

Cross-Tensioned Concrete Pavement: An Alternative Modern PCCP Design

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The rapid deterioration of Portland Cement Concrete Pavement (PCCP) is most often due to intrusion of water into the pavement and foundation layers through transverse joints and cracks. To minimize this problem, transverse joints are sealed with a flexible sealant that allows the joint to open and close while keeping water out. However, water does eventually get in and deterioration begins due to freezing and thawing, erosion of the subbase, etc. One possible way to solve this problem is to eliminate all transverse joints and to constrict the cracking tendency of the pavement by applying an external force in the form of post-tensioning. The advancement of post-tensioning products and procedures over the last twenty years has made this a fairly simple and inexpensive procedure. A reduction in slab thickness and elimination of sawing and sealing transverse joints can offset the cost of the post-tensioning hardware and process. The limited success of post-tensioning PCCP in the past was due to the design of longitudinal post-tensioning within the slabs. Longitudinally post-tensioning PCCP requires the construction of gap slabs where the actual post-tensioning work takes place. The gap slabs tend to deteriorate very fast. The need for gap slabs can be eliminated by cross-tensioning PCCP. This procedure may not only eliminate the need for any transverse joints, but will also resist the tendency of the pavement to crack in any direction. Key words: pavement, PCCP, gap slab, cross-tensioning, post-tensioning.

INTRODUCTION

The rapid deterioration of Portland Cement Concrete Pavement (PCCP) is most often caused by intrusion of water into the pavement layers. The water usually infiltrates through transverse joints and cracks. During construction process and routine maintenance, the transverse joints and cracks are typically sealed with a flexible joint sealant. The sealant keeps the majority of water out, however, some infiltration still happens. Concrete pavement deterioration then occurs due to freezing and thawing, erosion of subbase, etc.

Elimination of transverse joints and cracks is one solution to this common problem of PCCP. Pre-stressing PCCP could eliminate joints and cracks. By applying an external force in the form of post-tensioning, theoretically all joints in the pavement can be eliminated, and no cracking should happen. Extended pavement life may also be expected due to pre-stressing of PCCPs. The potential elimination of all transverse joints will provide a smooth and comfortable travelling surface, lower maintenance cost, and increased load-carrying capacity of the pavements.

Pre-stressing is a broad term that covers many different types of applied external forces to PCCP. The types include post-stressed, pre-tensioned, and post-tensioned. Post-stressing is accomplished

by applying an external force to the ends of the slabs and is done without wires, strands, or cables. Pre-tensioning is done before the concrete is cast. Once cast, strands, cables, or wires are used to apply compressive forces. The force is transferred to the PCCP through surface friction. Post-tensioning, on the other hand, is applied after the concrete has cured. The post-tensioning force is applied through unbonded strands to the ends of the pavement. The aforementioned procedures are generally referred to as "pre-stressing" (1) in generic term.

Post-tensioning of PCCP is not a new concept. It has been tried all over the world. The first construction of a post-tensioned pavement was at the Orly Airport, Paris, in 1946. The Europeans have long since advocated the use of post-tensioning in airport pavements. Europe has also taken the lead in the application of post-tensioning to highway pavements. During the 40s, 50s, and 60s, the Europeans constructed over thirty post-tensioned pavements. During the same time, the United States constructed only six airport pavements that were post-tensioned. Finally, in the early 70s three highway pavements and an access road at Dulles International Airport were constructed. Since the 70s only one post-tensioned highway, near Phoenix, has been built by the Arizona Department of Transportation (ADOT) (2).

THEORY

Post-tensioned pavement design is unlike that of any other PCCPs. Conventional PCCP design is based on the modulus of rupture of concrete and does not take advantage of the high compressive strength of concrete. Post-tensioned concrete pavement increases the stress range during flexure of concrete. Resulting advantages are the following: (1) absence of cracks from the road surface, (2) reduced cost through a reduction in slab thickness and elimination of joint construction and maintenance, and (3) increase in load carrying capacity (3).

The fundamental formula for design of pre-stressed concrete pavements is (3):

$$f_t + f_p \geq f_{\Delta t} + f_F + f_L$$

where,

f_t	=	allowable concrete flexural stress
	=	modulus of rupture/factor of safety;
f_p	=	compressive stress in concrete due to post-tensioning;
$f_{\Delta t}$	=	curling stress due to difference in temperature between top and bottom surfaces of the concrete slab;

$f_F =$ stresses due to subgrade friction; and

$f_L =$ stresses due to traffic load.

The allowable concrete flexural stress may be taken as high as 80 to 100 percent of the modulus of rupture of concrete. Introduction of the compressive stress in the concrete pavement changes the failure criterion from a bottom tension crack to a top circular crack. The failure load is at least twice the load that produces the first bottom crack. This allows the designer to choose a factor of safety between 1 and 1.25 for f_t (3).

Allowable stresses in the post-tensioning strands, f_{sc} , after all losses, should not exceed 80 percent of the ultimate strength, f_u of the post-tensioning steel. A typical post-tensioning monostrand will be a 0.5 in (12.5 mm) diameter strand, made with six wires twisted around one wire. The ultimate strength of post-tensioning strands is 270 ksi (1,862 MPa) (4).

The curling stresses in concrete can be calculated from (3):

$$f_M = \pm \frac{\alpha E_c \Delta t}{2(1-\nu)}$$

where,

- α = coefficient of thermal expansion (6×10^{-6} in/in/ $^{\circ}$ F, 3.5×10^{-7} mm/mm/ $^{\circ}$ C);
- $\frac{\Delta t}{h}$ = temperature gradient (3° F/in, 0.63° C/mm);
- h = slab thickness in inches or millimeters;
- E_c = static modulus of elasticity of concrete in psi or N/mm²; and
- ν = Poissons ratio for concrete (0.15).

Curling stresses in post-tensioned PCCP could be caused by the warping of a slab due to creep or due to differences in the temperature or moisture content in the zones adjacent to its opposite faces. Usually concrete curls when one face is warmer or cooler than the other face. The warmer face of the concrete wants to expand while the cooler face will not. This causes the slab to curl either up or down depending on which face is warmer. If the warmer face of the concrete is on top then the slab tends to curl down on the ends, however, if the opposite is true, the slab will tend to curl up on the ends (5). These changes in stress condition in the concrete slab can have adverse effects on the stresses within the strands. For example, suppose we have a slab where the stressed post-tensioning strands are in the lower half of the slab. When the lower face of the slab is cooler than the top face, the slab will try to contract on the bottom and expand at the top. The contraction at the bottom will cause some relaxation in the strands, hence the strands will loose some of their stresses. As a result, cracks may develop (3).

Fluctuations in stresses due to seasons can also cause adverse stress effects in concrete pavement. In Belgium, an 11,000 ft (3,353 m) pavement slab was post-stressed with screw jacks. Engineers tried for four years to maintain the stress in the concrete by frequently adjusting the screw jacks. The results of their attempt showed fluctuations in prestress that ranged from nearly 0 to 1,900 psi (13.1 MPa). If the total slab length were smaller, the adverse stresses caused by temperature differentials would not have fluctuated so drastically (2).

Creep also has adverse effects on stresses. Creep is the change in length of a pavement slab under a constant stress. The sustained post-tensioning force in the pavement results in creep of the concrete. Creep has similar effect on the prestressing force as curling, however, creep does not fluctuate as much as the curling stress. Higher compressive strengths of concrete produce less creep. Furthermore, creep does level off after 300 to 400 days of load application.

This allows the designer to design taking the creep effects of concrete into account.

The friction between the subgrade and the PCCP also produces a stress that is most significant in the middle portion of the slab. For a slab that is less than 700 ft (220 m) in length, the frictional stress (f_F) between the sub-grade and PCCP can be estimated as (3):

$$\max f_F = \frac{c\gamma L}{2 \times 144}$$

where,

- c = coefficient of sub-grade friction,
- L = total longitudinal length between ends of strands, and
- γ = unit weight of concrete (145 lbs./cubic ft or 2323 kg/cubic meter)

If the reactive force applied by the subgrade friction is too much, it could effect the stresses applied by the strands. Consider, for example, that a slab is supported on the subgrade at two different points between the ends of a post-tensioning strand. When the strand is pulled to tension, a compressive force is exerted on the concrete slab. However, the region between the two pins experiences no compressive force. This is the problem that subgrade friction imposes on post-tensioned PCCP. The problem becomes quite significant as the slab becomes longer. For this reason, the frictional stress between the slab and the subgrade must be considered in design (6).

The coefficient of sub-grade friction is substantial with a value of 0.2 to 1.5 for slabs resting on a sand or granular subbase. For design purposes, the coefficient of subgrade friction can be taken as 0.5 to 0.8 (6). Most historical designs of post-tensioned pavement incorporate two layers of 6 mil (0.15 mm) polyethylene sheeting which have a coefficient of friction of less than 0.2. However, in the ADOT post-tensioned PCCP project, it was discovered that almost no difference exists in friction between the slab and the subgrade on either 1 or 2 layers of polyethylene sheeting (7). In either case, it is still recommended to use a conservative value of 0.5 for the coefficient of friction in design. This gives the designer reasonable assurance that the value can be achieved in the field (6).

Conventional PCCP design consider traffic load as the primary factor affecting the required pavement thickness. For post-tensioned PCCP, traffic loads induce tensile stresses at the bottom of the pavement. This stress can be calculated by the Westergaard's formula. The edge loading of PCCP is always the controlling criteria. The edge is where the stress in the slab will always be the greatest under a tire load. The stresses in the pavement induced by successive traffic loads can lead to elastic deformation of the slab to the point where the maximum moment beneath the loaded area exceeds the sum of the flexural strength of the concrete and the induced force. At this point, a crack forms a hinge under the load, repeated load applications cause a moment in the slab some distance away from the loaded area. If traffic repetitions continue, tensile cracks may form at the top of the pavement. When loading is increased beyond this point, the load will eventually punch through the slab. For this reason, it is extremely important to consider traffic load in post-tensioned PCCP (6).

Westergaard's formula for stresses due to edge loading of PCCP is given as (5):

$$f_L = \frac{0.803P}{h^2} \left[4 \log \left(\frac{l}{a} \right) + 0.666 \left(\frac{a}{l} \right) - 0.034 \right]$$

where,

- f_L = maximum edge stress under load;
- l = radius of relative stiffness

$$E = \left[\frac{Eh^3}{12(1-\nu^2)l^3} \right]^{-0.333}$$

E = modulus of elasticity of concrete
 (assume 4,000,000 psi);
 k = modulus of subgrade reaction
 (assume 100 pci);
 P = concentrated load, lbs.; and
 a = contact radius

$$= \frac{P}{\sqrt{\text{Area Pressure}}}$$

For a typical maximum load of 22, 000 lbs (97,860 N) per axle on duals, P can be estimated as 5,500 lbs (24.5 kN) and the tire pressure can be estimated as 100 psi (0.69 Pa).

Deflections also occur in the slab. Excessive deflections in PCCP are most often caused by softer foundation support. Post-tensioned pavement, however, can span the softer spots in the subgrade. This happens due to an increase in flexural strength of the concrete due to the post-tensioning force, which results in controlled deflection of the post-tensioned PCCP under repeated loads.

TYPICAL DESIGN

In most post-tensioning PCCP projects, the post-tensioning had been done in the longitudinal direction of the PCCP. This does have its advantages and disadvantages. One of the advantages of this type of design is the simplified procedure of placing the strands in the pavement. Most slipform pavers can easily be adapted to accommodate the insertion of the post-tensioning strands. ADOT used this approach when it post-tensioned part of the Superstition Freeway near Phoenix. In longitudinal post-tensioning, a direct force perpendicular to the weak plane of the concrete, the transverse plane, is also applied. This reduces joint spacing and cracks in the concrete.

Longitudinal post-tensioning does have its disadvantages. First, slabs can only be designed to be so long before post-tension losses, such as, those induced by the frictional stresses between the subgrade and the PCCP, become so great that they cannot be overcome unless more strands are added. For this reason, most post-tensioned slabs tensioned in the longitudinal direction are limited to less than 500 ft. (152 m) in length. Second, longitudinally post-tensioning PCCP requires the work areas, known as gap slabs, be constructed between two post-tensioned pavements. These areas are where the actual tensioning of the strands takes place and the hardware is placed. Contractors must have enough space in the gap slab to apply the tensioning force without bumping into the slab behind them. Gap slabs range in length from 6 to 10 feet (1.80 to 3.00 m). These gap slabs have been found to deteriorate more rapidly, affecting the ride quality. The elimination of gap slabs should increase the riding comfort on post-tensioned PCCP. Eliminating gap slabs also eliminates two joints where water infiltration is likely to occur. Many different joints have been developed to control the inflow of water at the transverse joints on either side of the gap slab. Most are either too difficult to install or are not at all a cost-effective solution.

PROPOSED DESIGN

Cross-tensioning PCCP may give the designer an option to construct nonjointed, uncracked concrete. The procedure for designing such a pavement is done in much the same way as that of a PCCP post-tensioned in the longitudinal direction. The only difference is the

interpretation of the frictional losses between the PCCP and the subgrade. In longitudinal post-tensioning design, the designer considers the pavement slab as having two ends that result in transverse joints. The length of the pavement between the two joints is the slab length that is subjected to the frictional force between the PCCP and the subgrade. In cross-tensioning, the designer post-tensions the pavement in diagonal directions from both sides. By cross-tensioning, the PCCP cannot expand in any direction. This allows for the design of a nonjointed pavement of virtually infinite length.

The angle at which the cross tensioning should be applied varies between 30 and 45 degrees to the longitudinal direction of the pavement. This allows the majority of the stress force in the strands to act against the weak plane of the concrete, the transverse plane. The 30 to 45-degree specifications also give the concrete less capability of cracking in the longitudinal direction, as did the ADOT longitudinally post-tensioned PCCP. It should be noted the smaller angle of post-tensioning results in less steel strands.

Strand location in the slab is most important. Historically, the strands of post-tensioning steel have been placed 0.5 in. (12.5 mm) below the mid-depth of the slab. At this depth, the strands are able to carry very well the loads induced on them by truck traffic. Lowering the strands to 0.5 in. (12.5 mm) below mid-depth causes the slab to have an induced negative moment (3). When a truck passes over the pavement, the induced negative moment is cancelled by the moment generated by the axle load. Placing the strands at or above mid-depth will only add to the load already present due to the axle load. This should never be done.

Strand placement is also very significant at the edge of the pavement. It is important that the strands tensioned in different directions, on the same side of the pavement and very near each other, be placed so they each apply a compressive force between them. This requires that the strands be crossed very close to the pavement edge. For example, assume a pavement is stressed with the 45-degree post-tensioned strands. Consider now that the strands are laid out such that two strands, perpendicular to each other, are very close, but not crossing at the pavement edge. This will cause a tensile stress in the concrete between the two strand ends. If the tensile stress is too great, the concrete may develop a transverse crack. Now consider the same two strands as crossing very near the pavement edge. The only stress that will exist between the two strands in this case is a compressive stress. It is well known that concrete is very weak in tension. In fact, the American Concrete Institute (ACI) code requires that the tensile strength of concrete should be neglected in all axial calculations (4). The tensile strength of concrete is highly variable and is usually considered to be only 10 to 15 percent of the compressive strength (5).

The thickness of concrete used in post-tensioned PCCP is less than conventional PCCP thickness. Pavements as thin as 3.5 in. (90 mm) have been developed for use with longitudinally post-tensioned pavements. However, problems associated with coverage and uniform paving make this an unfavorable choice on most highway pavements. It is recommended by ACI that a pavement thickness of at least 65% of the thickness of an alternative plain concrete pavement be used (6). This allows for appropriate coverage and variations in construction. For most cases, a pavement thickness of 6 in. (150 mm) is sufficient for coverage and construction tolerances.

Special consideration needs to be given to the stressing operation. The strands cannot be tensioned to design values until the concrete has gained sufficient strength. ADOT tensioned its longitudinally post-tensioned PCCP in three stages. Since cracking occurs from

volume change, thermal gradient, and subgrade restraint, it is imperative to apply the first stage tensioning to the cables at the earliest practical time, usually within 24 hours. Some fine cracks may form before initial jacking; however, they should close upon application of the jacking force. The second jacking should be done within 24 hours of the previous one. Lastly, the final jacking should be done when the concrete strength has reached at least 3,000 psi (21 MPa), independent of time. It is imperative not to jack the strands beyond the strength of the concrete. Jacking forces should be determined considering the size and thickness of the bearing plate end anchors and minimum concrete strength necessary to withstand the applied force. It may be necessary to increase the bearing plate size to distribute the high stresses at the slab edges (7).

CONCLUSIONS AND RECOMMENDATIONS

Post-tensioned PCCP of the cross-tensioned variety may be a suitable solution to the problems associated with conventional PCCP. Post-tensioned PCCP can reduce pavement thickness, reduce pavement deflection, allow for unjointed design, and increase the load-carrying capacity of PCCP. As with any new design, this needs to be proven. It is, however, possible that cross-tensioned PCCP could be everlasting pavement for the 21st Century.

Further studies and actual field test of cross-tensioned PCCP should be done before any attempt is made to apply the theory to an actual PCCP construction. The most extensive research should be done to check the stress condition in the areas where the strands cross each other near the pavement edge. At this location, little is known about the behavior of the concrete. Studies should also be done on the behavior of the concrete at any location where strands cross each other. Furthermore, researchers

should study the effects of applying a skew force to the strands. This will cause some side force on the strand near the pavement edge. Additionally, the construction of cross-tensioned pavements will need to be reviewed. Some new and innovative construction techniques may need to be developed for installation of the crossed strands.

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