Method

(Slide 2) The PCA thickness design method is a ***mechanistic-empirical*** design method in that it relies heavily on mechanistic analysis of the stresses and deflections in concrete pavements along with empirical relationships to determine the pavement life as a function of those stresses and deflections.

The PCA thickness design method considers two types of failure:

1. Fatigue failure due to tensile stress repetitions in the slab

2. Erosion failure due to repeated deflection of the slab into the foundation

A finite-element analysis of the deflections and stresses at the joints, corners, and edges of slabs revealed two things:

1. Edge loads produce the worst stresses in the pavement

2. Corner loads produce the worst deflections in the pavement

As a result, fatigue failure is analyzed based on the flexural stresses produced by edge loads and erosion failure is analyzed based on the deflections produced by corner loads.

(Slide 3) Both the fatigue and erosion analyses use Miner's cumulative damage hypothesis. The stresses or deflections produced by a given vehicle class or axle load class are used to predict the number of passages needed to fail the pavement. With that, we can calculate the pavement life consumed by all the vehicles or axles in that class:

$$d_i = \frac{n_i}{N_i}$$

The total pavement life consumed by the vehicle mix is found by summing over all of the vehicle or axle load classes:

$$D = \sum d_i = \sum \frac{n_i}{N_i}$$

The goal is to determine the slab thickness for which the pavement life consumed by the design traffic is exactly equal to 1.0 (pavement life).

Fatigue Failure

Fatigue analysis is based on wheel loads applied near the edge of the slab midway between the transverse joints. This is the worst loading condition from the standpoint of flexure, especially if there is no shoulder or an asphalt shoulder because the wheel loads have to be supported by half as much slab as in the interior of the pavement.

As the contact patch moves into the slab interior, edge stresses drop off rapidly. So you can't just assume all of the trucks are at the pavement edge or well away from the pavement edge. You have to take ***wander*** into account.

By law, trucks can't be more than 8½ feet wide. Most highway lanes are 12 feet wide, so a truck centered in the lane is driving nearly 2 feet from the edge of the pavement. In other words, only a few trucks actually approach the edge of the pavement. This is especially true when the shoulder is unpaved, because drivers want to ensure they don't inadvertently run off the slab.

Studies have shown that as much as 6% of trucks encroach on the pavement edge if the shoulders are paved but less than ½% encroaches on the pavement edge if the shoulders are unpaved.

If 100% of the trucks travel exactly at the edge of the pavement, existing mechanistic formulas for the edge stresses could be used directly to estimate the number of repetitions to failure, N_i. As more and more trucks move away from the edge, the number of repetitions to failure increases because the edge stresses aren't as severe as when the trucks are exactly at the pavement edge.

Using finite element analyses, PCA researchers calculated the average fatigue consumption as a function of the percentage of trucks at the edge of the pavement. They then equated this average to an equivalent edge stress. In other words, what universal edge stress would produce the same amount of fatigue consumption as the mix of edge stresses produced by the wandering trucks?

It turned out that if you calculate fatigue life using 89.4% of the edge stress produced by a truck running exactly at the edge of the pavement, you'll get the same fatigue life as is produced by a mix of trucks, 6% of which are running exactly at the edge.

(Slide 4) This 89.4% edge stress factor is built into the PCA fatigue life equations, which have the general form of

$$\log N_f = f_1 - f_2\left(\frac{\sigma}{S_c}\right)$$

where σ is the flexural stress in the slab and S_c is the modulus of rupture of the concrete.

If the flexural stress is less than 45% of the modulus of rupture, the pavement will last indefinitely. If the flexural stress is more than 55% of the modulus of rupture, the pavement life is given by

$$\log N_f = 11.737 - 12.077\left(\frac{\sigma}{S_c}\right)$$

Between 45% and 55%, the pavement life is given by

$$\log N_f = \left(\frac{4.2577}{\frac{\sigma}{S_c} - 0.4325}\right)^{3.268}$$

For each axle load class, you will need to calculate a flexural stress ratio and a pavement life, then determine what percentage of the pavement life is consumed by the axles in that load class.

Erosion Failure

Erosion failure takes into account such things as pumping, the creation of voids beneath the pavement corners, and joint faulting. These are all related more to the deflection of the slab than they are the stresses in the slab.

(Slide 5) Actually, deflection alone turned out to be a poor predictor of pavement life. A better predictor was the rate of work done on the foundation by the deflecting slab. The rate of work is proportional to the contact pressure and deflection and inversely proportional to the radius of the deflection basin (the more concentrated the load, the faster the load is applied and released as a wheel rolls over the pavement). The actual equation used is

$$P = 268.7\frac{p^2}{hk^{0.73}}$$

where p is the contact pressure, h is the slab thickness, and k is the modulus of subgrade reaction, which relates p to the slab deflection and is used here as a surrogate for deflection. Note that the radius of the deflection basin is related to the radius of relative stiffness, which is related to the thickness of the slab and the modulus of subgrade reaction. That's how h gets in the equation.

The resulting fatigue equation (which is empirical) is given by

$$\log N = 14.524 - 6.777\left(C_1 P - 9.0\right)^{0.103}$$

where C_1 = 1.0 for slabs on untreated subbases and C_1 = 0.9 for slabs on stabilized subbases.

Distance from the pavement edge is just as important in erosion analysis as fatigue analysis. In this case, though, it depends on whether or not there is shoulder support. Shoulder support comes from tying the traffic lane into a concrete shoulder using tie bars.

(Slide 6) If there is an asphalt or gravel shoulder (or no shoulder at all) there is no support for the outside edge of the traffic lane. In that case, the ***corner*** loads produced by the 6% of trucks riding right against the edge are critical and the erosion damage is calculated as

$$D_{erosion} = \sum_i \frac{0.06 n_i}{N_i}$$

In other words, first calculate how long the pavement will last if all the trucks are running at the pavement edge, then multiply by 6% to account for the fact that only 6% are running at the edge.

If there is a concrete shoulder, corner deflection is not significantly affected by the placement of the wheel loads (at that point, all of the wheel loads are interior to the tied pavement system) so the corner loads produced by the 94% of trucks that don't encroach on the shoulder are the most important:

$$D_{erosion} = \sum_i \frac{0.94 n_i}{N_i}$$

Since the deflections are much smaller when the slab is supported by a shoulder, the N_i values will not be the same as those calculated when there is no shoulder support.

Curling Stresses

The PCA design method purposefully ignores stresses due to curling and/or warping (the latter results from a temperature differential through the slab, the latter from a moisture differential).

With regard to warping, the thinking is that most slabs are wetter on the bottom than on the top, so the slabs will want to curl upward but can't. This induces tensile stresses in the top of the slab and compressive stresses in the bottom of the slab. The compressive stresses in the bottom of the slab will offset some of the tensile stresses due to wheel loading (as in prestressed concrete) so it is conservative to ignore warping stresses.

With regard to curling, the bottom of the slab is warmer than the top more hours per day than the reverse, so most of the day (except in the middle of the afternoon) the slab will want to curl up, which induces compressive stresses in the bottom of the slab that also offset some of the tensile stresses due to wheel loading. During the afternoon, the tensile curling stresses will be somewhat offset by the compressive warping stresses, reducing the need to consider them in the analysis.

Thickness Design Procedure

(Slide 7) Only four design parameters are needed in the PCA design procedure:

1. the modulus of rupture of the concrete
2. the modulus of subgrade reaction of the slab foundation
3. the ***design traffic volume***
4. the axle load spectrum

The ***modulus of rupture*** is just the average 28-day modulus of rupture obtained from third-point loading of concrete beams.

To account for variability in concrete strength, the design charts were calculated using a modulus of rupture 15% lower than the average, based on the observation that concrete strengths have a coefficient of variability of 15% if quality control on the job site is adequate. So they actually use the mean minus one standard deviation.

To account for strength gain over time, the design charts were also calculated using a modulus of rupture that rises over time, albeit at a steadily decreasing rate.

The ***modulus of subgrade reaction*** for the subgrade soil could be obtained from plate load tests, but more often it is found through correlations with the CBR because the CBR test is much less expensive than the plate load test. Since we typically only determine the pavement thickness to the nearest ½″, we really don't need any more accuracy than that.

(Slide 8) If the pavement system will incorporate a subbase, the *k*-values have to be adjusted to include the stiffening effect of the subbase. The PCA design guide includes tables for estimating the composite modulus of the subgrade and subbase. One table is used for untreated subbases and the other for cement-treated subbases. The values in those tables were found using a two-layer Burmister analysis of the plate load test (much as we did in an earlier homework problem).

> NOTE: In concrete pavements, we usually refer to the layer between the slab and subgrade as a subbase rather than a base because "base" implies a structural layer. Instead, the subbase is usually there to provide drainage, prevent pumping, or help mitigate frost heave, not provide structural support to the pavement.

Unlike flexible pavement analysis, seasonal variations in subgrade modulus are not considered in the PCA method because the AASHO Road Test results suggest that the required slab thickness does not change appreciably if seasonal changes are included.

In parts of the country where freeze/thaw is a problem, the improved support during the winter freeze makes up for the degraded support during the brief spring thaw. In the rest of the country, the subgrade moduli may rise during the dry seasons and fall during the wet seasons, but the changes are far less than experienced during freezing and thawing.

(Slide 9) The ***design traffic volume*** can be estimated in much the same way as it is for asphalt pavements. You want to know how many trucks will use the design lane over the chosen ***design period***. The equation is similar but not identical to the Asphalt Institute and AASHTO formulas:

$$V = 365(ADT)(T)(D)(L)(G)(Y)$$

In the PCA method, only trucks with 6 tires or more are used for design purposes, so your ***truck factor*** should include only vehicles in FHWA Class 3 and above.

(Slide 10) Recall that the Asphalt Institute method uses the ***growth factor***

$$G = \frac{(1+r)^n - 1}{r}$$

to convert the initial ADT (or ADTT) into a ***total*** traffic volume over the ***entire*** design period. This is perfectly valid and there's no reason you can't use this for rigid pavements, too.

(Slide 11) The PCA manual suggests a somewhat simpler alternative. Simply calculate the traffic volume halfway through the design period (relative to the starting traffic volume):

$$G = (1+r)^{Y/2}$$

and use that as the average traffic volume over the entire design life.

> So this G converts the starting traffic volume into the design year traffic volume. You still have to multiply by the design life Y to get the total traffic over the entire design period.

(Slide 12) The lane distribution factor (L) can be determined from this graph. The y-axis is the one-way ADT in the design year (which, as we said above, is simply halfway through the design period).

(Slides 13-14) The primary difference between the traffic analyses we performed earlier and the traffic analysis used in the PCA method is that we ***don't*** multiply the design lane traffic volume by a truck factor to convert everything to ESALs. Instead, we use the axle load spectra (for both single and tandem axles) directly.

(Slide 15) The general design procedure is as follows:

1. Choose a trial slab thickness.

2. For each axle load being considered, determine the number of repetitions to failure for a slab of that thickness. This is done twice: once for fatigue failure and once for erosion failure.

3. Divide the actual number of load repetitions in each load class by the number of repetitions to failure to get a damage factor for each load class. These represent the amount of pavement life consumed by the vehicles in each class based on either the fatigue or erosion criterion.

4. Sum the damage factors over all the load classes to get the total pavement life consumed by the projected traffic mix for both fatigue and erosion.

If ***either*** result is greater than 1.0 (life), we need to increase the slab thickness by ½″ and redo the calculations. If ***both*** results are less than 1.0, we could reduce the slab thickness by ½″ and repeat the calculations to see if we can save some money.

Design Nomographs

To keep you from having to do a lot of number crunching, the PCA design manual uses a series of tables and nomographs to compute the allowable number of load repetitions N_i for each axle load class in your histogram.

We'll start by looking at the fatigue analysis.

In general, the number of repetitions to failure, N_i, is a function of the ***stress ratio***, which is the ratio of the edge stress to the modulus of rupture of the concrete:

$$\frac{\sigma_e}{S_c}$$

In an elastic analysis, the edge stress is directly proportional to the wheel load:

$$\sigma_e = \frac{3P}{\pi h^2}\left[\cdots\right] = P \times f\left(a,k,h,\ell\right)$$

If you can calculate the edge stress for one wheel load, you can determine the edge stress for any other wheel load using a direct proportion. Twice the wheel load, twice the stress.

The slab thickness (h) and the modulus of subgrade reaction (k) determine the radius of relative stiffness ℓ, so if you know h and k and make some simplifying assumptions about the contact radius a you can calculate the value of the function $f\left(a,k,h,1\right)$, which is just the edge stress per pound of wheel load.

That's exactly what's been done in the PCA manual.

(Slide 16) These tables provide the edge stress produced by an 18,000-lb single axle load and a 36,000-lb tandem axle load for select combinations of h and k.

The table on the left is used when there are no tied concrete shoulders to support the edge of the pavement and the table on the right is used when there is shoulder support.

For example, the edge stress produced by an 18-kip single axle load applied to an 8" concrete pavement with tied shoulders supported by a foundation with a 200 psi/in modulus of subgrade reaction is 197 psi and the edge stress produced by a 36-kip tandem axle load is 168 psi.

The edge stress values from those tables are divided by the modulus of rupture of the concrete to produce a corresponding edge stress ratio for both single-axle and tandem-axle loads:

$$\frac{\sigma_e}{S_c}$$

Because the edge stresses are directly proportional to the wheel loads, this stress ratio is used as a multiplication factor to convert the axle loads for each load class into an edge stress ratio that can then be used to calculate the expected pavement life under that axle load.

(Slide 17) The PCA manual recommends that you first multiply the axle loads in each load class by a ***load safety factor*** that varies based on the user costs that would be incurred if the road has to be shut down for maintenance.

For roads and streets with low truck traffic volumes, they recommend LSF = 1.0. For highways and arterials with moderate truck traffic, the recommend LSF = 1.1. For interstate highways, they recommend LSF = 1.2 and suggest that a load safety factor as high as 1.3 might be appropriate for premium facilities (say urban interstates with lots of commuter traffic in addition to trucks).

(Slide 18) This nomograph is used to convert the factored single and tandem axle loads into an expected fatigue life for the pavement.

A line drawn from the factored axle load on the left scale through the appropriate stress ratio on the middle scale will intersect the right scale at the correct fatigue life.

Another set of tables and nomographs do the same thing based on the erosion failure criterion.

In this case, it's slightly more complicated because the amount of erosion damage depends on the presence or absence of tied shoulders and the presence or absence of dowels. As a result, there are four tables instead of two. There are also separate nomographs for pavements with and without shoulders. Other than that, though, the procedure is the same.

(Slide 19) These tables provide an "erosion factor" produced by either an 18-kip single axle load or a 36-kip tandem axle load for select combinations of h and k for pavements with tied concrete shoulders. This erosion factor is used in another nomograph **(Slide 20)** that converts the factored axle loads into an expected number of repetitions to failure due to erosion.

(Slide 21) These tables are for pavements without tied concrete shoulders (i.e., with asphalt or gravel shoulders or no shoulder at all). They go with this nomograph **(Slide 22)** that converts the factored axle loads into an expected number of repetitions to failure due to erosion.

(Slide 23) The best way to illustrate all of this is with an example.

(Slide 24) We're going to design a concrete pavement for a 4-lane rural interstate highway with average daily traffic of 12,900 vehicles, of which 19% are trucks. The traffic is expected to grow by 4% per year over the 20-year design life of the pavement.

(Slide 25) The traffic volume halfway through the 20-year design period (relative to the starting traffic volume) is given by:

$$G = (1+r)^{Y/2} = (1.04)^{10} = 1.48 \text{ (say 1.5)}$$

(Slide 26) So the ***one-way*** ADT halfway through the 20-year design period will be

ADT (D) (G) = 12,900 (0.5) (1.5) = 9675

(Slide 27) Based on a ***one-way*** ADT of 9675 and two lanes in each direction this graph gives a lane distribution factor of 0.81, so the number of ***trucks*** in the design lane over the 20-year life of the pavement will be **(Slide 28)**

$$\mathrm{V} = 365(\mathrm{ADT})(\mathrm{T})(\mathrm{D})(\mathrm{L})(\mathrm{G})(\mathrm{Y}) = 365(12{,}900)(0.19)(0.5)(0.81)(1.5)(20) = 10.9 \text{ million}$$

(Slide 29) We'll assume that the pavement will be supported by a 4-inch-thick granular subbase on a clay subgrade with a 100-psi/in modulus of subgrade reaction. The pavement will be a JPCP with dowel bars and asphalt shoulders. The modulus of rupture of the concrete is assumed to be 650 psi. Note that this is the ***only*** concrete property needed for the PCA design method.

(Slide 30) These tables can be used to estimate the ***composite*** modulus of subgrade reaction of the foundation material. The combination of a 4-inch-thick granular (i.e., untreated) subbase and a subgrade with a 100-psi/in modulus of subgrade reaction produces a composite k of 130 psi/in.

(Slide 31) We'll assume that this histogram gives the anticipated number of single axle loads in each of 10 different load classes over the 20-year life of the pavement. Weigh station data can be used to determine the mix of axle loads (say, per 1000 trucks) and those results scaled up to the 10.8 million trucks we anticipate over the life of this pavement.

(Slide 32) Similarly, this histogram gives the anticipated number of tandem axle loads over the life of the pavement.

(Slide 33) Here is the upper half of the worksheet we'll use to determine the required thickness of the slab. The upper half is used for the single axle loads and the lower half **(Slide 34)** is used for the tandem axle loads.

(Slide 35) We'll start by assuming a 9.5-inch concrete pavement. We've already been told that it will be a doweled pavement with no tied concrete shoulders. The composite modulus of subgrade reaction of the subbase and subgrade was found to be 130 psi/in and the modulus of rupture of the concrete was given as 650 psi.

(Slide 36) Since this is an interstate highway, we'll use a load safety factor of 1.2. This is also filled in at the top of the sheet **(Slide 37)**.

(Slide 38) We'll do the fatigue analysis first. For an assumed slab thickness of 9.5 inches with no concrete shoulders and a subbase-subgrade modulus of 130 psi/in, we interpolate an equivalent edge stress of 206 psi for single axles.

(Slide 39) Dividing the 206 psi single-axle stress by the modulus of rupture of the concrete, we get a single-axle stress ratio factor of

$$206 / 650 = 0.317$$

Now we can start entering the axle load classes from the histograms. We start with the ***highest*** load for reasons that will become apparent in just a minute.

The highest single axle load is 30 kips. Applying a 1.2 factor of safety increases that to 36 kips. From the earlier histogram, the number of axle loads expected in that class is 6310.

(Slide 40) To determine the fatigue life of this pavement under a 36-kip single axle load, we draw a line from 36 on the single-axle side of the axle load scale, through 0.317 on the stress ratio scale, producing a fatigue life of 27,000 load repetitions.

(Slide 41) If we're going to apply 6310 axle loads to a pavement that can withstand 27,000 load repetitions before failing, we're consuming

$$6310 / 27{,}000 = 0.234 = 23.4\%$$

of the pavement's life with the axles in this load class.

(Slide 42) We can repeat the same procedure for the 28-kip load class, the 26-kip load class, and so on. Note that as the axle loads go down, the fatigue life goes up.

(Slide 43) Eventually we'll get to an axle load class for which the projected fatigue life is off the scale. At this point, we call the fatigue life infinite and stop. (That's why we start with the highest load class and work our way down; you'll almost always achieve an infinite fatigue life before you get to the lowest axle load classes.)

(Slide 44) Finally, we sum up the percentages of pavement life consumed by the axles in each of the load classes. In this case, all of the single axles traversing this pavement over the next 20 years will consume 61% of the pavement's life.

(Slide 45) Now we turn our attention to the tandem axle and repeat the same procedure.

(Slide 46) For an assumed slab thickness of 9.5 inches with no concrete shoulders and a subbase-subgrade modulus of 130 psi/in, we interpolate an equivalent edge stress of 192 psi for tandem axles.

(Slide 47) Dividing the 192 psi single-axle stress by the modulus of rupture of the concrete, we get a tandem-axle stress ratio factor of

$$192 / 650 = 0.295$$

The highest tandem axle load is 52 kips. Applying a 1.2 factor of safety increases that to 62.4 kips. From the earlier histogram, the number of axle loads expected in that class is 21,320.

(Slide 48) To determine the fatigue life of this pavement under a 62.4-kip tandem axle load, we draw a line from 62.4 on the tandem-axle side of the axle load scale, through 0.295 on the stress ratio scale, producing a fatigue life of 1.1 million load repetitions.

(Slide 49) If we're going to apply 21,320 axle loads to a pavement that can withstand 1.1 million load repetitions before failing, we're consuming

$$21{,}320 / 1{,}100{,}000 = 0.019 = 1.9\%$$

of the pavement's life with the axles in this load class.

(Slide 50) We can repeat the same procedure for the 48-kip load class. Applying the load safety factor, we'll enter the histogram **(Slide 51)** with a tandem axle load of 57.6 kips. Drawing a line through the stress factor of 0.295, we get a projected fatigue life off the scale, so we're done.

(Slide 52) Adding the tandem axle results to those of the single axles, we find that we'll consume 62.9% of this pavement's life with the traffic loads we've assumed over the next 20 years.

(Slide 53) So far, this would seem to be a successful, albeit somewhat conservative, design. But we're only halfway done because we also have to perform the erosion analysis.

(Slide 54) For an assumed slab thickness of 9.5 inches with dowels but no concrete shoulders and a subbase-subgrade modulus of 130 psi/in, we interpolate an erosion factor of 2.59 for single axles.

(Slide 55) We've already entered all of the single-axle data into the worksheet, so all we have to do is determine the allowable repetitions in each load class from an erosion perspective.

(Slide 56) Entering the nomograph with a factored single-axle load of 36 kips and drawing a line through an erosion factor of 2.29, we get a pavement life of 1.5 million.

(Slide 57) That means our ***highest*** single-axle load only consumes 0.4% of the pavement's erosion life.

(Slide 58) If we repeat that for all of the other single-axle loads (including for some lighter load classes not used in the fatigue analysis) we find that the single-axle loads will consume only 6.1% of the pavement's erosion life.

(Slide 59) Turning our attention to the tandem axles, we need to first come up with an erosion factor to use in the nomographs.

(Slide 60) For an assumed slab thickness of 9.5 inches with dowels but no concrete shoulders and a subbase-subgrade modulus of 130 psi/in, we interpolate an erosion factor of 2.79.

(Slide 61) Our first tandem-axle load class is 52 kips (which is 62.4 kips with the safety factor).

(Slide 62) Starting at a tandem-axle load of 62.4 kips and drawing a line through an erosion factor of 2.79, we get a pavement life of 920,000 (if we have really good eyes!).

(Slide 63) So our highest tandem-axle load consumes 2.3% of the pavement's erosion life.

(Slide 64) If we repeat that for all of the other tandem-axle loads (including for some lighter load classes not used in the fatigue analysis) we find that all of the axle loads combined consume 38.9% of the pavement's erosion life.

So this still seems to be a successful, albeit somewhat conservative, design. It would be worth it to repeat all of these calculations for a 9-inch slab thickness to see if we could save some money. If ***either*** the fatigue or erosion life consumed exceeds 100%, the slab is too thin and we'll specify a 9.5-inch slab thickness and we're done.