Synopsis: Since the first two mile stretch of slip-formed pavement was constructed in 1954, almost 2,500 miles of this type paving have been constructed on the Iowa secondary system. Its use has spread to the Interstate System, airport runways, etc., meeting tight tolerances. Economical low-cost pavements begin in the design stage and continue through construction.

This paper discussed various facets of design and construction which enable concrete pavements to be designed for specific traffic, subgrade and concrete strengths resulting in low annual costs for secondary pavements.

In 1954, Greene County, Iowa, contracted for a two-mile stretch of concrete pavement. These two miles became the first two continuous miles of slip-form pavement ever constructed. The original 10-foot width paver developed by James Johnson of the Iowa Highway Commission was used. It required two passes to produce the 20-foot completed slab.

From this humble beginning, through the 1970 construction season, almost 2,500 miles of secondary paving using the slip-form paver have been built on the Iowa secondary system. The original two-mile project required almost two weeks. During the 1970 construction season over two miles of 22-foot wide, six inch thick pavement were constructed in Clinton County in one day!

Iowa is not the only State building secondary roads with concrete. Minnesota, Nebraska, Ohio and Michigan, among others, have employed slip-form paving and Illinois has awarded its first low-cost county slip-form project.

If I may digress just a little, slip-form paving is not a second-class substandard construction method to be used only on secondary routes. In fact, Brus has found that good slip-form pavements generally will be smoother than pavements constructed with forms (1). The results of a 1968 questionnaire showed that nine States used only slip-form construction on their primary systems. Of the rest of the reporting States, almost 60 percent of the concrete paving employed the slip-form paver (2).

During 1969, a 16-inch thick main runway and taxiway were constructed at Atlanta Municipal Airport using a slip-form paver. Favorable results at Atlanta opened the specifications elsewhere, and in 1970 a runway and taxiway were constructed at Seattle-Tacoma International and O'Hare International as well as a taxiway at Toronto International. These pavements varied in thickness from 14 to 16 inches. In all, at least 12 airfields in the United States have constructed facilities using this type of equipment. The tight tolerance requirements of airfield construction have been met, and generally at a lower cost than form-type construction.

Not only has the widespread use of "formless" paving reduced the cost of construction, the adoption of the latest concepts of design has further reduced the cost. In Illinois and elsewhere, pavements designed for equivalent loads will in most cases be less expensive with concrete. This does not even consider the long-range results of lower maintenance costs and higher performance indexes.

The purpose of this paper is to discuss current design and construction procedures of concrete paving generally and slip-form paving in particular.

An economical low-cost pavement begins in the design stage and continues through construction. The goal of any pavement design is to provide a desired facility at an acceptable level of performance for a given time at the lowest possible annual cost. To accomplish this goal, a balanced concrete design must be made. This will consist of three parts: the pavement, the subbase, and the subgrade. The pavement, or concrete layer, must be of the proper thickness and have provision for proper jointing to control temperature and load stresses. The subbase must be of proper thickness and of proper material to control high-volume-change soils, to aid in controlling frost action and to prevent pumping. The subgrade must provide reasonably firm support for the pavement structure.

SUBBASE.

Excessive differential shrinkage and swelling of high-volume-change soils causes nonuniform subgrade support. As a result, concrete pavements may be distorted enough to impair surface smoothness and riding quality. Excessive shrinkage and swelling of expansive soils is often prevented by adequate moisture and density controls during compaction. It is important to compact both moderately and highly expansive soils at not less than optimum moisture as determined by the AASHO standard method (designation T99-57). In Kentucky, there are very few areas where there are high-volume-change soils, thus, control of expansive soils is not a major problem, although it is still worthwhile to compact most soils at moisture content close to or slightly above the standard optimum. However, a granular subbase layer is not required to control high-volume-change soils in Kentucky.

Subbases are also used to aid in the control of frost action. When water freezes it expands nine percent in volume. For an extreme condition such as a subgrade moisture content of 25 percent and a frost penetration of 24 inches (which is the maximum in Kentucky (3)), this
nine percent expansion would cause a heave of about one-half inch. This is not enough to damage a concrete pavement.

Detrimental heaving is due to the growth of ice layers or lenses in the subgrade. Ice lens growth stems from differences in the freezing temperatures of water in the subgrade soils. Water in the larger soil pores freezes at or slightly below 32°F, while moisture in the smaller soil pores requires a lower temperature before freezing occurs. When freezing temperatures penetrate into fine-grained subgrade soils, water in the larger pores freezes at about 32°F. Moisture from the smaller soil pores moves to the frozen zone, freezes on contact, and expands. As ice lenses grow during this process, the pavement and subgrade above the formation of the frozen zone are lifted or heaved upward. If sufficient moisture is available, a series of ice lenses may form causing a severe differential frost-heel.

Control of frost action is needed only to prevent this excessive heave and to maintain a reasonably uniform subgrade support. As in the case of expansive soils, control of frost action is most easily accomplished during grading operations. The methods employed are similar to those used in all climatic conditions to ensure uniform subgrade support and good pavement performance. They include the following: (1) setting grade lines high enough and constructing side ditches deep enough so the highly frost-susceptible silts and fine sandy soils are beyond the capillary range of free water tables; (2) placing highly frost-susceptible silts and fine sandy soils in lower parts of embankments and cross-hauling less susceptible soils to form the upper part of the subgrade; (3) where highly frost-prone soils are pocketed in less-susceptible soils, the pockets are excavated and backfilled with soils like those surrounding the pocket. If the normal soil texture is sand or gravel, sand or gravel is used for backfill. If the normal soil is clay, clay is used for the backfill. Experience has shown that replacement need not exceed one-third to one-half the depth of frost penetration.

Proper grade designs, selective grading, and compaction control are effective and proven methods for control of frost action. These methods produce uniformity and resistance to rapid capillary flow in the upper part of the subgrade. This prevents differential or excessive heaving and precludes the need of subbase granular materials.

Mud-pumping may occur when concrete pavements are placed directly on fine-grained plastic soils. Mud-pumping is a forceful ejection of a mixture of fine-grain soils and water from beneath joints, cracks, and pavement edges. Mud-pumping is caused by the frequent deflection of slabs by heavy wheel loads when fine-grain plastic subgrade soils are saturated. Studies have shown that three factors are necessary for mud-pumping to occur: (1) a subgrade soil that will go into suspension; (2) free water between the pavement and subgrade or subgrade saturation; and (3) frequent passage of heavy wheel loads (4). In Kentucky, much of the subgrade will be a soil that will go into suspension, that is an A-4, A-5, A-6 or A-7 soil. And, most subgrades will at times become saturated. However, subbase surveys made over many miles of concrete pavements show that two-lane pavements designed to carry not more than about 300 to 400 heavy axle loads per day do not require subbases to prevent pavement damage from mud-pumping. Thus, if a proper analysis of future traffic requirements is made, a subbase (that is, a granular layer between the native soil and the concrete) may not be required. This can save considerable amounts of money per mile of concrete pavement.

The designer of the slab has the opportunity to further reduce the cost of a pavement if he analyzes the expected traffic. For any given thickness of pavement and strength of subgrade, the maximum stress in the concrete can be determined (5). If this stress is less than one-half the ultimate concrete strength, the slab can safely carry an unlimited number of load applications. For example, if the flexural strength of the concrete is 700 psi, then one-half the flexural strength of the concrete is 350 psi. From the design chart for single axles (Fig. 1) a 350-psi concrete and a subgrade k of 100 (clay) will carry an unlimited number of 18-kip loads on a 6-inch thick slab (6). If this stress becomes greater than 0.50, a reduced number of load applications can be carried. For example, from the same design chart, a 24-kip load under the same conditions will create an actual stress of about 450 psi. This is approximately 0.64 the ultimate strength of the concrete. A stress ratio of 0.64 will allow 11,000 load applications (Fig. 2) over the life of the pavement.

![Figure 1.](image)

If, for instance, during the life of the pavement, 110 load applications of 24 kips are expected, then 110/11,000 = 1 percent, meaning that 1 percent of the fatigue resistance had been consumed. If, however, 11,000 load applications of 24 kips are expected during the lifetime of the pavement, then 1,100/11,000 = 10 percent, meaning that 10 percent of the fatigue resistance has been consumed. This operation of examining the stresses for each group...
of loads first for single axle and then for tandem axles, (Fig. 3) is continued. When 100 percent of the fatigue resistance has been consumed and some heavy loads have not yet been examined, the designer may desire to use a thicker slab and study it for resistance. The complete thickness design manual with more detail is available from PCA. This method of design requires a knowledge of anticipated traffic. Sometimes the state "W-4" may be used for this purpose.

Spring thaws will reduce the bearing value of the subgrade. Because of the rigidity and high modulus of elasticity of concrete, the following theorem is true. As the load-carrying capacity of the subgrade decreases, the area of subgrade which carries the load will increase resulting in a reduced stress on the subgrade. This is the reason that concrete has no dramatic spring break-up as do flexible pavements.

Jointing is equally important in a balanced design. If no jointing of any kind were provided, a plain pavement would crack both longitudinally and transversely. The transverse cracks would probably be spaced about 20 feet apart and the longitudinal crack would be somewhere near and parallel to the centerline. Jointing theory requires a low maintenance joint be placed where cracks are expected to occur. On lane-at-a-time paving, the construction joint along the center should be keyed and tied with a deformed tiebar. In full-width paving, a deformed tiebar should also be used and a weakened-plane longitudinal center joint sawed or formed into the slab along the centerline. It is essential that the depth of the joint be less than one-fourth the thickness of the slab. If this minimum depth is not maintained, the joint will not control longitudinal cracking.

For transverse contraction joints, the most economical design is a plain pavement with a comparatively close-spaced undoweled contraction joint. A plane of weakness is created by means of a groove formed and finished while the concrete is plastic, a strip inserted in the plastic concrete, or sawing a groove after the concrete is hardened. The joint depth should not be less than one-fifth the slab thickness. Where joints are sawed, the depth of the saw cleft should not be less than the diameter of the largest-size coarse aggregate. Irregular faces of the slab edges that form below the groove or saw cleft provide aggregate interlock for load transfer across the joint. An alternative design employs distributed steel and placement of joints further apart. With this design the contraction joints are not placed to control cracking. Instead, the distributed steel is designed to prevent slab faces from separating after cracking occurs.

For low-cost pavements on rural pavements carrying less than 300 to 400 heavy trucks per day on a twolane facility, the most economical pavement will normally be a plain concrete pavement, six or seven inches thick, with transverse joints spaced 20 feet apart. The only steel used in this type of pavement is the tie-bars across the centerline joint. When the amount of truck traffic exceeds this figure, it is often more economical to construct a plain concrete pavement with doweled joints. This is usually more economical than using dowels and distributed steel.

Most engineers feel that mesh in a pavement contributes little if any strength or additional life to the slab. This is because the primary function is to hold the fractured edges together so that aggregate interlock will transfer the loads across expected cracks. This was borne out in the AASHO road test. In this test, concrete slabs

** Table 1 from "Concrete Pavement Design" by Phil Fordyce and R. G. Packard presented at 49th Annual Meeting of AASHO Committee on Design, Portland, Ore., October 1963.**

** Unlimited repetitions permitted for stress ratios of 0.50 or less.**
were placed with 15 foot panels and no mesh and 40 foot panels with mesh. The short, unreinforced panels performed as well as, if not better than, the panels with reinforcing steel. This trend has continued in the observations made since the test road was opened to regular interstate traffic.

It behooves the engineer to design pavements for anticipated loads. In many cases where thick concrete pavements with steel and granular or stabilized subbases are now used, a six- or seven-inch concrete pavement with no steel and constructed on an existing subgrade will serve the purpose.

**CONSTRUCTION.**

When the State of Iowa began slip-forming, 34-E pavers were used along with subgrade planers that had been modified by the addition of tracks. The line where the tracks were to be operated was trimmed to proper line and grade by use of the form grader operating off a stringline. The planer followed and trimmed the subgrade to line and grade. Most planers were equipped with provisions for trucks to drive over the top. This was necessary because of the narrowness of grade.

**Figure 4.** Concrete being deposited from dump trucks into a hopper mounted onto the front of an automated subgrade machine.

Batch trucks were charged with aggregate and cement at a central plant site and transported to the job. There the concrete was mixed in the paver and deposited in front of the slip-former. A small subgrade planer was usually used just before the slip-former to remove any irregularities caused by the trucks operating on the subgrade.

Most of the spreads now being used consist of a central plant for complete mixing of eight to nine cubic yard batches. These are transported to the job site in regular dump trucks. They are transported over the subgrade which is to be paved. This has normally been trimmed to a rough grade and left slightly high.

**Figure 5.** Concrete being placed onto a newly trimmed subgrade in front of the slip-form paver.

The concrete is deposited into a specially designed hopper on the front of an automated subgrading machine (Fig. 4). A belt carries the concrete over the subgrade machine and places it ahead of the slipformer (Fig. 5). The subgrader then becomes the last piece of equipment prior to the concreting operation. It has cutting blades which trims the subgrade very accurately (Fig. 6). The automated subgrader operates off a stringline which controls both the line and grade and leaves the subgrade in a smooth, reasonably uniform condition (Fig. 7).

The slip-former then spreads, vibrates, and consolidates the concrete into the shape of the finished slab. Tie-bars for the centerline joints are also placed at this time, often by hand. Only a small amount of hand finishing is necessary between the trailing forms. The entire operation, from subgrade trimming to final hand finishing is completed within a very short period of time.

The final finish is a burlap drag which is often pulled along at the back of the trailing forms (Fig. 8).

The slab is cured with a pigmented curing compound. Care is taken to ensure that the edges are treated also. The final operation is sawing of the transverse and longitudinal joints and joint sealing with an asphaltic material.

The coming of the slip-form paver with the opportunity of easily varying the thickness of a concrete pavement has made the design of pavements for specific loads practical. No longer is a designer tied to the thickness...
of forms owned by local contractors. Now he may design six- and seven-inch pavements as well as thicker pavements if conditions warrant.

The designer is also rediscovering the benefits of plain, unreinforced concrete pavements when placed on a clay subgrade. The engineer once again is able to design specific pavements for specific cases and to obtain the lowest possible cost per mile that will provide a desired facility at an acceptable performance level for a given time at the lowest annual cost. For this, we have to thank the flexibility of the slip-form paver.

REFERENCES


2. J. W. McKnight, "Description and Cost Comparison of Modern Concrete Paving Equipment Systems," PCA, p. 4.


