PRESTRESSED PAVEMENT DEMONSTRATION PROJECT

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This report describes the installation of the first full-scale prestressed concrete pavement in Pennsylvania. A detailed account of the construction and placement methods used and pertinent cost data are included. The purpose of this project was to employ pavement prestressing techniques on a production basis. A variety of construction problems encountered provided valuable experience as to what can be expected on future projects of this nature. Some 23 post-tensioned slabs were placed on the main line, each with a nominal length of 600 ft (183 m). The concrete was placed with a slipform paver that also guided the prestressing strands into the pavement by feeding them through metal tubes on the paving equipment. A unique method was used to construct the joints where the slabs meet. During paving, a 3-ft (0.9-m) jacking space was provided between slabs. This space was later filled with concrete, which was prestressed by transferring the load from the strand anchors through the joint concrete. The slab ends were keyed together with an interlocking beam system to prevent faulting at the joints. Paving work was completed in December 1973. The riding quality over the pavement joints is rated as excellent. The joints are functioning well and are providing for slab length changes caused by temperature variations. The project is being closely observed and its serviceability will be documented in future reports.

•THE use of prestressing techniques for highway pavement has the potential for providing a longer lasting roadway than conventionally reinforced concrete. Prestressing eliminates cracking and transverse contraction joints, both of which are major causes of distress and failure in concrete pavements. Recent experimental installations have shown that prestressed pavement will perform well (1, 2). Excellent riding quality should be obtainable because of the presence of joints only at 600-ft (183-m) intervals. A significant reduction in materials is also achieved because of the substantially reduced pavement slab thickness and reduction in the amount of reinforcing steel.

SCOPE

The main-line pavement consists of 23 post-tensioned slabs with a total length of 13,232 ft (4033 m). The slabs are all 24 ft (7.32 m) wide, 6 in. (152 mm) deep, and nominally 600 ft (183 m) long. Each slab contains 12 prestressing strands, as shown in Figure 1. Maximum grade on the main-line pavement was 1.50 percent, and the maximum curvature was 3.0 deg.

MATERIALS

The pavement is supported by an aggregate bituminous base course 6 in. (152 mm)

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thick and an aggregate subbase course 6 in. (152 mm) thick. Concrete used in the pavement was a 6.25-bag/yd^3 (8.17-bag/m^3) mix conforming to PennDOT Class AA specifications for normal paving concrete. Prestressing strands were 7 wire strands of high-tensile steel in a polypropylene conduit, prepacked with corrosion-inhibiting grease (Table 1).

CONSTRUCTION PROCEDURE

Slipform Paving

Concrete placement was performed by a conventional CMI slipform paving train. Since no transverse reinforcing steel was used, a method was developed for feeding the prestressing strands into the concrete and positioning them at the design depth of 3.5 in. (89 mm). Steel tubes were attached to the spreader machine and the strands passed through these into the concrete. The 12 reels of strand were carried ahead of the paving train on a modified flatbed truck from which they were unwound onto the base, to be picked up by the placement tubes on the concrete spreader (Figures 2 and 3).

The design of prestressed pavement requires that the coefficient of friction between the slab and base be less than 0.6 (3). A friction-reducing membrane was therefore provided by using 2 layers of 4-mil (0.10-mm) polyethylene sheeting between the concrete and base course. To ensure a smooth surface on the base course, sand was swept over it prior to paving. The plastic sheeting was unrolled onto the base ahead of the concrete spreader.

A slab length of 600 ft (183 m) was chosen as the optimum length. Shorter slabs would have increased costs due to placing more joints, whereas longer slabs would have had insufficient resistance to cracking at midpoint due to friction between the slab and base.

The remainder of the slipform paving operation was done by conventional methods. Concrete curing was accomplished with wet burlap, straw, and plastic sheeting for the first 11 slabs. After that, white membrane curing compound was used.

Joint Placement

The continuous placement of prestressed pavement required that a jacking space of at least 3 ft (0.9 m) be left between slabs. A method of placing these joints was devised to prevent interruption to the slipform paving operation. The sequence of operations is shown in Figures 4 through 11 and is described in the following.

Blockouts, consisting of wooden boxes, 3 ft (0.9 m) in length, were staked out in a row on the base at the desired joint location. As the concrete spreader passed over the joint, the tubes that placed the strands passed between the boxes. Paving and finishing were then completed normally over the boxes. After the paving train passed the joint area, the boxes were lifted out of the concrete by a crane. To lift them out they were hooked onto a framework with ropes and lifted in unison. The remainder of the concrete in the joint void was removed by hand, leaving a void slightly longer than 3 ft (0.9 m).

One of the 2 slab ends at the joint was formed by placing a permanent steel beam that distributes the load of the strands across the end of the slab. This beam is known as the female beam and will be discussed later. A steel bulkhead was placed at the other slab end to form a smooth concrete face. Concrete to fill the joint would later be poured against this face after the jacking was completed. The female beam and bulkhead were lowered in place by the crane and positioned properly, after which concrete was placed against them, vibrated, and finished. Slots in the female beam and bulkhead allowed them to be placed over the strands, which were not cut until the following day. This completed the joint-forming operation, and the crew moved ahead to repeat the sequence when the paving train reached the next joint.

Figure 1. Pavement cross section.

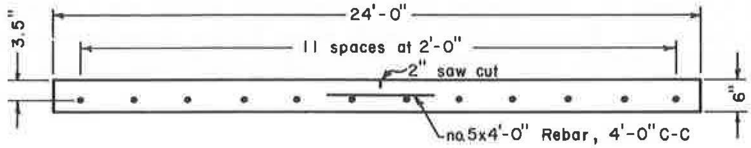


Table 1. Strand data.

Item	Dimension
Strand diameter	0.6 in.
Steel area	0.215 in.^{2}
Length per pound	1.36 ft
Modulus	28×10^6 psi
Ultimate strength	58.6 kips
Temporary force maximum (80 percent of ultimate)	46.9 kips
Stressing load (70 percent of ultimate)	41.0 kips
Design load (60 percent of ultimate)	35.2 kips

Figure 2. Paving operation.

Figure 3. Concrete spreader.

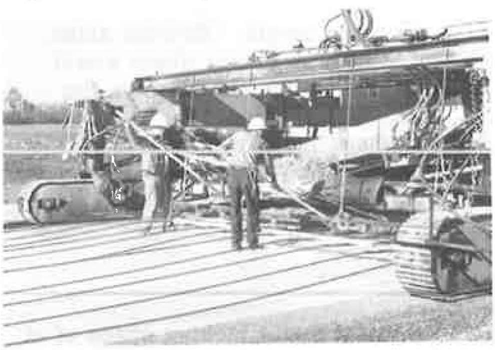


Figure 4. Joint blockout boxes.

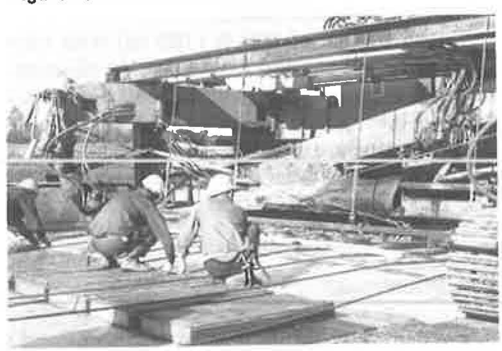


Figure 5. Preparing lifting ropes.

Figure 6. Hooking ropes on lifting frame.

Figure 7. Lifting of blockout boxes.

Figure 8. Placing female beam and bulkhead.

Figure 9. Placing concrete at joints.

Figure 10. Finishing concrete at joint.

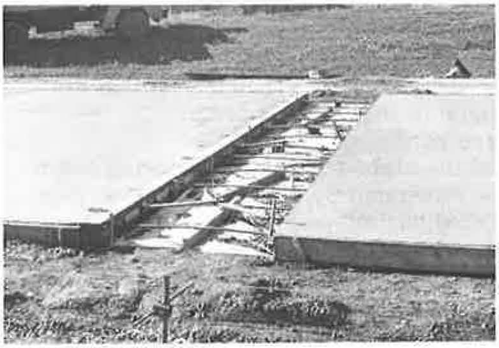


Figure 11. Completed joint placement.

A time limit was placed on the joint-forming operation to prevent the possibility of a cold joint when concrete was placed back against the bulkhead and female beam. The contractor was allowed 14 minutes after the paving train passed the joint to remove the wooden boxes and place the beam and bulkhead. Placing and screeding the concrete behind the beam and bulkhead were to be completed within another 6 minutes, or a total of 20 minutes after the paving had passed the joint.

Jacking

A 2-step loading was specified; the initial load of 10 kips (44.5 kN) was applied when the concrete reached a strength of 1,000 psi (6895 kPa) and the final loading of 46.9 kips (207.6 kN) was applied at 2,500 psi (17 238 kPa). Concrete strengths were determined from field-cured cylinders molded when the end of the slab was placed. Prior to placing the initial load, it was necessary for the contractor to sever the strands at the joints and place the strand anchors.

After several slabs were placed, a decision was made to allow an initial load of 20 kips (89 kN) to be placed if the concrete strength was over 1,500 psi (10 343 kPa). This decision further ensured that no shrinkage cracking would occur in the slabs if a sudden drop in temperature or a period of rapid hydration of the concrete occurred.

Jacking was done with portable hydraulic ram jacks capable of loading 1 strand at a time (Figures 12 and 13). The loading sequence used was to jack the center strands first and then jack on alternate sides out to the edges of the slab. The jack rams had a throw of only 10 in. (254 mm) and it was necessary to reposition the jack after each 10 in. (254 mm) of strand elongation was achieved. Jacking was done at both ends of each slab to reduce friction losses in the strands.

Joint Construction

After jacking was completed, the joints were prepared for concreting. A unique method was devised whereby the prestress would be applied to the joint concrete, resulting in movement only at 1 joint gap. To accomplish this, the load from the anchors at 1 end of the slab was transferred to permanent strand anchors cast into the joint concrete. The load transfer was accomplished by releasing the anchors at the end of the slab against which the joint concrete was placed. To release the load, a jacking bridge was used behind each strand anchor (Figure 14). This bridge was later cut after the joint concrete had cured sufficiently. The top and bottom horizontal bars were cut at one side of the strand to allow the load to transfer to the permanent anchor. To cut the jacking bridges, voids (Figure 15) had to be formed in the joint concrete. These were filled with concrete after the jacking bridges were removed.

The completed joint provides for movement of the slabs with an interlocking beam system at the joint. This system is a product of Pavement Systems Inc. and carries the trade name "PAJO". The female beam, placed during paving, becomes integral with the slab and is held to it by the force of the strands. Anchors in the female beam were set into anchor pockets so that they would not protrude from the beam. An anchor pocket is shown in Figure 16. These were filled with cement mortar after jacking.

Male beams were placed inside each female beam prior to placing the joint concrete. It was necessary to fabricate the male beams in short sections due to the interference of the vertical ribs that are part of the female beam (Figure 17). When placing the male beams, a $\frac{1}{4}$-in. (6.4-mm) spacer of expanded foam sheeting was placed between each male beam and the female beam to allow for expansion of the slabs. A piece of foam was also clipped onto each vertical rib of the female beam to maintain the same spacing at this point. To prevent spalling when the joint closes, a hand-tooled edge was made where the joint concrete meets the top plate of the female beam.

After the permanent anchors were placed on the strands, it was necessary to "set" the wedges on each to ensure that the strand would be held when the jacking bridge was cut. This was done by placing the jack between the temporary anchor and the permanent

Figure 12. Hydraulic jack.

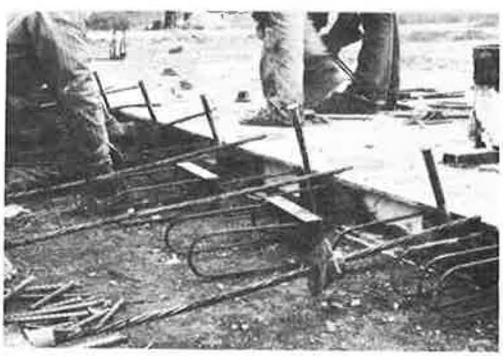
Figure 13. Jacking setup.

Figure 14. Jacking bridge.

Figure 15. Jacking bridge after cutting.

Figure 16. Anchor pocket in female beam.

Figure 17. Placing male beams.



anchor and jacking against them to a load of 30 kips (13.3 kN). The permanent anchors were then tied to 2 transverse reinforcement bars to suspend them at the proper height (Figure 18). A mat of reinforcement bars was placed in the joint and supported by chairs (Figure 19). To prevent bonding of the strands to the joint concrete, pieces of conduit were slipped over them.

After preparations were complete, the joints were filled with class AA concrete, the same as used for conventional paving but with a higher slump. Jacking bridges were not cut until the joint concrete reached a strength of at least 3,000 psi (20 685 kPa).

Terminal joints were used at each end of the job and at the approaches to the structure (Figure 20). The design is applicable to any slab end that must adjoin conventional pavement. Expansion joint material was omitted at the south end of the job where the adjoining pavement is bituminous concrete.

COST DATA

The costs given in Table 2 are those of the original contract, bid for 9-in. (229-mm) reinforced concrete pavement on 9 in. (229 mm) of subbase, versus the negotiated price to substitute 6-in. (152-mm) prestressed pavement on 6 in. (152 mm) of aggregate bituminous base course and 6 in. (152 mm) of subbase.

OBSERVATIONS

Slipform Paving

The system of guide tubes on the concrete spreader proved to be a successful method of placing the strands at the desired depth and alignment. Depth checks were made periodically to determine whether there was any difficulty in achieving the specified 3.5-in. (89-mm) placement depth. The strands were generally within ± ¼ in. (6.4 mm) of the specification. A wider variation in strand depth occurred at the joints, however, because of the disturbance caused by placing the joint. Both low and high strand placement resulted at the joints on several occasions. Other aspects of the slipform paving, such as concrete mixing and delivery, vibrating, screeding, finishing, and curing, proceeded in conventional fashion.

Although the maximum length of pavement placed in 1 day was 2,529 ft (771 m), there is every reason to believe that runs of 3,000 ft (914 m) or more could easily be achieved. The low daily production for this slipform operation can be attributed to difficulties in placing the plastic sheeting on windy days, plant breakdowns, limited batch plant output, delays caused by winter curing, and late morning starting because of low temperatures.

Plastic Sheeting

The major problem encountered during paving was the placement of the plastic sheeting. The operation began by unrolling 2 overlapping rolls, 12.5 ft (3.81 m) wide, of double-layer polyethylene sheeting behind the strand pay-off truck and ahead of the spreader, allowing the strands to hold the plastic down. But, because the spreader dumped the concrete off a conveyor at the centerline and pushed it toward the edges with rotating augers, the plastic was pulled along with the concrete. This caused a space of up to 1 ft (300 mm) at the centerline without plastic. After trying various methods, taping the 2 rolls together proved to be the most successful. Rolls of plastic 25 ft (7.62 m) wide would have been more suitable but were not available.

Another problem with the plastic was its tendency to fold up as it was pushed by the concrete under the spreader. It was feared that these folds were becoming trapped in the concrete slab, causing potential weak planes. Whether this actually occurred or

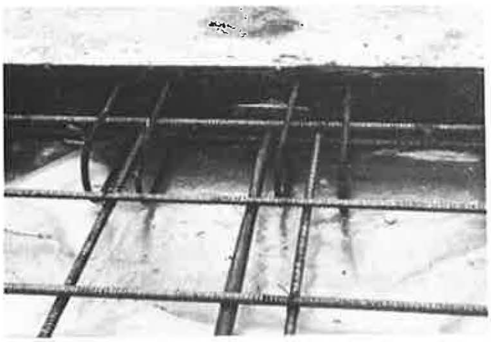


Figure 18. Permanent anchor and joint reinforcement.

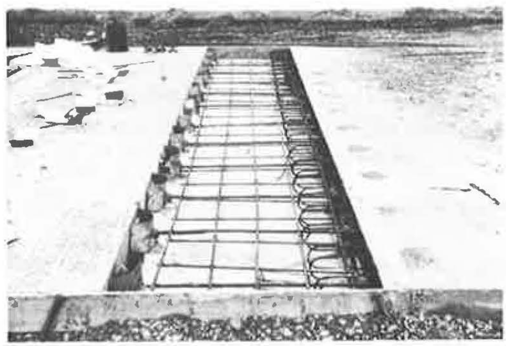


Figure 19. Joint ready for concrete placement.

Figure 20. Terminal joint.

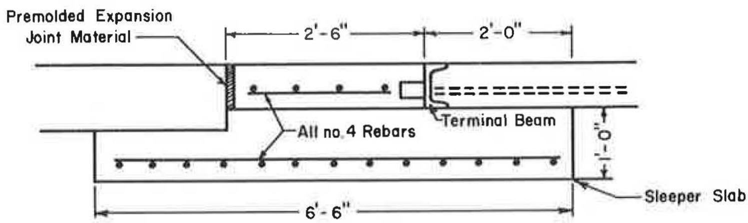


Table 2. Cost data.

Original Bid				Adjusted Price			
Item	Quantity (yd²)	Price per yd² ($)	Total Price ($)	Item	Quantity (yd²)	Price per yd² ($)	Total Price ($)
9-in. reinforced concrete pavement	37,608	8.80	330,950.40	6-in. prestressed pavement	38,268	9.40	359,719.20
9-in. subbase	73,796	1.58	116,597.68	6-in. aggregate bituminous base	41,650	2.90	120,785.00
10-ft shoulder, 9 in. (outside)	14,873	3.00	44,619.00	6-in. subbase	73,796	1.18	87,079.28
10-ft shoulder, 9 in. (median)	14,873	3.00	44,619.00	6-in. × 8-ft subbase under shoulder	23,800	1.50	35,700.00
				10-ft shoulder, 6 in. (outside)	14,873	2.50	37,182.50
				10-ft shoulder, 6 in. (median)	14,873	2.50	37,182.50
Total			536,786.08	Total			677,648.48
				Difference: Total			+140,862.40
				Per square yard			+3.68

Table 3. Sample joint movements.

Date	Temperature (F) Air	Temperature (F) Concrete	Reading (in.)[a]
11-27-73	54	47	10.061
11-29-73	44	44	10.109
12-6-73	50	47	10.084
12-7-73	39	39	10.220
12-12-73	35	29	10.444
12-14-73	44	38	10.322
12-27-73	57	50	10.154
1-28-74	46	47	10.270
2-5-74	12	7	10.643

Note: Pavement placed 11-2-73, joint placed 11-21-73.

[a]Distance between measuring points.

not is a matter of speculation, but no adverse effects have been noted. This problem was never adequately solved. A concrete spreader that drops concrete from a moving hopper rather than pushing it with augers would have been more suitable.

Wind proved to be the most adverse problem with the plastic. The sheeting tended to billow up and fold over at the edges with only a moderate breeze. On several occasions when the wind was quite strong and gusty, a crew of 10 or more men was required to handle the sheeting. When the conditions were calm, 2 men were sufficient.

Joint Placement

A crew of about 6 men was required for the joint-placing operation. With some practice the crew could complete the operation in about 30 minutes. This included removal of the blockout boxes and concrete, placing the female beam and bulkhead assembly, placing concrete back against them, and finishing the concrete.

Construction Joints

Interruptions in slipform paving can occur at any time for a variety of reasons such as a plant breakdown, equipment failure, or sudden rain. The logical place to cease paving for the day was at a joint location, but the possibility of having to stop part way through a slab was always present. This occurred on 2 occasions, once due to a plant breakdown and once due to an unexpected cement shortage at the concrete plant. The choice became that of placing a joint wherever the breakdown might occur or making a construction joint or "cold" joint.

The decision was made to make a construction joint at the first breakdown because of the added expense of placing an extra full joint. Only 204 ft (62.2 m) of the second slab had been placed when a plant breakdown occurred. A bulkhead was placed and paving commenced the following day, placing concrete against the previous day's pavement. As the concrete cured, the construction joint opened up to a width of about ⅛ in. (3.2 mm). This was caused by shrinkage of the concrete. The slip plane provided by the plastic and the initial gain in strength of the concrete are apparently sufficient to prevent cracking initially in a slab 600 ft (183 m) long; however, the addition of a cold joint caused the 2 parts of the slab to behave independently of each other and move apart. The initial 20-kip (89-kN) tensioning of the strands failed to close the joint. Only after the final load was placed did the strands have sufficient force to pull the 2 slabs together. The joint closed shortly after final jacking and remained closed. This indicated that construction joints could be successfully placed in post-tensioned pavement slabs. The same procedure was followed on the second breakdown.

The construction joints both closed to an eventual opening of 0.005 in. (0.13 mm), where they remained. Full closure was prevented by the intrusion of incompressible material. On February 5, 3 months after placement, the temperature dropped to 7 F, at which time the construction joints were open to a width of 0.015 in. (0.38 mm). Temperatures had been dropping gradually over a 3-day period prior to reaching the low on February 5. The joints closed to their former size when the temperature rose again.

Jacking

The jacking operation proved to be time-consuming with the available equipment. Initial tensioning of the strands was normally required the day following paving, so jacking had to be done regardless of weather conditions. The joints were cleaned out and the anchors placed the morning after paving; jacking did not begin until afternoon. Approximately 2 hours or more were required for the initial jacking on both ends of each slab, using a 2-man crew and a single jack. Final jacking required about 4 hours per slab because the jack had to be reset for each 10 in. (254 mm) of strand elongation. Only 1 jacking crew was available most of the time, and the jacking fell behind schedule as the job progressed. Final strand tensioning was applied as long as 13 days after paving some slabs. Fortunately the 20-kip (89-kN) initial strand load on these slabs was sufficient to prevent shrinkage cracking.

Strand Elongation

The theoretical elongation for the strands is calculated as follows:

$$\text{Percent elongation} = \frac{P}{AE} \times 100 = \frac{46.9 \text{ kips}}{(0.215 \text{ in.}^2)(28 \times 10^3 \text{ ksi})} \times 100 = 0.78$$

Measurements of actual strand elongations were taken by inspection personnel. The average percent elongation for all strands tensioned was 0.68. This is 87 percent of theoretical, indicating a loss of 13 percent due to friction and take-up at anchorages. Further losses would be expected due to the load transfer at the joints, concrete shrinkage, and creep.

Jacking Bridges

The use of the jacking bridges to transfer the load on the strands through the joint concrete was successful, although several problems arose during construction that led to improvements in design and procedure. Shortly after final jacking began, the steel bars used as bridges were bending under the load of the anchors. The bending was more severe where the strand was not exactly perpendicular to the slab end. It appeared that adequate consideration had not been given to the relation between the span of the bridge and the strength of the materials. When a shorter span for the bridge was put into use, the problem was eliminated.

The original plan for severing the jacking bridges to transfer the load through the joint specified flame cutting. This idea was abandoned in favor of cutting them with an electric arc welder. In this way, much less heat was applied to the strand because the total cutting time for each bridge was only about 15 seconds. The amount of heat on the strands was not even sufficient to melt the polypropylene conduit. A gradual release of the load on the temporary anchors occurred as the force was transmitted through the joint concrete to the permanent anchors. The temporary anchor moved approximately ¼ in. (6.4 mm) toward the slab from its original position, due to elongation of the strand in the joint.

Slab Length Change

The movements of the slabs at each joint are being evaluated to determine the changes due to thermal expansion and contraction as well as other slab behavior such as shrinkage and migration. An invar bar equipped with a dial gauge indicator is used to record movements at the joints. Measurements are taken between a mark on the female beam and a brass plug embedded in the joint concrete and between brass plugs in the terminal joint and adjoining pavement. Indications are that the slab length change is very sensitive to ambient temperature changes. Sample movements for one joint are given in Table 3. It is evident that slab shrinkage has accounted for an increase in joint opening since the joint was placed.

Total shrinkage of the slabs was measured by recording the distance between slab ends at the time of placement and later at about 100 days. The differences in measurements were averaged (after adjustment for temperature at time of measuring) to determine an average shrinkage of 1.56 in. (39.6 mm) per slab or 217×10^{-6}. A high initial rate of shrinkage, as reported by Friberg and Pasko (4), occurred prior to placing the joints.

CONCLUSIONS

1. Prestressed concrete pavement can be placed successfully on a production basis using conventional slipform paving equipment. Paving rates equal to those for conventional reinforced concrete pavement can be achieved.

2. The need for a treated base course is the principle reason for the higher cost of prestressed pavement on this job. Average construction costs in this area for 9-in. (229-mm) reinforced concrete pavement are presently \$9.38 per yd^2, nearly equal to the cost of 6-in. (152-mm) prestressed pavement on this job (5). Continuously reinforced concrete pavement presently averages \$10.19 per yd^2 for 9-in. (229-mm) thickness. The following factors must be taken into account when considering the prices on this job: The price was negotiated rather than bid competitively; initial investment in equipment and modifications to the paving train were required; and there was probably apprehension on the part of the contractor due to the uncertain amount of construction time involved and the need for on-the-job training of labor inexperienced with prestressing work.

3. Prestressed pavement has the potential for longer pavement life with less maintenance because of the elimination of transverse contraction joints and the elimination of cracks, both major causes of pavement deterioration.

4. Prestressed pavement may be the answer to potentially severe shortages of reinforcement steel and cement in the future.

5. Construction joints can be placed in prestressed pavement slabs at desired locations to accommodate the slipform paving operations. No long-term adverse effects are anticipated, although the joints should be grooved and sealed with a suitable joint sealant to prevent intrusion of debris.

6. The opening of the construction joints at very low temperatures indicates that the coefficient of friction between the base and slab is not as low as anticipated. This could possibly be caused by the less-than-satisfactory methods used to place the polyethylene sheeting. It also creates concern over whether there is compression in the other slabs to resist cracking near midpoint at low temperatures or during sudden temperature drops.

7. Transverse reinforcement steel in prestressed pavement can be eliminated.

8. Load-transfer devices can be used to prestress the joint concrete, allowing all pavement concrete to be in compression.

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