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Foreword

Slip-form techniques have been developed over the last decade for the construction of virtually any concrete pavement design. Pavements so constructed can be at least as smooth riding as those laid between conventional side forms, and there is usually a welcome reduction in cost. For these reasons, slip-form paving is becoming widely used. The papers in this Record definitively record the development and current practice across the country. They were originally presented at a well-received symposium on slip-form paving at the 44th Annual Meeting of the Board.

The lead-off paper by Smith is an introduction that traces the history of the development, growth and spread of slip-form paving since 1947.

Clauson's report describes the well-established use of slip-form paving in Iowa to provide low-cost unreinforced concrete pavements on secondary roads.

The first use made in Ohio of slip-form paving is discussed by co-authors Dixon and Marshall. They point out how initial problems are overcome as experience is developed.

Kawala, in his paper, draws attention to the essential need for adequate subbases to provide not only pavement support, but also to give an accurately level track for the slip-form paver. Proven methods and machines for preparing both granular and cement-treated bases are illustrated.

Authors Gillis and Spickelmire explain the successful and wide use of slip-form paving in California on all classes of highways, including those constructed up to three lanes wide at a time, while Zulian comments on the extensive use of slip-form paving methods on Colorado's Interstate System. He emphasizes the refinements based on experience that have been introduced.

Lyon's report shows that slip-form methods are as easily applied to urban construction as they are to rural road building. Burke and Mascunana describe an experimental project in Illinois to develop methods of installing reinforcing steel and load transfer devices in slip-formed pavement.

Swanson takes the contractor's viewpoint and explains how simplifications and the savings in men and machines may revolutionize the concrete pavement construction industry.

Halm, in the final paper, summarizes the latest developments in practice and shows how advancements in methods and equipment are accompanying the rapidly increasing use of slip-form paving.

Contained in these papers are many of the answers to the questions and problems which may arise when slip-form paving is tried for the first time. The experience of those States that have become large volume users is that, given willing cooperation between contractor and Highway Department, initial difficulties can be rapidly overcome so that acceptable concrete pavements are produced at lower cost. Rapid advancements in equipment and methods are also taking place to match the increased use and spread of slip-form paving throughout the country.

Contents

Introducing Slip-Form Concrete Paving

PETER SMITH
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As an introduction to the 1965 Highway Research Board Symposium on Slip-Form Paving, the general historical development and spread of this method of constructing concrete pavements in the United States from 1947 to the present time is briefly described.

•IN 1947, J.W. Johnson, Materials and Testing Engineer of the Iowa State Highway Commission, speculated that if the side forms of a paver are taken away before the concrete sets, good-quality concrete when properly consolidated would stay in place and retain its shape without running down the grade.

To try out the idea, the first pilot model of a slip-form paver was built (Fig. 1). It placed a concrete ribbon 3 in. thick and 18 in. wide sufficiently well that in 1948 another pilot model, large enough to lay a 6-in thick, 3-ft. wide strip, was built and tested. The real promise of the idea appeared to be as an economical method of providing low-cost pavements for secondary roads. The next version was full-size, with 11-ft long trailing side forms, as shown in Figure 2, which could lay a 6-in. thick, 10-ft. wide, slab. Field experiments on two small sections of pavement in O'Brian and Cerro Counties proved that it worked. This first practical slip-form paver was later modified in many ways; for example, it was made self-propelling. However, it was soon realized that further development was necessary, for example, to lay 24-ft wide pavement in one pass, and that such development was more properly the job of those engaged in building and using concrete paving equipment than of a state highway department.

Therefore, the Quad City Construction Company took over further development work. Crawler tracks, tamping bars, tube vibrators, oscillating finishing belts, etc., were added. Also, since proper preparation of the grade appeared to be a key prerequisite to smooth pavements, suitable form graders for the track paths and subgrade finishing machines were developed. The first commercial paver was used in 1955. Gradually, use spread from secondary to primary routes as the equipment and techniques were improved, so that by the end of 1964, as Figure 3 shows, more than 1,200 mi of slip-form paving had been laid in Iowa alone.

State highway officials, contractors, and equipment manufacturers gradually became interested in the potential ability of slip-form pavers to lay smooth concrete pavement at lower cost. Slowly at first, but later with ever-increasing speed, slip-form paving spread from Iowa to other states. It has thrived in California on unreinforced pavements with stabilized bases laid to a width of 36 ft or more in one pass. Much early work was also done in Colorado, including experimental work to incorporate reinforcing mesh. During the past decade several new machines have been developed, and construction techniques, particularly those for attaining smoothness or building complicated layouts, have been refined. As shown in Figure 4, by 1964 slip-form paving had attained considerable proportions in Iowa, California, Colorado, and Oklahoma, and had at least been tried in 20 other states. The mileage of concrete pavement constructed by the slip-form technique has risen to 4,000 mi in the United States in the last 15 years. This has included work on all classes of highways, rural or urban, from farm-to-market roads to Interstate routes. Furthermore, slip-form paving has already been used in France, and will soon be tried in England and other countries.

Paper sponsored by Committee on Construction Practices—Rigid Pavement.

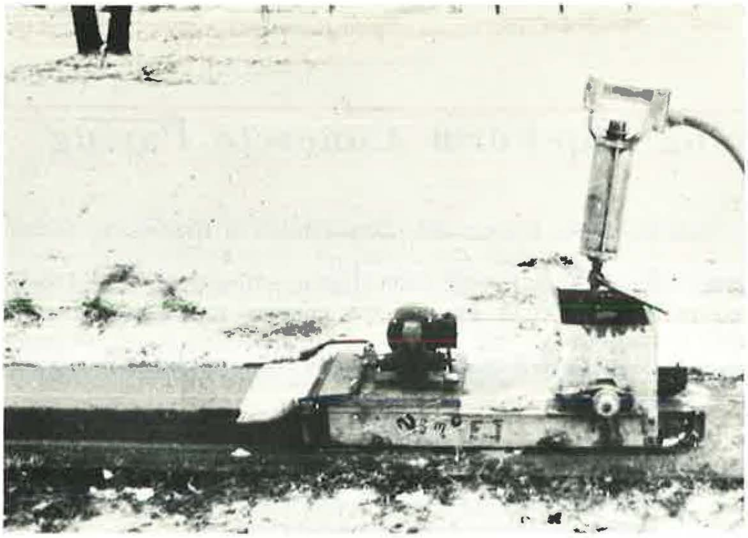

Figure 1. First pilot model slip-form paver; built in Iowa, 1947.

Recent rapid growth coincides with the big breakthrough in the development of an economical and practical method of incorporating mesh and dowels in a slip-form pavement. This milestone in slip-form paving occurred on the Oklahoma Turnpike in the fall of 1963, and means that slip-form paving techniques although of course still capable of refinement and improvement, can now lay any design of concrete pavement on any class of highway.

Our committee met in Iowa and inspected the first use of slip-form pavers to build a reinforced concrete pavement as part of their Interstate mileage. The method used

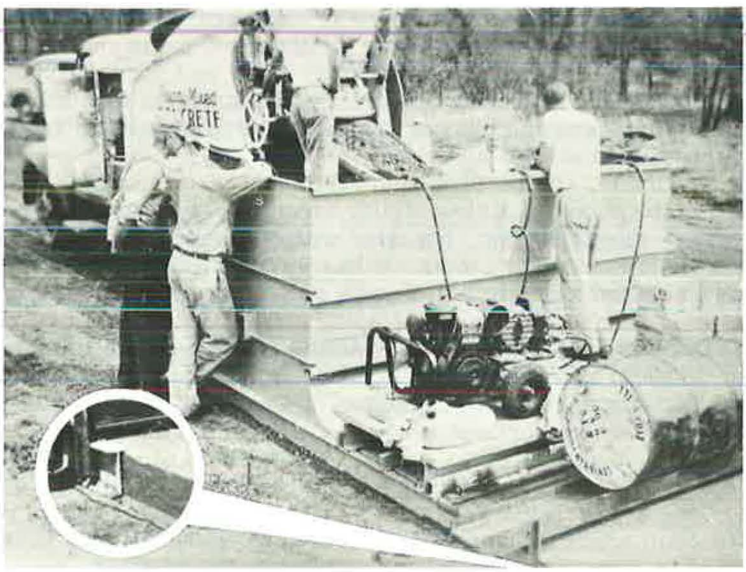

Figure 2. First practical slip-form paver laying an experimental concrete pavement; Iowa, 1949.

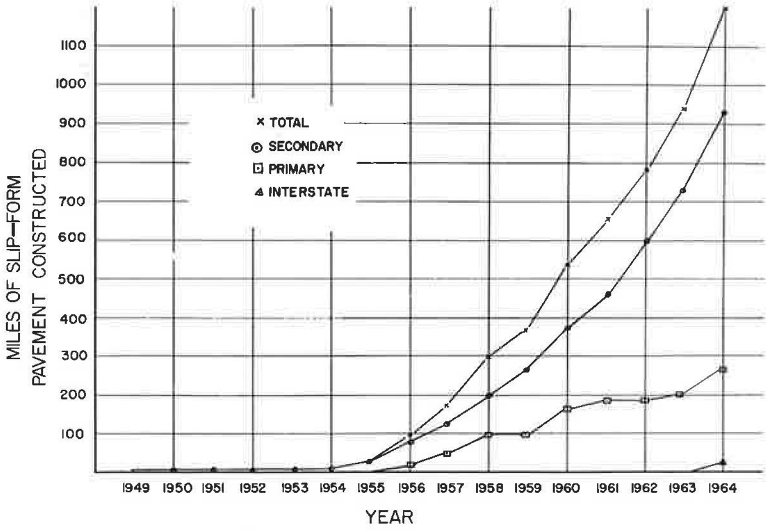

Figure 3. Fifteen-year progress of slip-form concrete pavement in Iowa, showing total miles constructed.

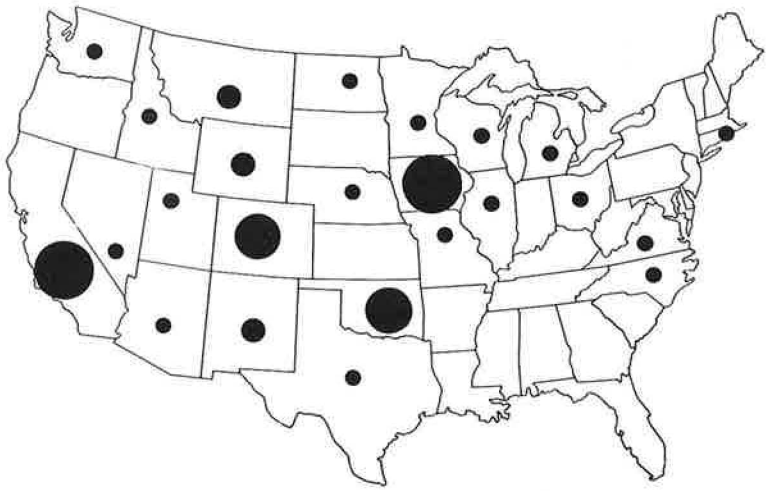

Figure 4. States where slip-form concrete paving has been used up to Dec. 1964.

was simple and worked just as well as it had the fall before in Oklahoma; two-course construction with two slip-form pavers was used, the first striking off the bottom lift to allow the steel to be placed and the second straddling this to lay and finish the top. As we drove back to our motel that evening, Phil Fordyce of the Portland Cement Association Paving Bureau said, "You know, Pete, after what we've seen today, it's goodbye forms within five years!"

Slip-Form Paving—Construction Practices on Iowa's Secondary Roads

L. M. CLAUSON, Chief Engineer, Iowa State Highway Commission

Since 1949 over 1,000 mi of slip-form pavement have been constructed in Iowa. Most of these miles are on secondary roads. Several considerations for this construction are presented. Paving on narrow grades, poor soils, subgrade construction, mixing and placing operations, concrete mixes, and smoothness are also discussed.

•SLIP-FORM PAVING in Iowa started in 1949 with a total of 1.5 mi of pavement placed on two projects. The first pavements were placed in 10-ft lanes, using a machine designed and constructed by the Iowa State Highway Commission. Since that time a total of more than 1,200 mi of slip-form pavement have been placed in the state. This type of pavement has been used successfully for secondary, primary, and interstate construction. Variations include use of doweled contraction joints, mesh reinforcing, and various types of subbase. About 75 percent of the slip-form pavement has been placed on secondary roads.

Secondary roads are vital to the agricultural portions of Iowa's economy. There are more than 90,000 mi of secondary roads in Iowa. More than 90 percent of these have some type of all-weather surface. About 34,000 mi are on the farm-to-market system which is essentially the Federal-aid secondary system. Traffic on secondary roads varies considerably, but most paved roads have present traffic varying from 125 to 600 veh/day with about 5 to 15 percent large trucks or similar vehicles. Maintaining granular surfacing on these roads for all-weather traffic is both costly and impractical. Usable aggregate sources are being depleted at a rapid rate, causing longer hauls and higher prices for granular surfacing. The secondary roads with heavy traffic must have a higher type of surface to reduce the annual cost of maintenance.

Road construction on Iowa's secondary roads is done according to standard specifications, using the same degree of inspection and quality control as primary construction. The county engineer is in charge of the work, and he acts in the capacity of a resident engineer for the state on projects involving state or Federal funds.

The paved roads have graded widths from 28 to 34 ft, depending on the age of the existing road, the terrain, and the existence of rock in the cuts. For snow storage, the side ditches are deep and narrow, and the foreslopes and backslopes are steep. The foreslopes vary, but the common foreslope is 2 to 1.

CONSTRUCTION

Subgrade

The roadbed soils are usually used as they are. Soils prevalent in Iowa are A-7-6 and A-6, usually with high index numbers. To obtain embankment soil for a high grade from a narrow right-of-way, the side ditches are usually deep, making soil from lower horizons available for the tops of grades. There seems to be a significant benefit from this.

The pavement may be placed on a roadbed constructed during previous years with little scientific soil selection. When soils are particularly poor, the condition is usually corrected by the county before paving operations begin. This process may include excavation of the roadbed and replacement with suitable material.

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Roadbeds usually have some loose granular material on and near the surface. Subgrade preparation work uses this material to the best advantage. The subgrade first receives a general shaping with a motor patrol. This includes scarification of granular material and soil to a depth of several inches. Some movement of this scarified material is required, both along the centerline and transversely. The material is placed and compacted in general conformance with the required final subgrade elevation. The desired grade line is modified, as necessary, to keep movement of material to a minimum. This is possible in rural areas. Changes usually are not greater than 0.1 ft in 100 ft. The loose material is well compacted. The compacted thickness varies considerably, but the thickness in any cross-section is fairly uniform and the change in thickness longitudinally is gradual. Because of the variation, a compaction density is not specified. The resulting subgrade is a soil-aggregate mixture. In some locations the existing roadbed has a particularly high or irregular crown. Several inches of granular material are first salvaged by windrowing. Lower soil is shaved by motor patrol to the desired elevation and wasted on the shoulder or foreslope. This initial subgrade work results in a more uniform subgrade which minimizes any tendency for longitudinal cracking or unevenness from settlement.

An adequate track path for the slip-form tracks is prepared with a form line grader or cutter. The surface of this path is of utmost importance. It must be true and firm for a smooth riding surface. The mixture of soil and aggregate is spread and compacted 1 ft outside this path to insure proper material in the track area. Paving hubs are placed at intervals of 50 ft on tangents and 25 ft on vertical and horizontal curves and transitions. These are offset 2 to 3 ft, depending on the shoulder width available. The contractor sets steel rods inside the hubs and connects them with a string line at the proper elevation. There is a reference guide on the form line cutter. Recently an electronic control device has been used in conjunction with a steel wire. After the track path is established, all traffic is kept away from the path except equipment which must use it.

The subgrader operates on tracks in the track path at some distance ahead of the concrete placing operations. There is no feasible manner for the batch trucks to detour. A bridge must be provided over this machine to permit trucks to pass. At least 500 ft of finished subgrade is required ahead of paving operations to assure a smooth surface. This minimizes the possibility of small swales which may not be noticeable to the inspector at any other time before the pavement is placed but are objectionable to high-speed traffic.

Immediately ahead of the paver is the tail plane, adjusted to the proper subgrade crown which provides for the desired pavement thickness. It operates on tracks in the track path.

Subgrade constructed in this manner appears to be quite satisfactory. The soil-aggregate mixture provides not only a uniform subgrade of better quality than the native soils, but also an excellent base for the track path.

The contractor has the option of covering the subgrade with paper or polyethylene film or sprinkling it with water. In the past, polyethylene film has been used on the subgrade rather than sprinkling immediately ahead of the paver. Batches must be trucked over the subgrade, which becomes wet enough when sprinkled for tires to pick up enough to leave an irregular subgrade surface and to contaminate the batches in the skip. Also, another water truck would reduce efficiency.

Placing Concrete

Space at the paver is limited. All paving operations must be done at least partly within the limits of the pavement edges. This includes the paving mixer and the haul trucks, since it is impossible to bring service trucks on the shoulder alongside new pavement, and the ditches are often not usable for this traffic.

Concrete is usually mixed on the grade, although ready-mixed and central-mixed concrete have been used successfully. The rate of progress is restricted by rate of delivery and mixing and not by the slip-form paver. For primary work, as many as three mixers have been used on the grade with one paver. For secondary work, the narrow roadbed limits grade mixing to one mixer. Placement rates of 3,700 ft of 6-in. pavement, 20 ft wide, are possible with an efficient operation.

Present slip-form pavers use either internal vibrators or pan-type vibrators to consolidate the concrete. Both seem to be satisfactory.

Edge slumping has been a major problem on only a few slip-form paving projects. It is experienced occasionally when consistency is not uniform and during days of high humidity. These areas are corrected by the use of wood forms kept in readiness.

Roughness and edge slumping seem to be related to the uniformity of the concrete. Air-entrained concrete seems to be more sensitive to the amount of water in the concrete than the non-air-entrained concrete. It is important to use good dispensing equipment and to keep it in good condition to insure a uniform quantity of admixture. Aggregate is being produced by high-volume plants. The stockpiling time is frequently short, causing large variations in aggregate moisture. It is evident that good control of both materials and moisture is necessary to achieve uniformity of the concrete. County engineers have been given technical assistance in training inspectors in control testing and inspections. Everyone concerned has learned the value of uniform consistency. On those projects where there is still a lack of uniformity, roughness and edge slumping are still problems.

Paving aggregate in Iowa contains some shale and other light aggregates which have a tendency to rise with vibration, causing a small amount to concentrate near the surface, which is objectionable. If this light aggregate accumulates ahead of the paver for some distance and is consolidated on the concrete surface at one location, the resulting pavement surface is very objectionable. This is mentioned because concrete for the thinner pavements used on secondary work is very sensitive to vibration, and equipment should be carefully controlled to provide for the correct vibration.

Curing

White-pigmented curing compound is used for initial and final cure. It is difficult to bring burlap to the new pavement and to keep it wet, since there is no room on the shoulder for either burlap trucks or water trucks. The ditches are often too deep and too narrow for such traffic. Early application of curing water to the pavement encourages edge slumping, and curing should start while the edges are still tender.

Shouldering

Shoulder soil is hauled in trucks, dumped in piles just off the pavement, and leveled by motor patrol. Hauling units having axle loads in excess of 12,000 lb are not permitted on the pavement during shouldering operations. There is no space for hauling equipment of any kind on the shoulder area.

Shouldering is permitted after the concrete has attained an age of 14 days. The engineer may delay shouldering if cool weather delays curing.

DESIGN

Most secondary designs in Iowa are for a uniform thickness of 6 in. and a width of 20 ft, although there have been some projects with thicknesses of 7 or 8 in. and widths of 21, 22, or 24 ft. The parabolic crown is usually 1 ½ in. based on 20 ft. The only steel reinforcement is a No. 4 bar across the centerline at 30-in. spacing. Longitudinal and transverse joints are sawed, the latter spaced from 20 to 40 ft. In some cases joints are sawed dry because getting water to the saw becomes a major problem.

For economy, some contracts have not required joint filling. To date, pavements with light traffic seem to perform about the same with or without joint filler.

The concrete used with most secondary pavements has 5.10 sk/cu yd of cement, along with 55 percent of 1 ½-in. coarse aggregate and 45 percent of fine aggregate. The specifications permit a wide range of mixes in which the cement is increased as the sand is increased. For economy the contractor has the option of using unseparated aggregate. This permits the use of aggregate from smaller sources which usually have less costly aggregate production equipment. The quality of the aggregate is the same as required for primary work.

This concrete mix is lean when compared to standards used by some other states. The pavements are designed for fairly light traffic, and the resulting concrete seems to be satisfactory for that purpose. Where heavier traffic is anticipated, a mix with more cement is specified.

PAVEMENT CHARACTERISTICS

Slip-form pavement characteristics can be considered from several approaches.

Pavement Strength

Concrete pavement cores showed an average 1963 strength of 3, 939 psi for all concrete with the 5. 10-sk cement factor. This strength includes an age correction factor for estimating the 28-day strength. A few of the counties spread salt for ice and frost control, though sand is used when necessary. Where salt is used, the spreading rate and frequency of use are usually less than those used for primary work. Some of the older pavements with heavier traffic show minor signs of surface abrasion, but this is not considered serious.

Smoothness

All new pavements are checked with a U. S. Bureau of Public Roads type of roughometer. This is a standard method for determining smoothness of the riding surface. These results, reported in inches of roughness per mile, have been classified only as slip-form and fixed-form pavement, with no classification by primary or secondary system. This roughness agrees numerically with the Bureau's roughometer. For 1963 all new slip-form pavement averaged 73 in./mi for 174 mi checked, and new fixed-form pavement averaged 98 in./mi for 59 mi checked. In 1964 slip-form paving averaged 72 in./mi for 273 mi measured, and new fixed-form paving in 1964 averaged 78 in./mi for 104 mi measured. Urban projects and short pieces of reconstruction are usually somewhat rougher, and they are usually paved with fixed forms.

These results show that the average slip-form pavement is smoother than the average fixed-form pavement. Slip-form pavement shows more variation in smoothness, particularly for new slip-form outfits—both equipment and crews—and for conditions of nonuniformity. Usually the pavement placed following a day's work joint is somewhat rougher. Lack of uniform consistency appears to be a cause for roughness. Frequent interruptions during a day's run usually results in rougher pavement. An improperly constructed track path may cause roughness or swales in the pavement. Although these are all potential sources of roughness which may be relatively more important for slip-form operations, the roughometer results indicate that these can be overcome.

Thickness Variation

Pavement contractors are paid on a square yard basis, adjusted for areas with deficient thickness. An analysis of thicknesses shows that the contractors seem able to control thickness about as effectively with slip-form pavement as with fixed-form pavement. A 1962 study showed that 97. 1 percent of the cores from all slip-form pavement placed that year were not more than ¼ in. deficient in thickness. This compares with 96. 5 percent for fixed-form pavement.

GENERAL COMMENTS

Customary evaluation methods show that slip-form pavement is comparable to other pavements. The special problems related to Iowa's secondary roads result from narrow and high grades and poor soils. High grades are beneficial for several reasons, including availability of better soils. The narrow roadbeds make special construction techniques desirable. Economies can be made in construction costs when fairly low traffic is anticipated.

Ohio's First Experience with Slip-Form Paving

JOHN C. DIXON and H. E. MARSHALL
Respectively, Rigid Pavements and Concrete Engineer, and Pavement Design Engineer, Ohio Department of Highways

The successful construction is described of approximately 8 mi of plain concrete pavement on the secondary highway system in Ohio using the slip-form technique. Design features, as well as construction experiences, are reported. The pavement was constructed on earth subgrade on fills and all cuts except for rock cuts where a 4-in. subbase was specified. The grade was prepared using an automatic subgrader. Concrete was produced in a central mix plant erected on the project and hauled to the paving site in trucks with dump bodies. A slip-form paver, without automatic controls, was used to extrude the concrete into a 24-ft by 7-in. concrete pavement.

• FOR SOME YEARS highway engineers in Ohio have followed with interest the development of slip-form paving techniques in such states as Iowa, Colorado and California. Six years ago, a project was planned in Ohio which called for 8-in. plain concrete pavement and permitted the contractor to place the pavement by conventional methods using forms or by the use of a slip-form paver. Since the project had a length of only 2 mi and involved placement of some variable width pavement, the successful bidder elected to use forms rather than procure the specialized equipment for slip-form work.

Several years later when plans were being developed for an 8.8-mi section of completely new construction on new line and grade on the Federal-Aid Secondary System in southeastern Ohio, the slip-form option was again considered. The plans called for elimination of a number of sharp curves, including one 66° hairpin turn, and reduction of the maximum grades from about 11 to 6 percent. The new alignment, having a 50-mph design speed, contained several 3° and 4° horizontal curves with only one curve at the maximum of 5°.

This project lies in the unglaciated Appalachian plateaus of southeastern Ohio. Local relief is on the order of 200 to 300 ft. Bedrock consists principally of shales, indurated clays, sandstone and occasional thin beds of limestone and coal. The rocks are essentially flat lying and belong to the Conemaugh formation of the Pennsylvanian system. The rock mantle is composed of residual silt clay and clay soils in the A-6 A-7-6 HRB classes. The area is generally subject to landslides and several small slides developed and were treated during the grading required for the project.

Traffic volume on this road is fairly light and relatively few heavy commercial vehicles use the road. The 1960 count ranged from 480 at the east end to 840 veh/day near Caldwell. The total commercial count was 60; however, as on many roads in this part of the state, opening of a coal mine in the vicinity may induce a large volume of heavily loaded coal trucks for a period of variable duration depending on the peculiarities of the particular mine in operation. Needless to say, these vehicles haul all that the law will allow.

The native rock and soil materials are not suitable for the development of the substantial quantities of aggregates required for major highway construction. The nearest large source of commercial gravel is approximately 50 mi away in the valley of the Muskingum River. Flexible pavements are normally selected for low traffic volume

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Figure 1. Gurries automatic roadbuilder.

roads in Ohio; however, on this project, because of the scarcity of aggregate, a careful study was made of the economics of alternate flexible and rigid designs. The predominant soil type on the project was determined to be an A-6 silt clay with a group index of 9 and with estimated CBR and K values of 6 and 150, respectively. For these conditions, the following alternate pavements were considered to have equal load-carrying capacity.

1. Rigid: 7-in. plain concrete—A 4-in. granular subbase was added in rock and shale cuts to provide a cushion between the slab and underlying bedrock. There was about 1.7 mi of this kind of subgrade.
2. Flexible: 4 in. hot-mixed asphaltic concrete surface and leveling material placed in three separate courses.
3. 6 in. crushed aggregate base.
4. 6 in. granular subbase.

An economic analysis of the probable cost of these alternates indicated that initial cost of both types was about the same, i.e., $60,000/two-lane mile. Our experience indicates that resurfacing will be required at a considerably earlier date and that routine annual maintenance costs will be somewhat higher for bituminous-surfaced pavement than for concrete. The 7-in. plain concrete design was, therefore, selected and the option of paving by the conventional method or by the slip-form method was made a part of the contract.

CONTRACT AND EQUIPMENT

The contractor for this 8.8-mi improvement of SR 78 in Noble County, Village of Caldwell, and Olive, Center and Stock townships elected to place the concrete pavement using the slip-form principle permitted by Proposal Note (see Appendix). Although the project was located on the Federal-Aid Secondary System, it was financed with state funds due to the size of the contract and to the need for Federal-aid funds elsewhere.

A new Johnson automatic batch plant with an 8-cu yd central mixer was erected on the project to produce the pavement concrete. The contractor rented a Rex slip-form machine for the paving. The subgrade, and the subbase in rock cuts, were prepared using a Gurries Automatic Roadbuilder.

The slip-form pavement was placed in the fall of 1963. A small quantity of pavement at the west end of the project was placed in the spring of 1964 using conventional

Figure 2. Subgrade approximately 1 in. above grade.

methods of construction. The conventionally placed concrete was used since a busy at-grade intersection with traffic maintained, and two closely spaced structures were grouped in this area with short stretches of pavement interspersed.

SUBGRADE PREPARATION

The Gurries was controlled by a tracer from a piano wire, preset parallel to the pavement grade for the first pass approximately 14 ft in width, as shown in Figure 1. The adjoining lane was controlled by a rubber-tired wheel operating from the adjacent finished lane. The subgrade for the pavement and the grade for the paver were prepared in the same operation with the two adjacent passes of the Gurries. The automatic subgrader, towed by a D-9 tractor, was operated over the entire project to bring the subgrade to approximately 1 in. above grade (Fig. 2). Normally two passes by the automatic subgrader were required to complete the subgrading. After the first pass, large stones at grade were removed by two laborers working behind the subgrader with picks. Next, material free from large stones was bladed back onto the grade and construction traffic as well as local traffic was permitted to use the roadbed. The Gurries returned to make a final pass just ahead of the paving operation to bring the subgrade within the specified tolerance.

Ohio was experiencing a drought during pavement construction, and it was necessary to water the subgrade to obtain maximum density as well as to prevent absorption of water from the concrete after it was placed. Since the concrete trucks were using the subgrade for a haul road, it was not desirable to sprinkle to the extent that the subgrade would be damaged by the hauling units, or that the paver would slip on its treads. Therefore, water was generally applied to an area of subgrade the evening before it was to be fine-graded and paved. In this manner, the water would penetrate during the night resulting in a uniform moisture content for several inches in depth. Maximum density was then readily obtained and the subgrade was near optimum moisture when the pavement was placed.

CONCRETE MIX

Class D concrete as specified was composed of 6.5 sk/cu yd, sand, and two sizes of coarse aggregate. The dry weights of the aggregates per sack of cement were sand,

TABLE 1

SIZES OF COARSE AGGREGATES

Standard Sizes	Total % Passing (square openings)														
	4 In.	3½ In.	3 In.	2½ In.	2 In.	1½ In.	1 In.	¾ In.	½ In.	⅜ In.	¼ In.	No. 4	No. 6	No. 8	No. 16
No. 1	100	90-100	35-70	0-15	-	-	-	-	-	-	-	-	-	-	-
No. 12	100	90-100	65-85	25-60	-	0-15	-	-	-	-	-	-	-	-	-
No. 2	-	-	100	90-100	35-70	0-15	-	-	-	-	-	-	-	-	-
No. 3	-	-	-	-	100	80-100	20-60	0-20	-	0-5	-	-	-	-	-
No. 34	-	-	-	-	100	90-100	-	30-65	-	0-20	-	0-5	-	-	-
No. 4	-	-	-	-	-	-	100	80-100	20-60	5-30	-	0-5	-	-	-
No. 46	-	-	-	-	-	-	100	95-100	65-90	35-65	-	0-15	-	-	-
No. 6	-	-	-	-	-	-	-	-	100	90-100	-	10-35	-	0-5	-
No. 6a	-	-	-	-	-	-	-	100	90-100	40-70	-	0-15	-	0-5	-
No. 6b[a]	-	-	-	-	-	-	-	-	100	75-100	-	0-15	-	0-5	-
No. 9	-	-	-	-	-	-	-	-	-	100	95-100	60-90	-	0-20	0-10
No. 9c[a]	-	-	-	-	-	-	-	-	-	100	90-100	0-50	0-10	0-5	-

[a]No. 6b and No. 9c are sizes having rigid void control.

Figure 3. Central mix plant.

170 lb; No. 3 coarse aggregate, 165 lb; and No. 4 coarse aggregate, 146 lb. Limestone was used for the No. 3 coarse aggregate and gravel for the No. 4 coarse aggregate (Table 1). Entrained air was maintained between 4 and 7 percent by use of air-entraining admixture, Darex.

MIXING AND PLACING CONCRETE

Concrete was produced in a central mix plant and discharged directly into dump trucks for transportation to the paving site (Fig. 3). On arrival at the slip-form paver the concrete was dumped into pull-type spreader boxes which spread the concrete uniformly on the subgrade. The concrete was then extruded into the final pavement, 24 ft wide and 7 in. thick, in a single pass operation by the slip-form machine.

The central mix plant consisted of a Johnson automatic batch plant with an 8-cu yd mixer. Cement was transported by rail to a siding at Cumberland, Ohio, where it was transferred to trucks for the remaining 12 mi to the plant site. A 675-barrel cement silo was erected at the plant for temporary storage. Water was obtained from Caldwell and was stored in a 26,000-gal water tank maintained at the plant. Aggregates were stockpiled at the plant site in such a manner that the coarse aggregates could be

Figure 4. Uniform spread of concrete ahead of slip-form paver.

Figure 5. Hydraulic ram on front of slip-form machine striking off concrete.

sprinkled before use to meet the moisture requirements of the specifications. Coarse aggregates were moved by front-end loaders to hoppers where they were elevated to the bins by conveyor. The fine aggregate was dozed into the hopper and similarly conveyed to the plant bins. Batches were weighed automatically, charged into the mixer by conveyor belt, mixed for a minimum of 90 sec after all the ingredients were in the drum.

Some of the dump trucks used to transport the concrete had fillet plates welded into the corners of the dump bodies to prevent buildup and had gasket material around the tail gate to prevent loss of mortar. As additional trucks were used to increase production, the fillet plates and gasket material were omitted and little difference was noted in buildup or mortar loss. On arrival at the paving site the trucks backed in ahead of the paver and one of the two spreader boxes operating side by side was attached. The concrete was discharged into the spreader which moved forward, spreading concrete uniformly ahead of the slip-form paver (Fig. 4).

Figure 6. Finishers correcting surface and edging concrete along forms.

Figure 7. Burlap drag.

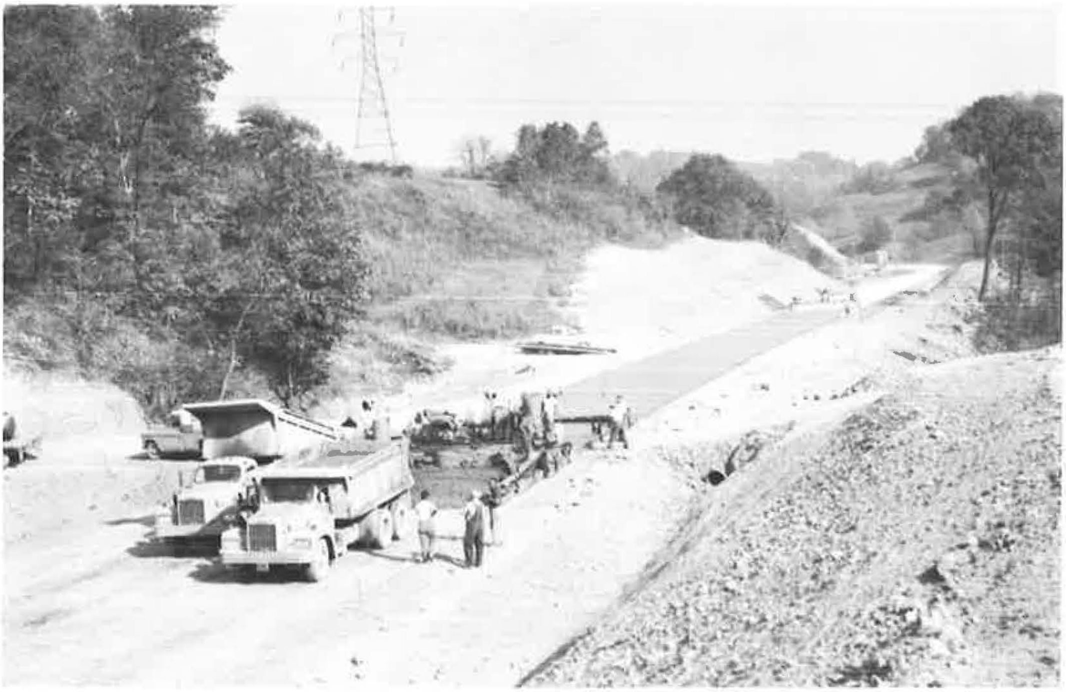

Figure 8. Application of membrane curing material.

The hydraulic ram on the front of the slip-form machine struck off the concrete, filling the voids left by the spreaders at the center and at the edges (Fig. 5). The concrete was vibrated by full-width pan vibrators before being further consolidated by mechanical tampers. The concrete then passed through the 42-in. extrusion meter where it was further compacted and shaped into the specified pavement dimensions. The initial surface finish was immediately applied by a rubber belt with a reciprocating lateral movement. The hydraulic ram, pan vibrators, mechanical tampers, extrusion meter, and reciprocating belt were all components of the paving machine.

Thirty-two feet of trailing forms were used to protect the pavement edges while the surface was being straightedged. Within the trailing forms, four finishers checked and corrected the surface and edged the concrete along the forms (Fig. 6). A burlap drag was fastened to the crossframe at the end of the trailing forms to texture the pavement surface (Fig. 7).

After the water sheen had disappeared from the surface, membrane curing material was applied by a spray machine riding on rubber tires and operating outside the edges of the pavement (Fig. 8).

Transverse contraction joints were usually sawed the same day the pavement was placed; however, when the nights became cool the concrete placed late in the day could not be sawed until the following day. The joints were sawed dry, using abrasive blades, to a minimum depth of $1\frac{1}{4}$ in. and a minimum width of $\frac{1}{4}$ in. Compressed air was used to clean out the joints before sealing with a hot-poured sealer. The longitudinal joint was required to be sawed within 3 days, and was generally sawed the following day.

CONSTRUCTION FEATURES AND CONCLUSIONS

An attempt was made to water the coarse aggregates on the conveyor belt as they were being charged into the plant bins. A spray bar was positioned at the bottom of the belt and appeared satisfactory for the low absorption aggregates during uniform production. However, when production varied, saturation varied correspondingly, resulting in variable slump concrete which was especially troublesome for slip-form paving. After a few days the watering on the conveyor was discontinued in favor of sprinkling systems on the coarse aggregate stockpiles. Uniform saturation of the aggregates was accomplished and, therefore, uniform slump concrete was obtained.

After using the spreader boxes for several days, the contractor elected to dump the concrete directly on the subgrade to increase production. By tailgating, the concrete was easily spread ahead of the paver and production was increased. Also, a problem encountered with the boxes on subbase in the rock cuts was eliminated.

Concrete had a tendency to adhere to the truck beds even though the truck bodies were modified by fillet plates in the corners. Therefore, the contractor decided to hose out the trucks beds on return to the plant after each round.

If low-slump concrete (1 to 1½ in.) was used, the edges of the concrete pavement exhibited little or no slumping, but additional hand finishing was required to close the open-textured surface of the concrete. With high-slump concrete (2½ to 3 in.), little hand finishing was needed; however, there was noticeable slumping at the pavement edges. The ideal slump appeared to be about 2 in. since edge slumping and hand finishing were both minimized with concrete at that consistency.

While discussing the slumping at the pavement edges it should be pointed out that, at the outset, considerable difficulty was encountered with the alignment. The paver was steered manually and occasionally veered off line, resulting in kinks in the alignment. When alignment corrections were made abruptly, considerable handwork was required, especially at the end of the trailing forms. This excessive handwork had a pronounced effect on the edge slump. An additional person was used to operate the steering mechanism until the operator had acquired sufficient experience to manage all mechanisms.

Edge slump is also the result of excessive edge finishing and long lengths of trailing forms. The length of trailing forms should be the minimum needed to permit hand finishing of the surface and edge finishing should be held to a minimum. Forty-eight feet (3- to 16-ft sections) of trailing forms were used for the first few days until the finishers became acclimated to working within the trailing forms. Then one section of the forms was eliminated and the remainder of the paving was placed using 32 ft of forms. The long lengths of trailing forms particularly affected the pavement edges at transitions into and out of the many superelevated curves. Changes in cross-slope at the paver were transmitted by the forms to the edges, further complicating control of the edges. Despite all these difficulties, pavement edges were considered satisfactory, even though slight slumping generally occurred throughout the project.

Construction joints at the end of each day's production consisted of a bulkhead with holes for 1-in. by 18-in. dowels. The contractor used a steel bulkhead specially fabricated for this project with holes for staking pins as well as dowels. In the last 25 ft of pavement placed each day, ¾- by 7-in. boards were placed along the inside edges of the trailing forms to reduce the pavement width to facilitate positioning of the paver when paving was resumed.

A longitudinal key joint without tie bars was required at various locations where local intersecting roads were encountered. The contractor was unsuccessful in his attempts to extrude a key groove in the edge of the 7-in. slab and it was necessary to install wooden forms, with keyways attached, and to hand finish the surface adjacent to the edges. This hand method was permitted because there were only a few intersecting roads where longitudinal key joints were required, and because it was impractical to procure metal keyways for insertion at the side forms at the front of the paver.

Production varied from approximately 400 lin ft on the first day to a maximum of 4,217 lin ft. On several days the 4,000-ft goal was achieved; however, an average production was near 3,000 lin ft.

Cores, removed to check thickness requirements, indicate that the concrete was uniform in depth and had satisfactory compressive strength. The average thickness for all cores removed was 7.3 in. Only one core was less than the 7 in. specified; it was 6.9 in.

As this was the first sizeable job in recent years with plain concrete pavement without load transfer devices, a 2-mi test section of skewed joints was specified by Plan Note (see Appendix) to compare their merits with the joints constructed normal to the centerline of the pavement. The Plan Note required that the skewed joints be constructed diagonally across the full width of the pavement so that the right edge of the joint is 4 ft ahead of the left. Observations will be made periodically and a Chloe or a roughometer will be used in the future to determine the merits of these joints.

In Ohio, a device is towed over newly constructed pavements which indicates when the pavement is outside the surface tolerance of $\frac{1}{8}$ in. in 10 ft. The apparatus makes two passes in each 12-ft lane; each time tolerance is exceeded, the pavement is sprayed with diluted paint to denote areas to be corrected. The number of paint marks per profilometer mile is then determined. This slip-form pavement had 16 marks per profilometer mile, which compares favorably with conventionally built pavements on the primary system.

Based on the satisfactory results obtained in its first venture in slip-form paving, Ohio is looking forward to slip-forming reinforced concrete pavements on the Primary and Interstate Systems. A project on the Primary System has already been selected for use of the slip-form option and is to be awarded early in 1965.

Appendix

PROPOSAL NOTE

T-70, Portland Cement Concrete Pavement, as Per Plan

This item shall be placed either as described in Item T-70 using regular forming and placing procedures, or by the use of a slip-form paver. For either type of placement the pavement shall have a standard longitudinal joint located at the center of the slab and shall have sawed or impressed contraction joints without load transfer devices spaced at intervals of 17 ft. If the contractor elects to use a slip-form paver, the following provisions shall apply:

1. Preparation of Subbase—The area which will support the slip-form paver and subgrade machine shall be cut in the compacted subbase to the proper elevation, using a properly designed and operated machine. The subbase shall then be finished to required cross-section and grade by means of a self-propelled subgrade machine.
2. Concrete Consistency—The concrete shall be of uniform consistency such that there will be no slumping at the edge of the pavement after forms have passed. Slump of the concrete tested in accordance with ASTM Designation: C-143 shall be not greater than $2\frac{1}{2}$ in. nor less than 1 in.
3. Slip-Form Paver—In lieu of the procedures outlined in Sec. T-71.21 for placing and finishing concrete, the concrete shall be placed and finished by the use of a slip-form paver of the self-propelled type equipped with crawler-type tracks not less than 22 ft in length. The paver shall be equipped with a mechanically operated primary strike-off which meters the concrete to the vibratory mechanism. It shall also be equipped with a vibrator and temping bar extending over the full width of the pavement and an extrusion plate not less than 42 in. in length (measured longitudinally with the pavement) extending for the full width of the pavement, set with its leading bullnosed edge approximately $\frac{1}{2}$ in. higher than the trailing edge so that the concrete is pressed down and squeezed out, under load, behind the plate. It shall be further equipped with a 24-in. rubber belt set behind the extrusion plate mechanically operated with a lateral movement of 4 to 8 in.
4. Paver Operation—The paver shall be operated with a continuous forward movement and all operations of mixing, placing, and spreading shall be so coordinated as to provide a uniform forward progress with stopping and starting of the paver held to a minimum. If for any reason the forward progress is stopped, the vibrating and tamping element shall be stopped immediately.
5. Slip Forms—The slip forms shall be held together laterally by cross-frame mounted above the pavement and shall trail behind the paver for such a distance that no slumping of the concrete will occur, but in no case less than 32 ft.
6. Final Finish—Final finish shall be in accordance with Section T-71.214 Method B (drag finish).

All other pertinent sections of Item T-70 shall apply to the pavement placed by the slip-form method. Under either method, the unit price bid for this item shall constitute full compensation for performing all the requirements of the item.

PLAN NOTES

Contraction Joints

Contraction joints shall be constructed according to Item T-71.28 of the specifications, except that load transfer devices will not be required and except from Station 442+00 to Station 547+00 where contraction joints shall be constructed diagonally across the full width of the pavement so that the right edge of the joint will be 4 ft ahead of the left.

Construction Joints

Construction joints shall be constructed according to Item T-71.27 of the Ohio Department of Highways Construction and Materials Specifications and the standard joint drawings, except that construction joints shall not be placed closer than 5 ft to another transverse joint.

Finishing Subbases for Slip-Form Paving

EDWARD L. KAWALA, Paving Bureau, Portland Cement Association

An accurately graded, stable subbase is essential in slip-form paving to provide a smooth pavement slab of proper depth. Finishing subbases for slip-form paving requires different construction techniques than are normally used for pavements with side forms; the subbase must be constructed in advance without the advantage of using previously set paving forms as a guide. Equipment and methods that have been used successfully for finishing subbases are described. Three methods of finishing are commonly used: (a) clipping to "blue tops" with motor graders, (b) fine-grading from an accurately placed reference line, and (c) placing a controlled depth of loose material so that after compaction only minor grade adjustments are required. Both untreated and cement-treated granular subbases are discussed.

•SUBBASES have come into general use for concrete pavements only since World War II. The increased truck traffic during and after the war made it necessary to use subbases to prevent pumping of fine-grained subgrade soils. (Subbases are not required for city streets or for rural pavements carrying less than 300 to 400 heavy axle loads daily in both directions. This is well established by the performance of many miles of such pavements without subbases.)

Subbases perform several functions in the construction process. Where conventionally formed concrete is used, subbases provide a stable base for anchoring the forms and dowel baskets (if used), and an accurate surface on which to place the concrete and thus assure a proper slab thickness. With the advent of slip-form paving, subbase stability has become more important than ever. The subbase must provide a uniformly stable, accurate grade on which to operate the slip-form paver.

One of the most important advantages of the slip-form operation is that smoother concrete pavements can be built; the degree of smoothness depends to a great extent on the stability and accuracy of the subbase. Therefore, it follows that the key to the success of any slip-form operation is a firm, unyielding subbase built to close grade tolerances.

The accuracy of the wheelpaths over which the slip-form crawlers travel influences the smoothness of the pavement surface. The degree of accuracy to which the entire width of subbase beneath the slab is constructed influences the amount of concrete required to build the slab to proper grade. Low grades will cause high concrete overruns and thus higher paving costs; high areas result in thin pavement. Therefore, if the slip-form method of paving is to be used successfully to build a smooth-riding slab with a minimum overrun of concrete, accurate subbase grade control is essential.

The small percentage of fines in present subbases has resulted in materials that often do not have the inherent stability to carry slip-form pavers without displacement. As a result of this instability, the growing scarcity and correspondingly increased cost of such clean subbases, and the excellent performance of concrete pavements with cement-treated subbases in California, many states have turned to stabilized subbases.

Although other types have been used, cement-treated subbases are the most widely used stabilized subbases. Concrete pavements with cement-treated subbases are in service in more than 30 states and Canada. California alone has built well over

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1,000 mi of concrete pavement on cement-treated subbase, some 500 mi of which was built with slip-form pavers.

MATERIALS

The accuracy to which a subbase can be graded is influenced by the maximum size of aggregate used. Specifications generally limit the maximum size to 1 in. or less; using this maximum-size aggregate, subbases usually can be finished to within $^1/_4$ or $^3/_8$ in. of the grade shown on the plans.

In addition to limiting the maximum size and percentage of fines passing the No. 200 sieve, specifications for untreated subbases usually limit the plasticity index to 6 and the liquid limit to 25.

Where such materials are scarce or expensive, marginal materials available locally can be treated with cement to build acceptable subbases. Granular soils falling into AASHO Soil Classification Groups A-1, A-2, and A-3 are normally used for cement-treated subbases. These materials may contain up to 35 percent passing the No. 200 sieve and may have plasticity indexes of up to about 12. The use of fine-grained soils for cement-treated subbases for concrete pavements is definitely not recommended.

Generally, in cement-treated subbase construction, enough cement is added to produce a hardened material having a 7-day compressive strength of 300 psi or more. In areas subject to frost action, the hardened material should also meet the Portland Cement Association weight-loss criteria based on the standard AASHO-ASTM wet-dry, freeze-thaw tests for soil-cement.

CONSTRUCTION PROCEDURES

Mixing

Subbases should be compacted at optimum moisture content. Adding water and mixing of untreated and cement-treated material can be accomplished on the grade using traveling mixing machines. Another method is to process the material in a central mixing plant, haul it to the roadway, and place the moist material in a uniform layer on the subgrade by means of a spreader. Dumping material in piles on the subgrade should not be permitted. Complete discussions of methods used to mix, place, compact, and cure cement-treated subbases are available.

Finishing

The next step in construction involves finishing the subbase to accurate grade and crown. Care must be taken during finishing of the cement-treated subbase to assure that surface moisture lost through evaporation during finishing operations is promptly replaced by a light fog-spray.

Finishing subbases for slip-form paving requires different construction techniques than are normally used for pavements built between side forms. The subbase must be constructed in advance without the advantage of using previously set paving forms as a guide.

The methods used to finish untreated and cement-treated subbases are identical. However, when finishing cement-treated subbases one additional factor must be taken into consideration—the time element. To gain full advantage of the benefits imparted to the subbase by the addition of portland cement, the cement-treated subbase must be constructed and finished to grade within a time limit set forth in the specifications, usually 6 hr after the addition of moisture to the mixture.

The various finishing methods described here are those that have been used successfully on actual projects. Other methods can be used and, in fact, are continually being developed and improved as contractors gain experience with this type of construction. Development of new equipment specifically for this purpose has greatly simplified subbase grade control.

Three methods of finishing are commonly used: (a) clipping to "blue tops" (grade stakes) with motor graders; (b) fine-grading from an accurately placed reference

Figure 1. String line crew determining amount to be cut or filled and signalling to grader operator.

line; and (c) placing a controlled depth of loose material so that after compaction only minor grade adjustments are required.

For cement-treated subbase construction it is imperative that accurate grade be attained during initial construction. Adjustments in surface grade after the cement-treated subbase has hardened are costly, difficult to make, and are generally not satisfactory.

Method 1.—This procedure involves the use of a motor grader for clipping to grade, with blue tops placed transversely across the roadway as reference points. The blue tops are set at each edge of the subbase and, depending on the crown, at one or more points in a line across the section. A level is used to set the blue tops following completion of initial compaction. The longitudinal interval for setting blue tops is usually 50 ft on tangents and 25 ft on curves. The motor grader clips the section to grade starting at one edge and working toward the other. The grader operator is assisted by one or two stakemen, who observe the existing grade at each blue top and signal to the grader operator the amount to be cut or filled.

An alternate method involves stretching a string line across the section between grade stakes placed outside either edge of the subbase. The line is held taut at a specified elevation marked on the stakes. The amount to be cut or filled is determined by measuring down from the string line to the surface of the subbase, as shown in Figure 1. Usually two or more passes are required to obtain grade. The suitability of this method and the accuracy of grade obtained are greatly influenced by the capability of the grader operator. Grader attachments that permit automatic control of blade slope have been used successfully to finish subbases.

Method 2.—This procedure involves the use of a motor grader working to blue tops or to a string line, or an electronically controlled form-grader working to a string line (Fig. 2) to cut a trench to accurate grade at each edge of the subbase. The cutting edge of the rotor is automatically adjusted by means of a grid sensor riding on an accurately placed string line (Fig. 3). The trench grade should be checked immediately behind the machine (Fig. 4). Some handwork is usually required to correct minor variations in the trench grade. The central portion of the subbase is then cut to grade by means of a subgrade planer traveling in the prepared trenches (Fig. 5). The subbase should be cut slightly high (approximately ⅛ in.) to allow for a small amount of consolidation during final rolling.

Figure 2. Electronically controlled form-grader cutting trench at edge of subbase.

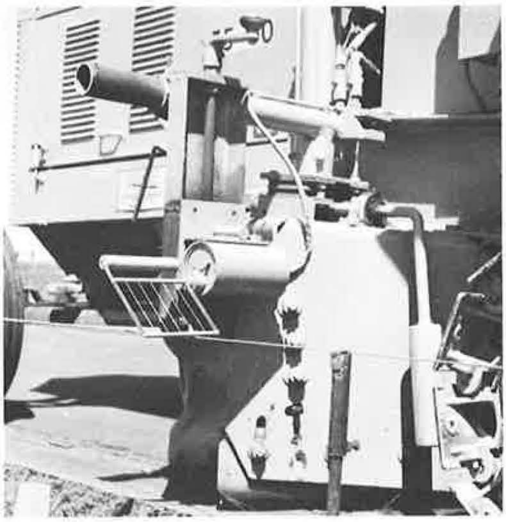

Figure 3. Cutting rotor automatically controlled by sensor riding a string line.

A similar procedure involves the preparation of a trench on one edge of the subbase. An automatic fine-grader, utilizing this trench as a reference for the intial pass, cuts the area adjacent to the trench to grade. The grade established by the first pass of the machine is used as a reference for the next pass. This procedure is repeated until the entire width of subbase is graded.

Automatically controlled fine-graders operating from wires placed along one or both edges of the subbase represent another method of finishing cement-treated subbases. These machines automatically maintain blade height and cross-slope in relation to a selected reference, usually a wire but sometimes an adjacent lane of pavement or graded area. The machines are available in widths of 13 to 30 ft, as pull-type (Fig. 6) or self-propelled (Fig. 7) models on rubber tires, or as self-propelled models on crawlers (Figs. 8 and 9). Because these machines are quite heavy, they require stable support to operate properly.

Method 3. —A somewhat different method for controlling grade involves the placement of the loose material to accurate depth so that after compaction only a minimum amount of grading is required. Most of the subbase work to date utilizing this method has involved a compacted thickness of 4 in.

One technique involves the careful grading of the subgrade and the placing of a uniform depth of moist material. The subgrade acts as a reference plane as the machine places a specific thickness of loose material. The mixture is processed from windrows on the subgrade (Fig. 10). After spreading from the windrows, oscil-

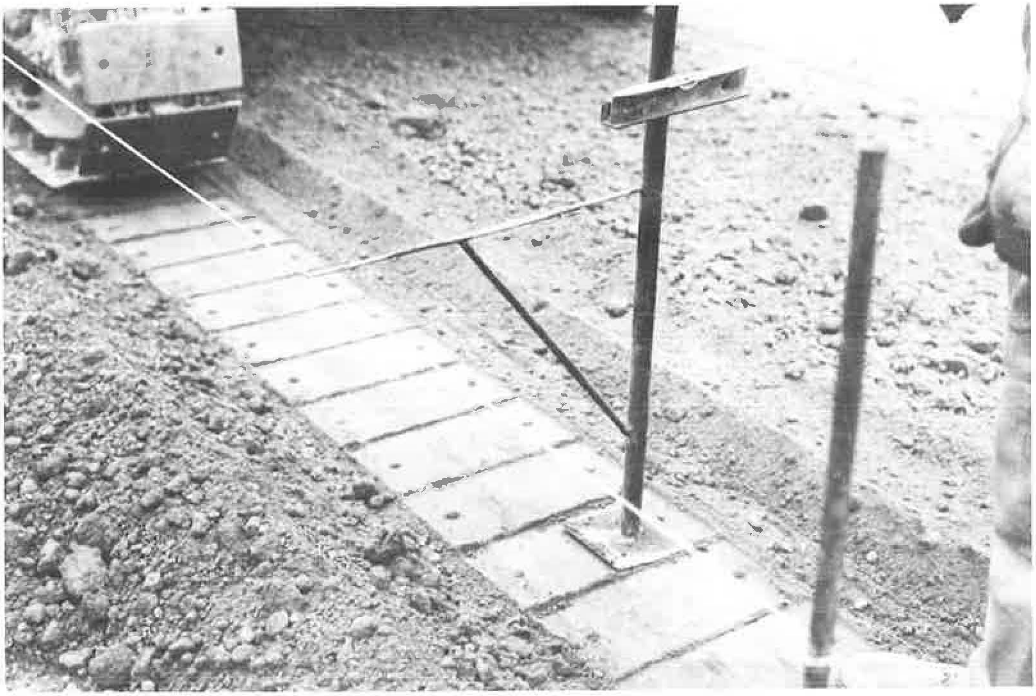

Figure 4. Accuracy of trench grade checked immediately behind form-grader with shop-made level.

Figure 5. Subgrade planer, running in prepared trenches, cutting central portion of subbase to grade.

Figure 6. Cutting blade of pull-type fine-grader controlled by a sensor riding on accurately placed piano wire.

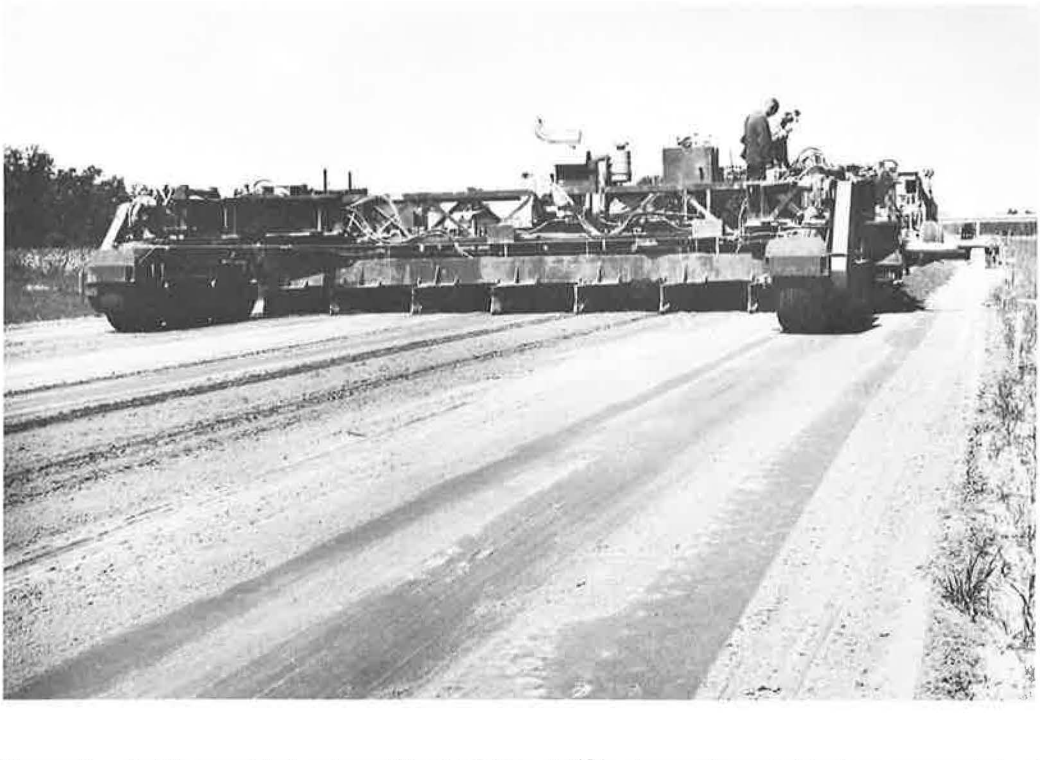

Figure 7. Self-propelled subgrading machine, built by paving contractor, supported on three large wheels in tandem at each corner to provide additional flotation in unstable sands.

Figure 8. Full-width (28-ft) self-propelled subgrader on crawlers, controlled from reference wire.

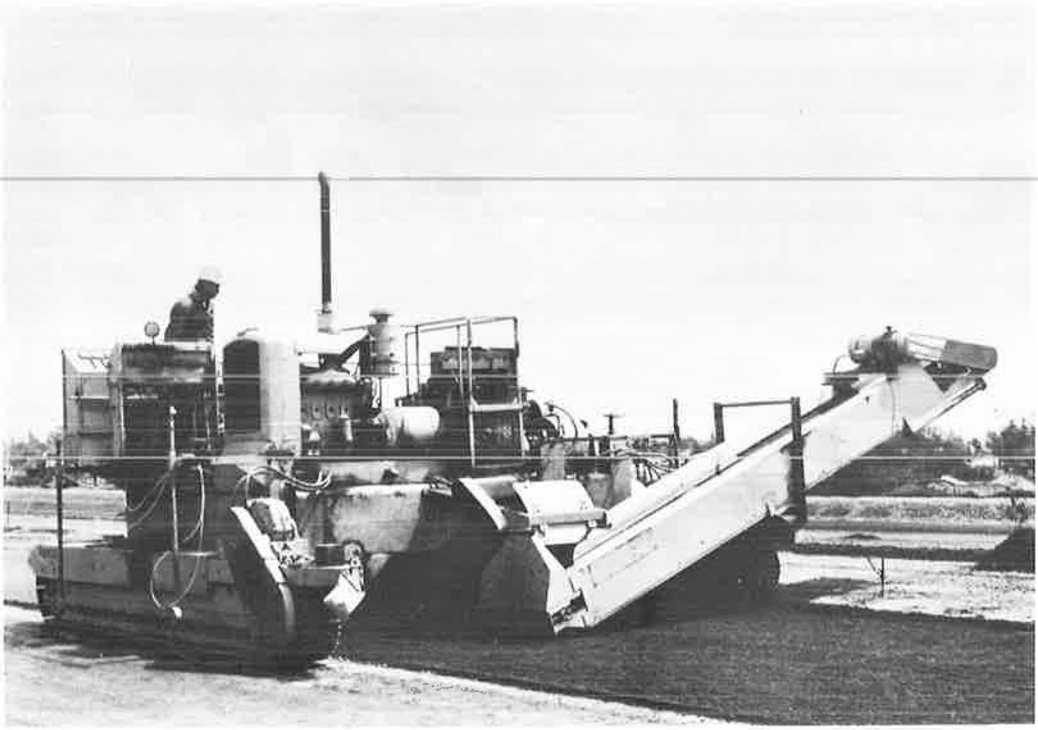

Figure 9. Half-width self-propelled automatic subgrader, controlled from reference wire.

Figure 10. Accurately controlled thickness of loose material placed 28 ft wide by machine.

lating frame-suspended screeds strike off the loose material to grade. A traveling paddle in front of each screed assures sufficient material in front of the screed to prevent low areas. The loose mixture is then compacted with steel-wheel and rubber-tire rollers. A machine somewhat similar in principle but controlled from a reference wire spreads the material from windrows, strikes it off to loose grade with vibrating screeds, and compacts the material with two full-width vibrators (Fig. 11).

Another technique of accurately placing subbase is to use electronically controlled asphalt pavers working off a heavy cord string line (Fig. 12). The screed control system on these pavers provides a means of automatically maintaining grade and slope on the surface of the material being placed with reference to a predetermined grade and slope. Grade is transferred from the string line to the control center by means of a grid sensor. Grade reference for placement of the second lane can be obtained from a sled attachment riding on the surface of the uncompacted mixture placed previously. Pavers have been built to place compacted thicknesses of up to about 8 in. (Fig. 13).

A slip-form paver composed of a combined unit which does everything except mix the concrete, including automatically finishing the subbase to grade, is presently under development (Fig. 14).

Final Compaction and Curing

Immediately after grade is obtained, the subbase is given a final rolling either by a rubber-tire roller or, depending on the type of granular material, a steel-wheel roller followed by a rubber-tire roller. This last rolling knits down any material loosened during finishing.

The final step in finishing cement-treated subbases is the application of the curing material. After rolling, the surface of the cement-treated subbase is given a light

Figure 11. Wire-controlled machine spreading, from windrow, striking off to loose grade, and partially compacting subbase material.

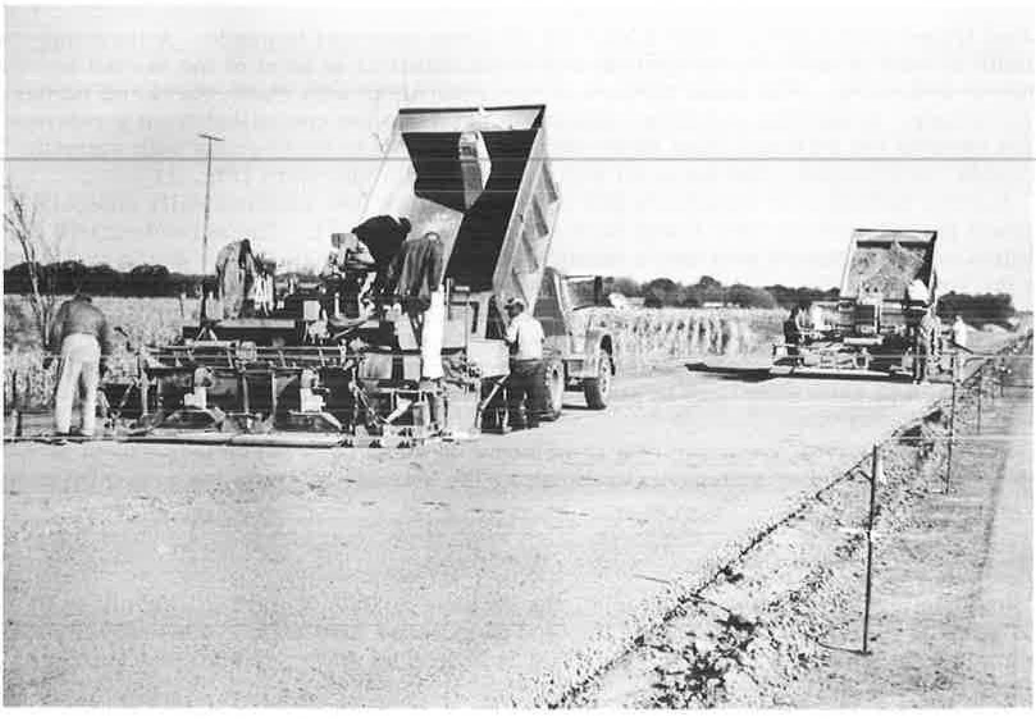

Figure 12. Electronically controlled asphalt pavers placing 4-in. thickness (compacted) on subbase material.

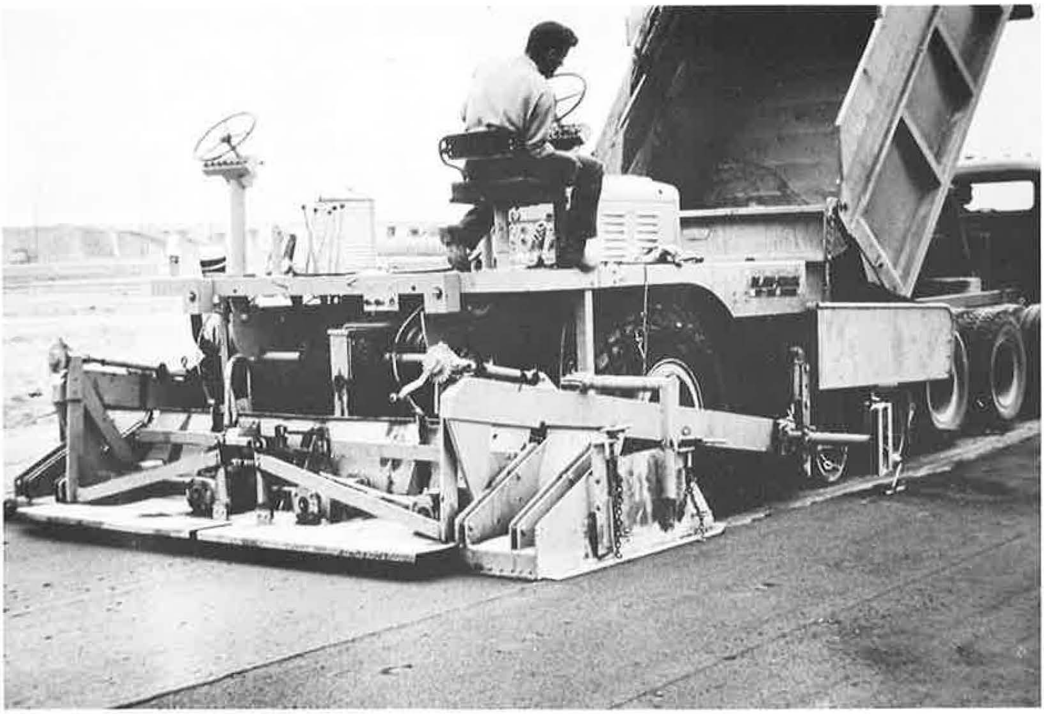

Figure 13. Paver capable of placing and partially compacting thicknesses of cement-treated subbase up to 8 in.

Figure 14. Prototype of combined-unit slip-form paver.

fog application of water. This is usually followed by the application of from 0.15 to 0.25 gal/sq yd of bituminous material for curing.

SUMMARY

A stable, accurately graded subbase is one of the key factors necessary for successful slip-form paving. Methods and equipment have been developed for accurate, rapid grade control. Cement stabilization permits the use of a wide range of granular materials and assures adequate stability of the subbase, regardless of weather conditions. This combination of factors permits mass production of accurately graded subbases and greatly reduces the contractor's downtime due to inclement weather.

Improvement in methods and equipment for finishing subbases will continue. Several manufacturers presently have under development construction equipment that will permit simpler, more accurate subbase grade control.

Slip-Form Paving—Construction Practices for 3-Lane at a Time Paving in California

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After 5 yr of use, slip-form paving now accounts for more than 80 percent of all concrete paving in California. It provides significant production advantages to the contractor and benefit of less cost to the highway user, as compared with side-form paving. Three different types of slip-form pavers have been successfully employed, but only one is capable of paving 3 lanes at a time. The procedures utilized are not significantly different than those utilized when paving narrower widths with the same type of equipment. Successful use of this type of equipment is dependent on standard operating procedures established through a logical analysis of cause and effect, technically qualified field level supervision, experience operators and mechanics, properly maintained equipment, uniform concrete at the paver, and close attention to operational details before, during and after concrete placement.

•SLIP-FORM PAVING has been used in California for 5 yr, and during this period 16 million sq yd (estimated on the basis of approximate usage factor) of pavement have been slip-formed. Of the 6 million sq yd of concrete pavement placed in each of the last several years, more than 80 percent has been slip-formed. This was accomplished irrespective of terrain, geometric features, location, or relative importance of the highway routes involved. All of our major paving contractors, except one, have now abandoned the use of side-forms in favor of slip-form. Obviously, this cannot be attributed to whim or caprice. It must be because the method is less costly, or more convenient and better integrated into overall job scheduling, or both.

A contractor on an Interstate project was recently faced with a last minute change in his plans for placing the 177,000 sq yd of concrete pavement, and was forced to decide on one of two possible alternatives: (a) utilize two paving crews, working two 11-hr shifts, to slip-form another job, then move the paver and work two 11-hr shifts to pave the principal job; or (b) pave both jobs simultaneously, using side-form equipment on the principal job. Although it involved a 2-wk delay, he selected the slip-form alternative on the basis of estimated savings in excess of $40,000.

This contractor is only one of many in California now able to exploit the advantages inherent in slip-form. Benefit to the highway user, as the ultimate recipient of all cost saving advances, is clearly apparent. Savings are also discernible in the trend of recent bid prices, as indicated in Table 1.

Lack of restriction on usage of slip-form methods regardless of topography, climatic conditions, geometric section or traffic considerations has undoubtedly contributed to this favorable trend. Several projects which have been slip-formed were located in mountainous terrain involving grades up to 6 percent and superelevation up to 12 percent. One of these projects was paved 3 lanes at a time. The other projects

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TABLE 1

BID PRICES AND CALIFORNIA HIGHWAY CONSTRUCTION COST INDICES

Year	Quarter	PCC Pavement		PCC Structures ($/cu yd)	Bar Reinforcing Steel ($/lb)	Asphalt Concrete Pavement ($/ton)	Const. Cost Index
		$/Cu Yd	$/Sq Yd[a]				
1961	1st	13.44	3.15	53.70	0.094	5.92	229.6
	2nd	15.35	3.60	52.32	0.093	6.36	252.8
	3rd	14.44	3.38	56.35	0.091	5.96	230.5
	4th	14.35	3.36	57.97	0.096	5.30	238.5
Avg.							239.1
1962	1st	14.87	3.48	57.02	0.092	5.99	235.7
	2nd	15.31	3.59	58.65	0.095	6.50	271.1
	3rd	15.20	3.56	59.22	0.091	6.71	289.1
	4th	14.45	3.39	56.30	0.091	5.68	232.6
Avg.							256.2
1963	1st	12.72	2.98	62.87	0.096	6.22	250.4
	2nd	12.64	2.96	58.69	0.093	6.47	243.7
	3rd	13.14	3.08	57.16	0.082	5.87	249.5
	4th	14.49	3.40	59.56	0.091	5.78	243.0
Avg.							246.8
1964	1st	14.00	3.28	58.34	0.084	5.61	246.1
	2nd	13.09	3.07	58.24	0.088	6.20	248.7

[a]Calculated on basis of estimated 1,650 cu yd/lane mile.

which have been slip-formed are located in flatter terrain. All of our urban projects are included in this group.

Paving 2 lanes at a time is the most common practice, largely because 24 ft is the most frequent width of pavement slab required. This paving width is also convenient in placing 48-ft pavements for the increasing number of 8-lane urban freeways being constructed today.

Placing 36-ft pavement, for the substantial mileage of 6-lane rural and urban freeways built in recent years, has been accomplished either by first putting down a 24-ft slab followed by a 12-ft slab or by paving the entire 36 ft, 3 lanes at a time. About the same amount of pavement is constructed by each procedure.

DIFFERENT TYPES OF SLIP-FORM PAVERS

Placing pavement in 36-ft paving widths, or 3 lanes, is not a separate subject in itself. The procedures used to place this width of pavement do not differ significantly from those used to pave narrower widths when proper allowance is made for certain basic considerations.

There are several different slip-form methods, just as there are several different types of slip-form pavers. These pavers are not all presently capable of placing pavements more than 24 ft wide in a single pass. Therefore, a description of construction practices for 3-lane at a time paving logically involves consideration of the procedures and techniques associated with the paver used for this purpose.

At this point, it would be well to explain in more detail what is meant by different methods of slip-form paving. The term slip-form paving undoubtedly originated because short lengths of sliding side forms are used instead of the preset side forms conventionally used. Although all methods utilize sliding forms, the term slip-form paving has come to be generally thought of in a more encompassing sense. We now think of it as applying to the upper surface of the pavement as well as to the edges, and in this respect significant differences in method are to be found.

Three different types of slip-form pavers have been used in California. Each type is different in operation, and each involves a different method of paving. One type forms the pavement surface by a repetitive screeding action. Multiple screeds are used as shown in Figure 1, and the operation is similar in many respects to conventional side-form paving. This type has not been used in 3-lane at a time paving.

A second type of equipment forms the pavement surface by conforming the concrete to desired cross-section and profile under a single, relatively large screed as shown in Figure 2. This action has sometimes been referred to as extrusion. For the purpose of this paper, the word extrusion will be avoided as it implies that concrete is pressed or forced into shape as is metal, through a die. In point of fact, the action is

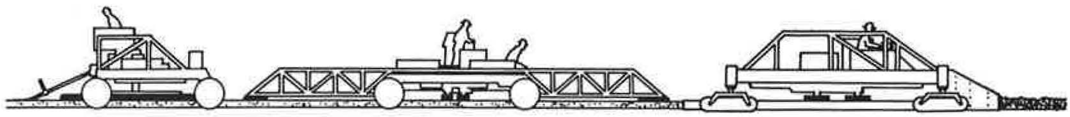

Figure 1. Multiple screed slip-form process.

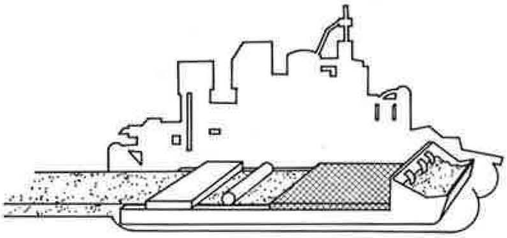

Figure 2. Conforming screed slip-form process.

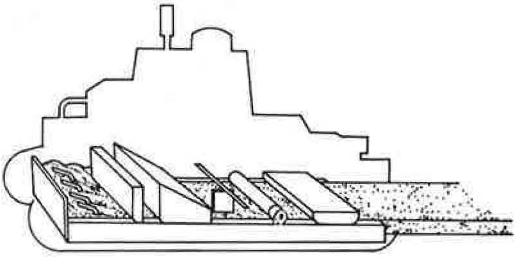

Figure 3. Pressure meter slip-form process.

that of flowing concrete into position to fill completely a transient form consisting of conforming screed, sliding side forms and underlying subgrade. The action compares more closely to the process of permanent mold-casting than to extruding metal. This second type of slip-form equipment is the only one used to date to place pavement 3 lanes at a time. With it, the paving width can be varied by changing the number of 12-ft wide modular sections which make up the main chassis.

A third type of equipment has been used only in experimental applications where the paving width was 24 ft. It incorporates an interrelated initial strike-off screed and a vibrating float pan as illustrated in Figure 3. An excess of material passing under the strike-off screed causes an upward pressure on the float pan which results in an automatic lowering of the strike-off screed. Conversely, the strike-off screed is automatically raised when a deficiency of material occurs under the float pan. This action is independent of the control derived from the grade wires and, in effect, meters the concrete to a rotating screed located behind the float pan. The rotating screed functions to remove the slight variations resulting because of the finite distance between strike-off and float pan.

In addition to these three classifications of slip-form pavers, there are two subclassifications which indicate the presence or absence of automatic controls. One subclassification includes pavers which are automatically controlled for line and grade by sensors operating on preset grade wires (Fig. 4). The other includes manually steered pavers which have preset screeds (Fig. 5).

There are nonautomatically controlled pavers of both the multiple and conforming screed types as well as automatically controlled pavers of the conforming screed and pressure meter types. This discussion will be confined to automatically controlled machines of the conforming screed type, although pavers of the pressure meter type also have a potential capability of placing pavement 3 lanes at a time. The equipment of interest in this report is that used where the pavement profile and cross-section is established by flowing concrete into position, by internal vibration, under a relatively large conforming screed automatically maintained at correct alignment and grade (Fig. 6).

KEY FACTORS INFLUENCING RESULTS

Success with this paving equipment is greatly influenced by the following factors:

1. Experienced field level supervision;
2. Skilled operators and maintenance personnel;

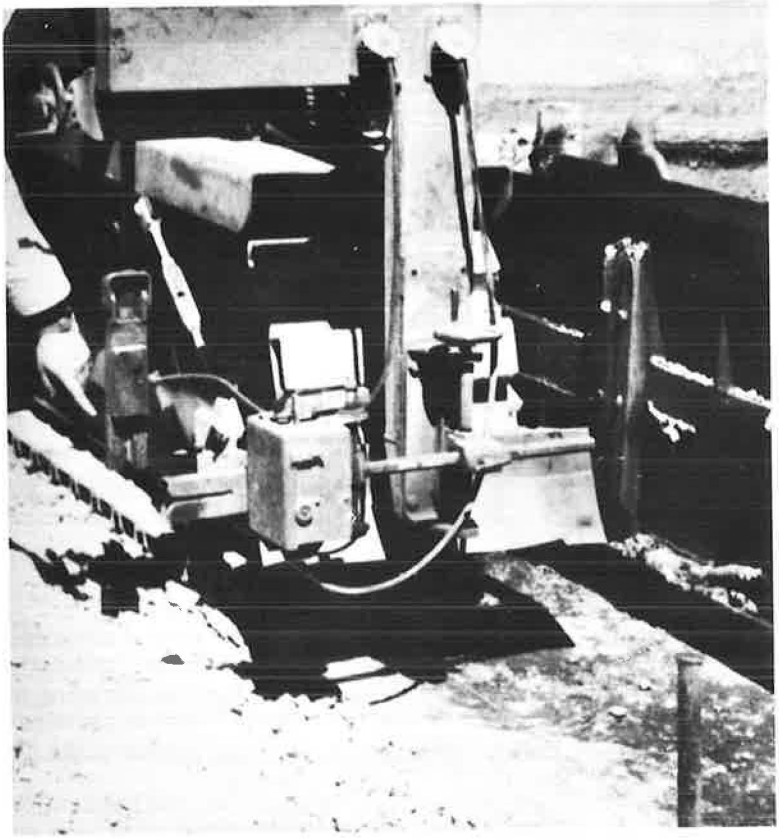

Figure 4. Grade and alignment sensors.

Figure 5. Plumb-bob and string line used for manual steering.

Figure 6. Thirty-six-feet highway slip-form paver.

3. Proper care and adjustment of the paver;
4. Consistent mix;
5. Uniform delivery of concrete;
6. Control and integration of all elements of the operation;
7. Continuous forward motion of the paver;
8. Single set of surveying stakes for subgrade and pavement;
9. Accurately set grade wires;
10. Well-compacted subgrade constructed to tight grade tolerances;
11. Proper type and length of side forms;
12. Effective location and frequency of internal vibration;
13. Means of compensating for variations in the concrete at the paver;
14. Constant surveillance of grade and alignment sensors;
15. Continuous audit of pavement thickness;
16. Conscientious final finishing; and
17. Progressive analysis of smoothness results.

The significance of these factors will become apparent as the discussion proceeds.

ANALYSIS OF CAUSE AND EFFECT

In the early period there were few known guidelines, and most efforts to improve results were frustrated by aimless, often frantic guesswork. This chaotic situation was not brought under control until the necessity for an orderly analysis of cause and effect was clearly understood.

The technique adopted then is valid today and it is recommended to all those embarking on their first slip-form experience. It is simply the preparation of a detailed log as the work progresses, listing chronologically all conditions and events which might conceivably affect the completed pavement. Daily analysis of the log for previous work in light of the results obtained will quickly pinpoint sources of difficulty and indicate proper corrective measures. California contractors still employ this technique when new equipment models are evaluated or unexpected difficulties are encountered.

The operating procedures evolving from these studies of cause and effect form the basis of our construction practice today.

ABILITY OF PERSONNEL

Any discussion of operating procedures must consider the skills required of the men who are to implement them. The skill and training of field supervisors, operators and mechanics required to cope with the complex, automated slip-form paving equipment is considerably greater than that required for conventional side-form equipment. Unfortunately, this fact is not always recognized. However, the so-called old pro is rapidly being replaced by men with the technical training necessary for an understanding of the equipment and the ability to analyze complicated situations and act with logical purpose.

MAINTENANCE OF EQUIPMENT

Proper maintenance and adjustment of the paving equipment is also an obvious prerequisite for successful employment of operational procedures. Our experience indicates that the manufacturers are coming to have an increasing responsiblity in this area. The complexity of slip-form equipment makes it of paramount importance that only skilled technicians be entrusted with the specialized care required. In practice, this requires occasional factory assistance, which only the manufacturer can provide, plus routine attention by qualified personnel on the contractor's payroll. The most effective arrangement seems to be for the manufacturers to maintain factory technicians where they can reach any job in hours, and for the contractors to employ specialized mechanics trained to service the interrelated hydraulic-electrical-mechanical systems involved.

Each time the paver is transported from one place to another, whether on or between jobs, it must be thoroughly inspected for misalignment, warping, breakage or inadvertant changes in the setting of various control elements. Adjustment of the screeds must also be checked. This is accomplished by driving steel stakes to an offset grade for each corner of the screed and measuring up when the paver is in position over them.

PRODUCTION AND CONTROL OF CONCRETE

A frequently heard sarcasm alludes to contractors' preoccupation with production at the expense of quality. Whether this is accurate or not, in general application there can be no question of their vital concern with quality in the use of slip-form methods. It is a matter of general agreement now that uniform quality is absolutely essential to a successful paving operation. And similar importance is attached to an adequate delivery rate at the paver. Accordingly, a significant change has come about in the proportioning and mixing equipment in current use.

On-site paving mixers, supplied by batch trucks, have been almost completely replaced by central mix plants. The new low-profile plants, in particular, have been well-received because of their portability and high productive capacity (Fig. 7). Several of these plants in current use are capable of producing 600 cu yd of concrete per hour. They can be moved from one location to another and set up for full operation in a matter of hours. One or two of our contractors have taken full advantage of this portability by relocating the plant several times during the course of long paving jobs. A signficant advantage of this procedure on a large project is the consequent reduction of hauling units.

Although most of the contractors are using stationary tilt-drum mixing units with the low-profile batching plants, a few are using the new tilt-drum truck mixers (Fig. 8).

Figure 7. Low-profile central mix plant.

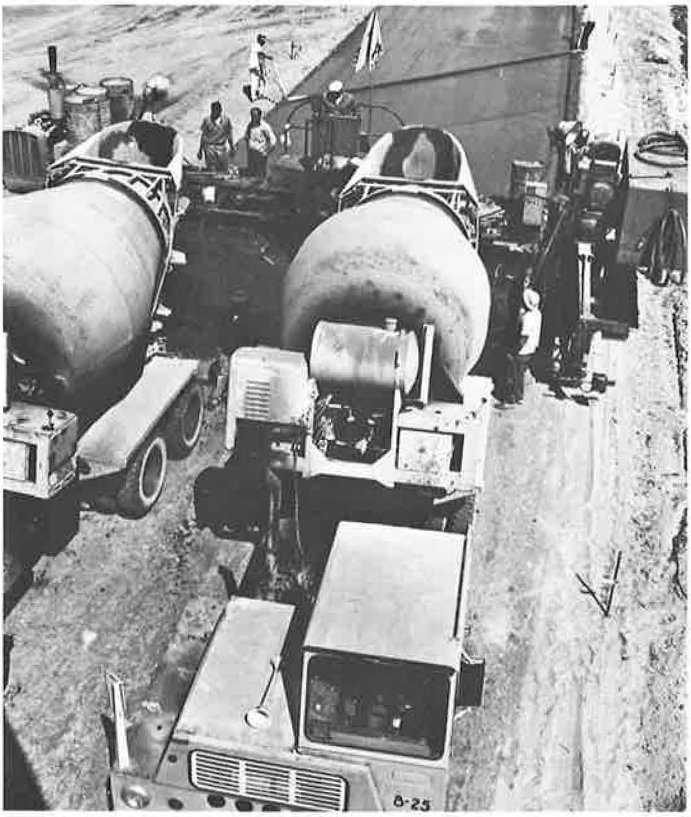

Figure 8. Tilt-drum truck mixers and slip-form paver.

An interesting new development has recently been exploited with respect to the location of the batching and mixing equipment. The contractor claimed substantial savings were realized in placing his batching plant at the aggregate source and moving his stationary mixer three times during the job. Double bottom-dump trucks were used to haul two 8-cu yd batches of proportioned aggregate between plant and mixer. At the mixer, a specially built transfer unit off-loaded the trucks onto a covered high-speed conveyor belt which charged the mixer. The portable transfer unit utilized a hopper with agitating side plates and a self-contained ramp for the trucks. Cement was batched directly into the stream of aggregate as it was charged onto the high-speed belt conveyor. There is reason to believe that this relatively dust-free technique may be well adapted for use on urban projects. On many, smog control rules pose a real problem because of the dust incident to normal batching operations.

Absorbed as they are with these developments in the type of plant setup, the contractors have not overlooked the importance of control facilities within the plant. There has been significant improvement in several important respects. Bins and conveyors have been modified to minimize degradation and segregation. The batching cycle and bin gates have been better coordinated to obtain optimum blending of ingredients before mixing. Cement silos have been redesigned to achieve better charging and batching rates. Fully automatic batching and mixing controls have been accepted as indispensable, and their proper use is more effectively policed by the contractors. These and other similar measures have contributed greatly to a noticeable improvement in the uniformity and quality of the concrete as well as in productive capacity.

With the increasing attention to all of these aspects of quality control and production capacity, it was inevitable that the subject of mixing times would also be appraised. For many years California has permitted a minimum of 50 sec for mixing paving concrete in on-site paving mixers. The performance of the paving concrete and the data from many quality tests all attest to the adequacy of this requirement. With stationary mixers, however, the criterion differed and minimum mixing time was dependent on mixer size. For an 8-cu yd mixer, the minimum was 3 min and 15 sec, i. e., 90 sec for the first cubic yard plus 15 sec for each additional cubic yard.

In view of the serious economic consequences of excessive mixing time requirements, a series of tests was made on various sizes and types of mixers. These tests clearly demonstrated the feasibility of modifying California's requirements. The revised requirements resulting from these studies had an important bearing on the development of slip-form paving in California. Obviously, 3-lane at a time paving would be prohibitively expensive with the additional mixing equipment necessary to provide sufficient mixing capacity if 3 min additional mixing were specified.

The basic requirement now is that all concrete must be mixed for a sufficient time to produce an adequate mixture, but in no event less than stated minimum periods which are dependent on the type rather than the size of the mixers. These minimums are 50 sec for both stationary and on-site paving mixers; 40 rev in special truck-type paving mixers; and 70 rev in conventional truck mixers.

Adequacy is determined by tests performed on samples of concrete taken from the first and last quarter of sample batches. Differences in slump and distribution of coarse aggregate are noted and the mixing time is adjusted if the data fail to conform to specified tolerances. This is a rare occurrence with modern mixing units in good condition, and minimum permissible mixing times are generally sufficient to produce an adequate mixture.

DELIVERY OF CONCRETE TO PAVER

Centrally mixed concrete is delivered to the paver in end-dump trucks which back into the dumping position on the subgrade in front of the paver. Normally, the trucks operate on the subgrade only for the limited distance in front of the paver necessary to line up properly into dumping position. In certain instances where space is limited, the contractors are permitted to use the subgrade as a haul road provided the trucks are not loaded in excess of legal load limits. Similar procedures are followed where the tilt-drum truck mixers are used.

The front of the paver is divided into as many bays as there are lanes being paved. Trucks back into one or another of these bays to dump into the receiving hopper. To prevent these trucks from coming into direct contact with the paver, the front plate of the receiving hopper in each bay is mounted so that it slides freely backward and forward independent of the forward travel of the paver. Five feet of travel between fixed stops is provided. It is the responsibility of the operator to control the forward travel of the paver so that the sliding plate is not against the backstops when a truck moves into dumping position (Fig. 9).

The dump men must balance delivery of concrete across the width of the paver and control the dumping rate. An unbalanced load on the paver may cause loss of traction at one of the tracks. This is especially true when paving 3 lanes at a time. Overloads, on the other hand, cause large variations in the forces acting on the concrete under the conforming screed and may well result in loss of traction at both tracks. The net result in either case is an area of excessively rough pavement.

In steep terrain it was necessary to run the paver downhill whenever possible for similar reasons. A recent project involving 6 percent grades and 12 percent superelevation is an example of 3-lane at a time paving in mountainous terrain. Paving was first attempted in an uphill direction on a 6 percent grade. Difficulty was immediately encountered. The main problem at first seemed to be loss of traction but, with experience, the dump men were able to overcome it by balancing the delivery of concrete and controlling dumping rate. Although this improved the result, the paving continued to be unacceptably rough. Despite all his efforts, the contractor was unable to meet specification tolerances consistently until he changed the direction of paving. Paving downhill resulted in a reduction of the roughness of from 9 to about 3 in./mi.

It has been emphasized that the dumping rate must be controlled. This involves maintaining the truck cycle as uniform and continuous as possible and managing the rate at which individual trucks discharge their loads. Reasons for the latter have already been discussed and need no further elaboration. Maintenance of a uniform and continuous truck cycle is important for somewhat different reasons.

The most obvious reason, of course, concerns the economics of truck operation. There are others which are equally compelling. Most relevant is the adverse effect on

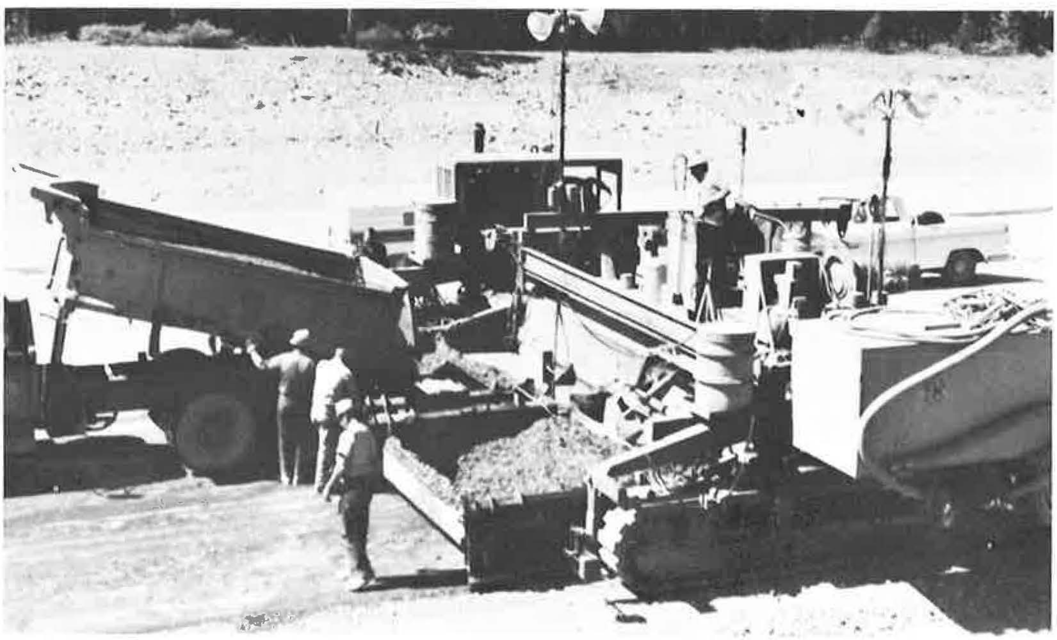

Figure 9. Sliding front plate on slip-form paver.

pavement smoothness produced by repeatedly stopping and starting the paver. The most satisfactory results are obtained where the paver is maintained at uniform speed. Since this depends on a uniform truck cycle, it is not always possible to attain. It is much better to slow the paver to a creep than to stop it completely during any break in the truck cycle. However, this is only an expedient and not a substitute for properly balanced and supervised trucking operations.

GRADE WIRES

Piano wire stretched tautly between steel stakes parallel to, and offset from, each edge of pavement is used to provide grade and alignment control for the paver. These grade and alignment reference lines are commonly called grade wires. They must closely parallel the desired profile for the edges of pavement. In practice, this means they are installed first by accurate measurement from the engineers' survey stakes and, secondly, by careful sighting along the wire for correction of any discrepancy either in the measurement or in the survey stakes.

The grade wires are offset approximately 30 in. laterally from each edge of pavement to provide room for the paver tracks, and approximately 8 in. vertically because of the location of the grade sensors. As the position of the grade sensors can be readily adjusted up or down through a range of approximately 8 in., the vertical offset to be used must be decided at the beginning of the job.

Because the pavement on many projects is interrupted, frequently by bridge decks at grade, there may be a tendency, for one reason or another, to use a different vertical offset in the installation of grade wires for some of the isolated segments of pavement. The following example of one project in California illustrates the advantage of maintaining a constant offset throughout the entire job. In this instance, the vertical offset was established at 8 in. For some reason, the contractor changed the offset to 7 in. in the area between two bridges, a distance of approximately 800 lin ft. Although all key personnel knew of this change and had been briefed to adjust the grade sensors accordingly, it was entirely forgotten in the confusion of moving the paver across one of the terminal bridges. The result was 800 ft of 24-ft wide pavement 1 in. deficient in thickness.

SURVEY STAKES

Although the grade wires are sighted to detect and correct for any discrepancies in the survey stakes, such discrepancies are a hazard incurred with each set of stakes used. If separate sets of stakes are used for the subgrade and the pavement, discrepancies between the two sets of stakes will affect the thickness of pavement. For this reason, it has been found highly desirable to use the same survey stakes for both purposes. In practice, this means that horizontal offset of the grade wires from edge of pavement is considered when locating the stakes at the subgrade preparation stage. It is preferable that they be at the same offset so that a direct vertical measurement alone is required to set the grade wire.

SUBGRADE PREPARATION

In California, subgrade for concrete pavement is prepared by constructing a cement-treated base to close tolerances for grade and cross-section. The treated base is required to extend 1 ft beyond each pavement edge. This is considered sufficient to overcome edge pumping, but it is not sufficient to extend the treated base to the full width of the paver tracks. In some instances, therefore, contractors have extended it at their cost an additional 6 to 12 in. to provide a smooth, firm track path area for the paver to travel on. These are exceptional cases though, for in most instances the untreated shoulder material compacted to proper grade has been adequate.

One of the more important problems with slip-form paving is the difficulty of subgrading the base to the very tight grade tolerances required. It has yet to be completely resolved. In an attempt to overcome this difficulty, most of our contractors are now employing automatically controlled subgrading equipment. Sensors and grade wires similar to those on the paver are used.

The most successful procedure at present involves subgrading for the treated base as carefully as for the pavement. When a uniform thickness of base is placed and compacted, only slight trimming is required to obtain subgrade to reasonably close tolerances.

The primary control of pavement thickness is established by making certain that the subgrade is at a minimum offset below the grade wires at all points. This is accomplished by stretching a string taut over the grade wires at periodic intervals and measuring down to the subgrade every 2 ft transversely (Fig. 10). High spots are then cut.

SIDE FORMS

The length of sliding side form was a subject of much concern to us five years ago. This concern was reflected in a requirement on our initial projects that 90 ft of trailing form be used. It was thought that the pavement edges would slump away if they were not supported by at least that length of side form, but experience proved that reducing the length of side form resulted in less rather than more edge slump. Accordingly, our current practice is to use only that length of form necessary to support the edges under the paver itself (Fig. 11).

Proper design of the side-form section proved to be a more troublesome problem than the length of form to be used. The original design provided for forms of monolithic cross-section, rigidly attached to the paver screeds. They were only slightly shallower than the pavement to allow them to clear the subgrade but prevent excessive waste of concrete. They were impractical because they bottomed out on local high spots in the subgrade or on particles of the coarse aggregate wedged between the forms and

Figure 10. Subgrade measurement from taut string line.

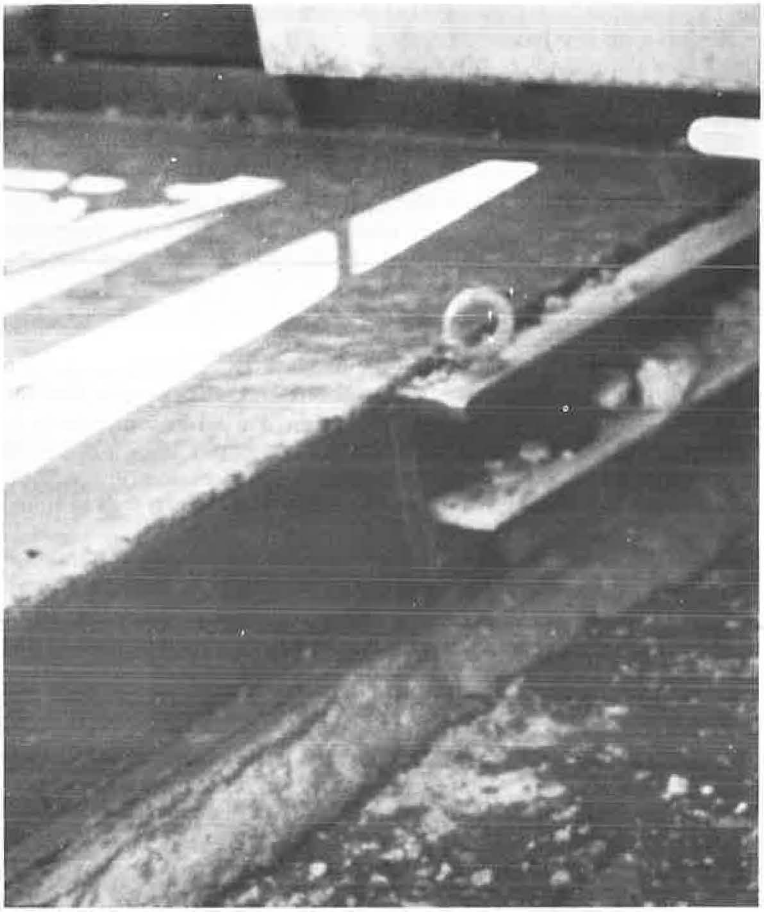

Figure 11. Pavement edge immediately behind side forms.

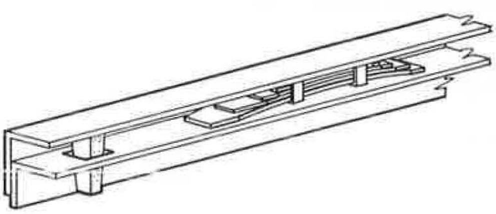

Figure 12. Spring-loaded side forms.

the subgrade. The paver would then be lifted above grade, causing roughness in the pavement. A floating action would also be induced by the extra concrete under the screeds, thus extending the area of roughness.

The solution finally devised was a two-piece, spring-loaded form design as shown in Figure 12. With forms of this design, the upper part is attached to the screeds. The lower part slides on and adjusts to variations in the subgrade without exerting excessive uplift pressure on the paver. Excessive waste of concrete either over or under the side form is prevented and local high spots in the subgrade do not result in rough pavement.

INTERNAL VIBRATION

Internal vibration, as used on slip-form pavers of the type employed for 3-lane at a time paving, serves two distinct purposes. It compacts the plastic concrete and overcomes surface tearing under the conforming screed.

Laboratory studies conducted to determine what minimum amplitude and frequency were necessary to compact concrete adequately indicated that a frequency of 5,000 vibrations per minute is the practical minimum, and that the amplitude should be sufficient to be perceptible on the surface of the concrete more than 1 ft from the vibrating element.

In practice, these minimum requirements are fulfilled by a series of spud-type vibrations mounted in the receiving hopper of the paver. They are spaced laterally at 30-in. intervals and positioned ahead of the conforming screed at a distance approximately equal to the thickness of pavement. The latter dimension, determined empirically, is somewhat critical. If the vibrators are positioned too closely to the screed, the surge behind the screed is uncontrollable. If moved too far ahead of the screed, the load on the paver is greatly increased and excessive tearing of the surface is incurred.

The second purpose of internal vibration, to overcome surface tearing, is accomplished with a tube-type vibrator mounted along the entire width of the conforming screed at the leading edge. There are approximately 2 in. of clearance between leading edge and the side of the tube, and the bottom of the tube is about ¼-in. lower than the screed.

Manufacturers have made determined efforts to accomplish both of these purposes with either the tube vibrator or the spuds rather than using both. All of these efforts have failed because the compaction is inadequate, tearing is not adequately overcome, or the amount of surge behind the conforming screed is uncontrollable. Furthermore, the ability to compensate for variations in the concrete at the paver is impaired.

Frequency of the tube vibrator need not be the same as for the spud-type vibrators. Best results have been obtained where means are provided for the paver operator to vary it between 3,000 and 5,000 vibrations per minute. This permits the operator to compensate for variations in concrete consistency, decreasing the frequency when the mix becomes wetter and surge behind the conforming screed increases, or increasing the frequency when the mix is dryer and tearing of the surface is encountered.

When a rotating screed is used behind the conforming screed, the operator can judge when and how to vary the frequency by the amount of grout carried ahead of the rotating screed. An increasing amount of grout is a signal to decrease the frequency.

Several of our paver operators have become very skillful at this and are often able to anticipate adjustments by the appearance of the mix in the receiving hopper. Careful attention to the technique can result in a significant improvement of the pavement smoothness.

SURVEILLANCE OF SENSORS

Another technique practiced by our contractors is that of stationing men at each side of the paver to give continuous attention to the operation of the control sensors. Many things can cause these sensors to leave the grade wires. A few moments of operation with any one of the sensors off the wire can produce roughness in the pavement requiring costly corrective measures. These measures are so costly as to more than offset the expense of two men to insure that it does not happen in the first place.

PAVEMENT THICKNESS

Measurement of pavement thickness is accomplished by two techniques: stabbing the actual depth of concrete (Fig. 13) and measuring down to the completed surface from a string line. Stabbing the depth of concrete is performed at random locations immediately behind the paver. A calibrated steel rod, ⅛ to ¼ in. in diameter and marked to indicate the proper depth, is inserted carefully into the concrete and worked down until the end touches the subgrade. This technique is not precise, but it will quickly show up gross errors.

For more precise determination, measurements are made of the completed surface from a string line stretched taut over the grade wires. The same locations at which the subgrade was measured are used so that the pavement thickness can be calculated by direct comparison of the data.

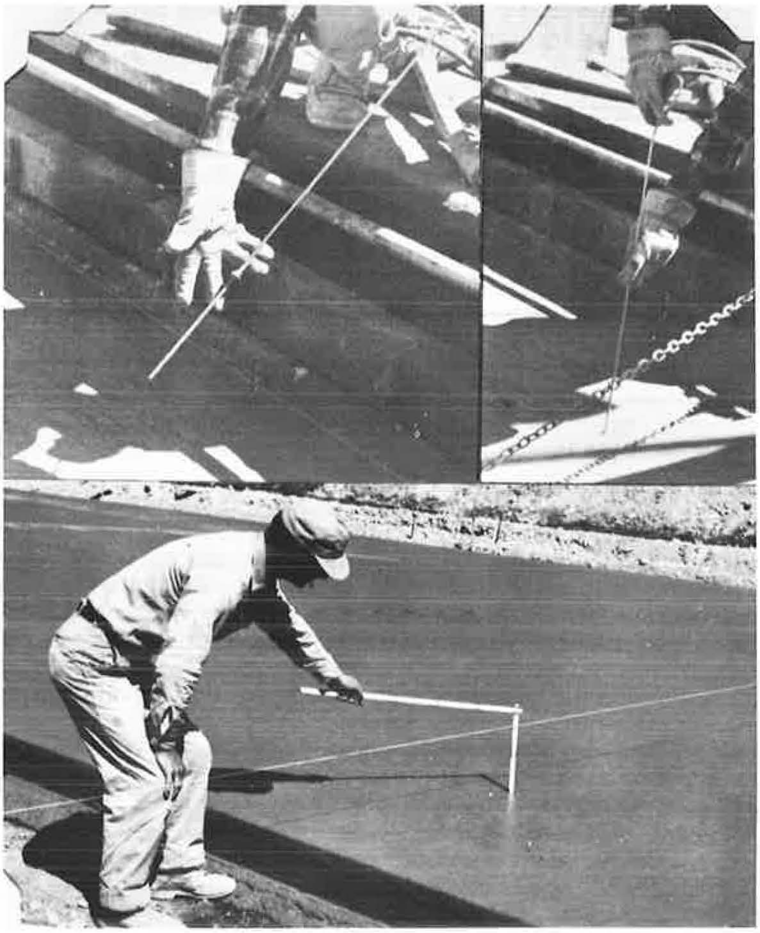

Figure 13. Pavement thickness measurement by stabbing.

FINAL FINISHING

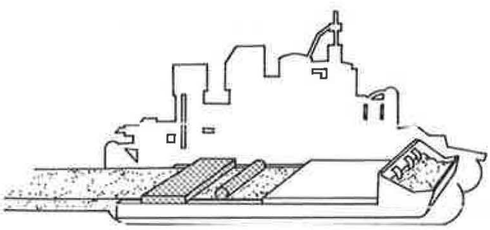

Figure 14. Rotating screed and pan float arrangement.

The final operation with the slip-form paver is to float the surface utilizing several pan floats, or a combination of a rotating screed and a single pan float, which are attached to the paver (Fig. 14). This removes minor imperfections and fills torn areas in the surface.

Final finishing consists of floating the surface with a pipe float, touching up and rounding the edges, and texturing the surface. Pipe floating is accomplished by manually towing a 6- or 8-in. aluminum pipe forward and backward over the surface with the pipe positioned diagonally across the slab (Fig. 15). This action develops a small amount of grout to eliminate minor imperfections and produce a uniform surface appearance.

Many of our contractors find it advantageous to straightedge the surface at this time when irregularities can readily be removed by the finishers. A 25-ft bow-type straightedge which utilizes a piano wire has been found to be effective.

Although reducing the length of side form reduces the amount of edge slump, there is normally some slight amount which seems unavoidable. It can usually be corrected by careful operation of the edgers used to produce a ¼-in. rounding. Where this is not effective, a slight amount of fresh grout is worked into the surface at the edge.

Finally, two burlap drags are drawn longitudinally over the surface to produce a nonskid texture, and the cure is placed. White-pigmented liquid curing compound, sprayed by machine at the rate of 1 gal/150 sq ft, is universally used as the curing medium (Fig. 16).

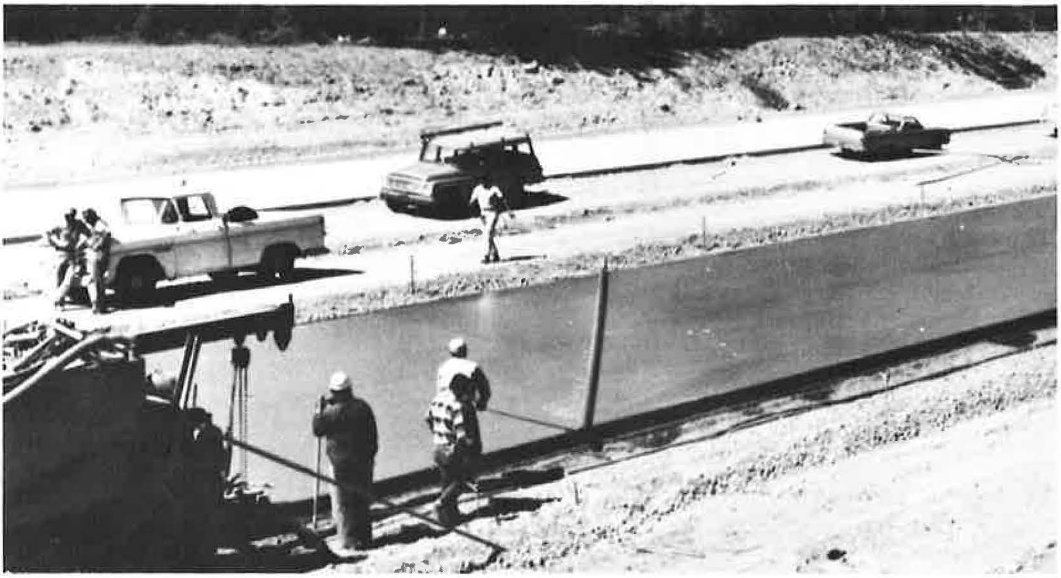

Figure 15. Pipe float procedure.

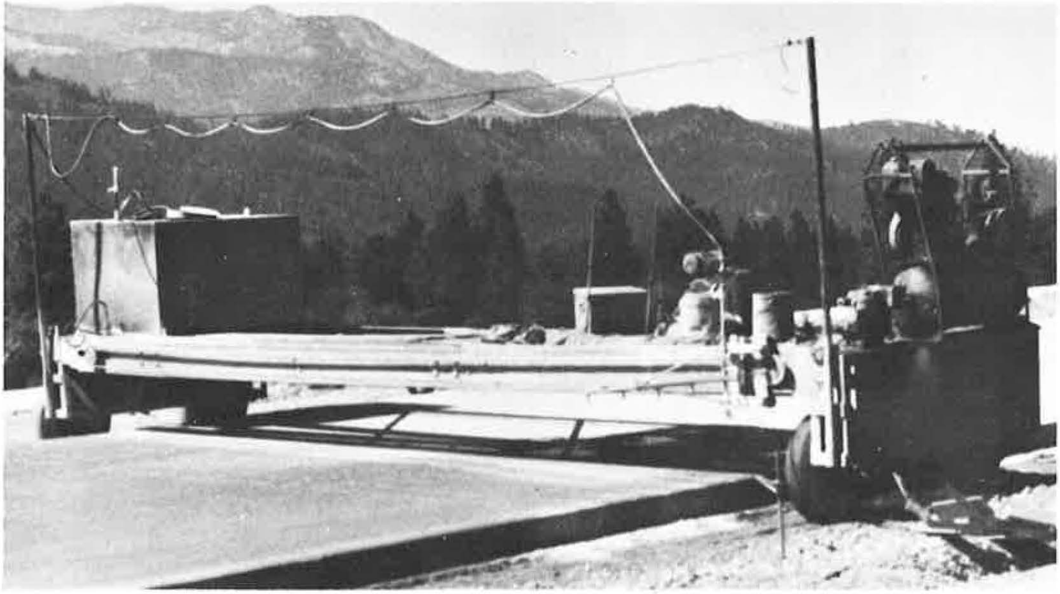

Figure 16. Curing compound application.

JOINT CONSTRUCTION

For some years before introduction of slip-form paving methods, our joint practice was standardized. Longitudinal and transverse contraction joints were sawed. Contact joints were used between contiguous pavement slabs where they were placed at different periods, and at night joints. Expansion joints were used only where structures interrupted the continuity of the pavement. Dowels and joint assemblies were not used. However, 30-in. long tie bars were placed across all longitudinal joints and at all transverse contact joints. These bars of ½-in. reinforcing steel were spaced at 30-in. intervals.

Slip-form methods made it feasible to substitute a joint insert for sawing in the construction of longitudinal contraction joints. A continuous strip of 4-mi thick polyethylene plastic is now inserted by a vibrating keel-like device attached to the paver (Fig. 17). One of these installing devices is used for each longitudinal joint. The plastic strip is 2 in. wide and is provided in 3, 000-ft rolls. It is installed in a vertical position with the top edge at or just below the pavement surface. Sawing is still the conventional means of constructing transverse contraction joints.

Expansion joints are used only at structures, as before. However, since the slip-form paver cannot place pavement flush against bridge paving notches, the practice has developed of leaving a gap of approximately 20 ft at each structure approach. These gaps are later placed and finished, using hand methods. This operation takes a great deal of care to avoid unacceptable roughness. These areas, and the night joints, are often the only ones requiring grinding to meet smoothness specifications.

Tie bars for the included longitudinal joints are now placed by mechanical installers located in front of the conforming screed on the paver. The installers are automatically

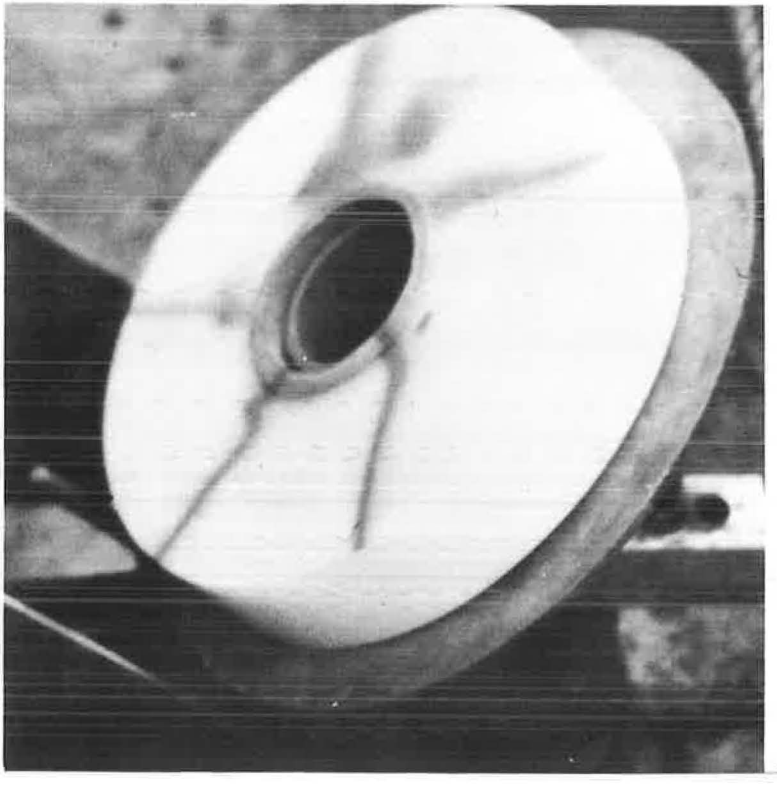

Figure 17. Longitudinal joint installer.

actuated by a triggering device on the track assembly, establishing the 30-in. spacing. The most successful installer used is a hydraulic ram assembly which is mounted on the back plate of the receiving hopper, as shown in Figure 18.

SMOOTHNESS MEASUREMENT

Compliance with smoothness requirements should be determined as early as possible. This is accomplished by using the California-type profilograph which is essentially a 25-ft long beam with a recording wheel at the midpoint and multiple support wheels at each end (Fig. 19). This instrument is operated over the pavement as soon as the concrete has hardened sufficiently to support it, usually during the morning of the first day following placement.

A continuous chart is obtained which is analyzed quantitatively as shown in the Appendix. The numerical indices derived by this test procedure must comply with specification tolerances.

There is reason to believe that the development and use of this profilograph has had an important influence on slip-form paving in California. Not only has it made

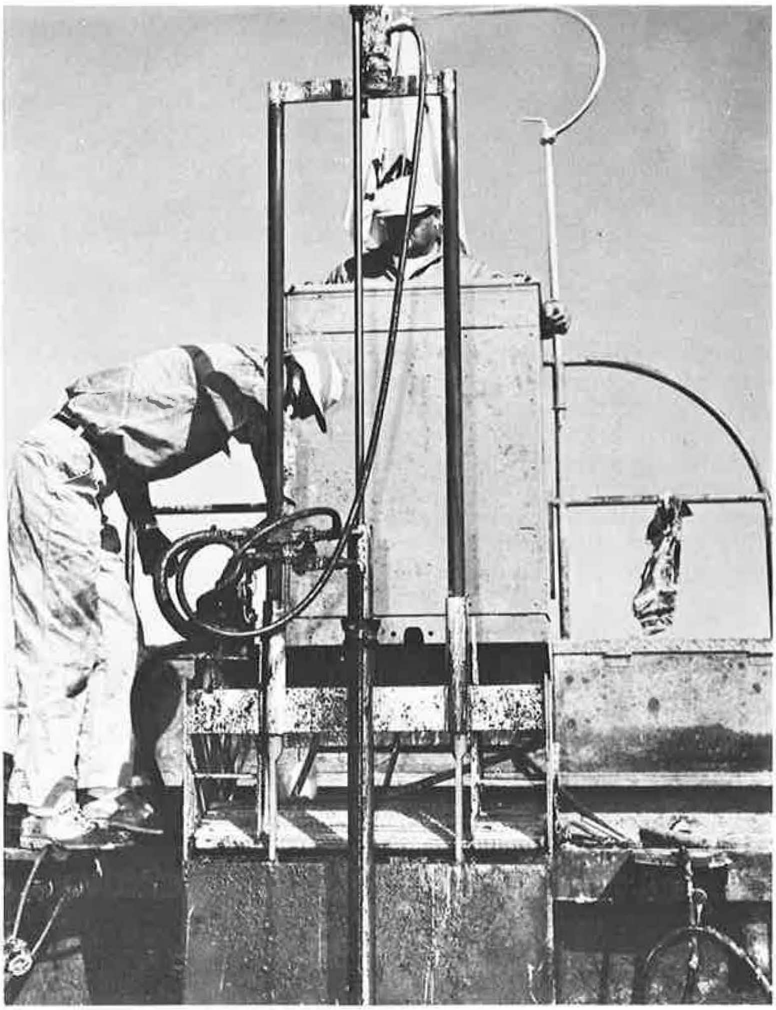

Figure 18. Tie bar installer.

Figure 19. California-type profilograph.

possible the establishment of a standard of acceptable performance, but it also has provided a means of qualitatively appraising the paving operation. The trace produced on the profilograph represents a very close approximation of the intimate profile of the pavement. As such, it can be used to examine the effect on pavement smoothness of adjustments of the paver, condition of the track path areas, superelevation and profile grade, operating conditions, and other pertinent factors. In effect, it is a permanent graphic presentation, foot by foot, of the paver performance with respect to surface smoothness. Used with the log mentioned earlier, and supplemented with a detailed on-site inspection, it has materially contributed to our progress.

SUMMARY AND CONCLUSIONS

1. In 5 yr, slip-form paving has become the most common technique used to construct concrete pavement in California.
2. Cost estimates and the trend of bid prices indicate cost savings in excess of $1.00/cu yd.
3. A higher level of technical ability is required of supervisors, operators and maintenance personnel.
4. Equipment manufacturers must be able to provide technical assistance in the maintenance of equipment.
5. Quality and uniformity of the concrete must be carefully controlled.
6. The subgrade must be very accurately graded, and improved subgrading equipment must be developed.
7. Increased production is possible and necessary to exploit the full advantage inherent in the method.
8. Proper use of internal vibration is essential for satisfactory concrete density and pavement smoothness.

9. Accurate adjustment and constant surveillance of automatic control elements are vital.

10. Pavement smoothness should be measured and recorded in a manner which permits adoption of rational standard of performance requirements and an early quantitative and qualitative appraisal of results.

Appendix

State of California
Department of Public Works
Division of Highways

MATERIALS AND RESEARCH DEPARTMENT

Test Method No. Calif. 526-C
July, 1963
(4 pages)

EVALUATION OF PROFILES

Scope

This method describes the procedure used for determining the Profile Index from profilograms of pavements made with the Hveem Profilograph and also describes the procedure used to locate individual high areas when their reduction is required by the contract special provisions.

The profilogram is recorded on a scale of one-inch equal to 25 feet longitudinally and one-inch equal to one-inch, or full scale, vertically. The determination of the Profile Index involves measuring "scallops" that appear outside a "blanking" band. The determination of individual high areas involves the use of a special template.

PART I. DETERMINATION OF THE PROFILE INDEX

Procedure

A. Equipment

The only special equipment needed to determine the Profile Index is a plastic scale 1.70 inches wide and 21.12 inches long representing a pavement length of 528 feet or one-tenth of a mile at a scale of 1″ = 25′. A plastic scale is provided with each Profilograph sent to the Districts by the Materials and Research Department. Near the center of the scale is an opaque band 0.2 inch wide extending the entire length of 21.12 inches. On either side of this band are scribed lines 0.1 inch apart, parallel to the opaque band. These lines serve as a convenient scale to measure deviations or excursions of the graph above or below the blanking band. These are called "scallops".

B. Method of Counting

Place the plastic scale over the profile in such a way as to "blank out" as much of the profile as possible. When this is done, scallops above and below the blanking band usually will be approximately balanced. See Figure I.

The profile trace will move from a generally horizontal position when going around superelevated curves making it impossible to blank out the central portion of the trace without shifting the scale. When such conditions occur the profile should be broken into short sections and the blanking band repositioned on each section while counting as shown in the upper part of Figure II.

Starting at the right end of the scale, measure and total the height of all the scallops appearing both above and below the blanking band, measuring each scallop to the nearest 0.05 inch (half a tenth). Write this total on the profile sheet near the left end of the scale together with a small mark to align the scale when moving to the next section. Short portions of the profile line may be visible outside the blanking band but unless they project 0.03 inch or more and extend longitudinally for two feet (0.08″ on the profilogram) or more, they are not included in the count. (See Figure I for illustration of these special conditions).

When scallops occurring in the first 0.1 mile are totaled, slide the scale to the left, aligning the right end of the scale with the small mark previously made, and proceed with the counting in the same manner. The last section counted may or may not be an even 0.1 mile. If not, its length should be scaled to determine its length in miles. An example follows:

Section length, miles	*Counts, tenth of an inch*
0.10	5.0
0.10	4.0
0.10	3.5
400′ = 0.076	2.0
Total 0.376	14.5

The Profile Index is determined as "inches per mile in excess of the 0.2-inch blanking band" but is simply called the Profile Index. The procedure for converting counts of Profile Index is as follows:

Using the figures from the above example:

Length = 0.376 miles, total count = 14.5 tenths of an inch

$$\text{Profile Index} = \frac{1 \text{ mile}}{\text{length of profiles in miles}} \times \text{total count in inches}$$

$$\text{PrI} = \frac{1}{0.376} \times 1.45 = 3.9$$

(Note that the formula uses the count in inches rather than tenths of an inch and is obtained by dividing the count by ten.)

The Profile Index is thus determined for the profile of any line called for in the specifications. Profile Indexes may be averaged for two or more profiles of the same section of road if the profiles are the same length.

Example:

	Section length, miles	*Counts, tenths of an inch* *Left wheel track*	*Right wheel track*
	0.10	5.0	4.5
	0.10	4.0	5.0
	0.10	3.5	3.0
400′ =	0.076	2.0	1.5
Total	0.376	14.5	14.0
PrI (by formula)		3.9	3.7

$$\text{Average} = \frac{3.9 + 3.7}{2} = 3.8$$

The specifications state which profiles to use when computing the average Profile Index for control of construction operations.

C. Limitations of Count in 0.1 Mile Sections

When the specifications limit the amount of roughness in "any one-tenth mile section," the scale is moved along the profile and counts made at various locations to find those sections if any, that do not conform to specifications. The limits are then noted on the profile and can be later located on the pavement preparatory to grinding.

D. Limits of Counts—Joints

When counting profiles, a day's paving is considered to include the last portion of the previous day's work, which includes the daily joint. The last 15 to 30 feet of a day's paving cannot usually be obtained until the following day. In general, the paving contractor is responsible for the smoothness of joints if he places the concrete pavement on both sides of the joint. On the other hand, the contractor is responsible only for the pavement placed by him if the work abuts a bridge or a pavement placed under another contract.

E. Average Profile Index for the Whole Job

When averaging Profile Indexes to obtain an average for the job, the average for each day must be "weighted" according to its length. This is most easily done by totaling the counts for the 0.1 mile sections of a given line or lines and using the total length of the line in the computation for determining the Profile Index.

PART II. DETERMINATION OF HIGH POINTS IN EXCESS OF 0.3 INCH

Procedure

A. Equipment

The only special equipment needed is a plastic template having a line one-inch long scribed on one face with a small hole at either end, and a slot 0.3 inch from and parallel to the scribed line. See Figure II. (The one-inch line corresponds to a horizontal distance of 25 feet on the horizontal scale of the profilogram).

B. Locating High Points in Excess of 0.3 Inch

At each prominent peak or high point on the profile trace, place the template so that the small holes at each end of the scribed line intersect the profile trace to form a chord across the base of the peak or indicated bump. The line on the template need not be horizontal. With a sharp pencil draw a line using the narrow slot in the template as a guide. Any portion of the trace extending above this line will indicate the approximate length and height of the deviation in excess of 0.3 inch.

There may be instances where the distance between easily recognizable low points is less than one-inch (25 feet). In such cases a shorter chord length shall be used in making the scribed line on the template tangent to the trace at the low points. It is the intent however, of this requirement that the baseline for measuring the height of bumps will be as nearly 25 feet (1-inch) as possible, but in no case to exceed this value. When the distance between prominent low points is greater than 25 feet (1-inch) make the ends of the scribed line intersect the profile trace when the template is in a nearly horizontal position. A few examples of the procedure are shown in the lower portion of Figure II.

REFERENCE

A California Method

End of Text on Calif. 526-C

EXAMPLE SHOWING METHOD OF DERIVING PROFILE INDEX FROM PROFILOGRAMS

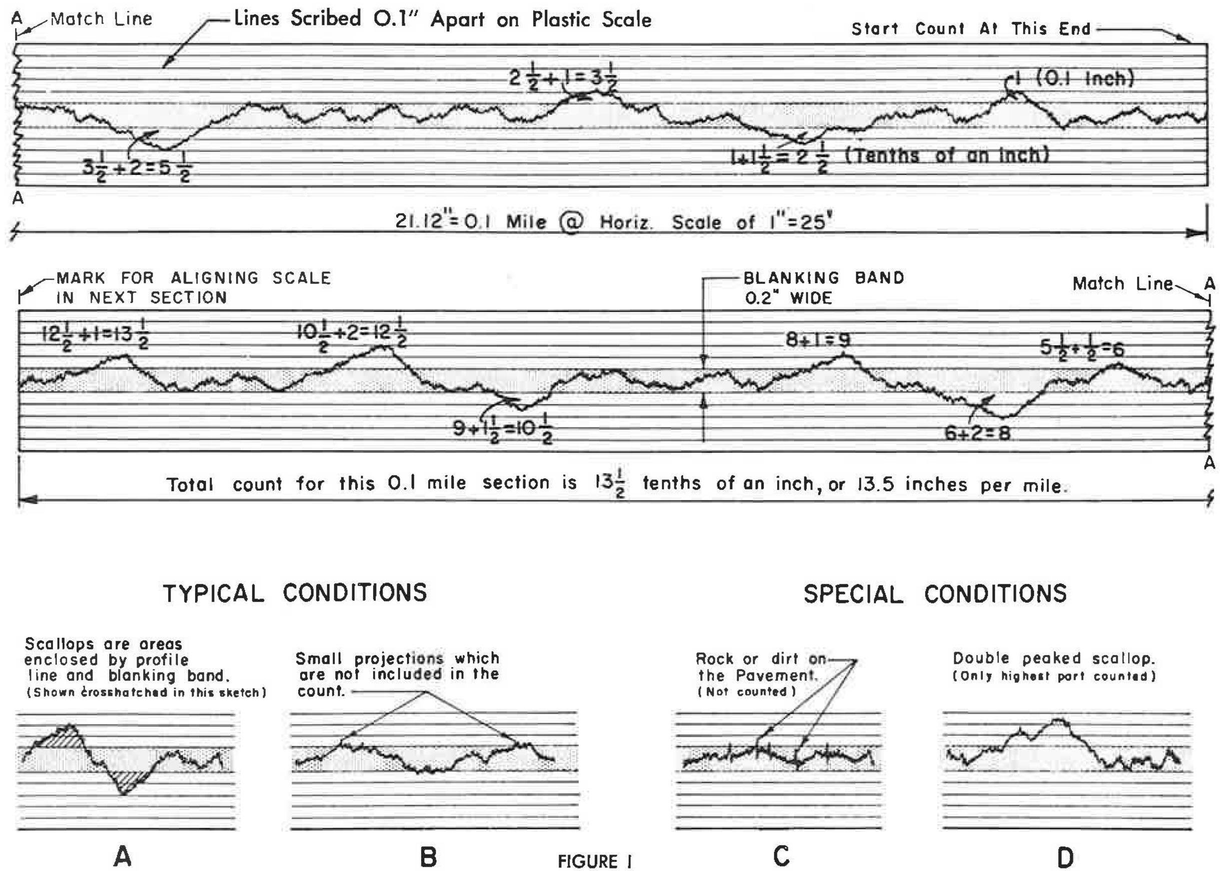

FIGURE 1

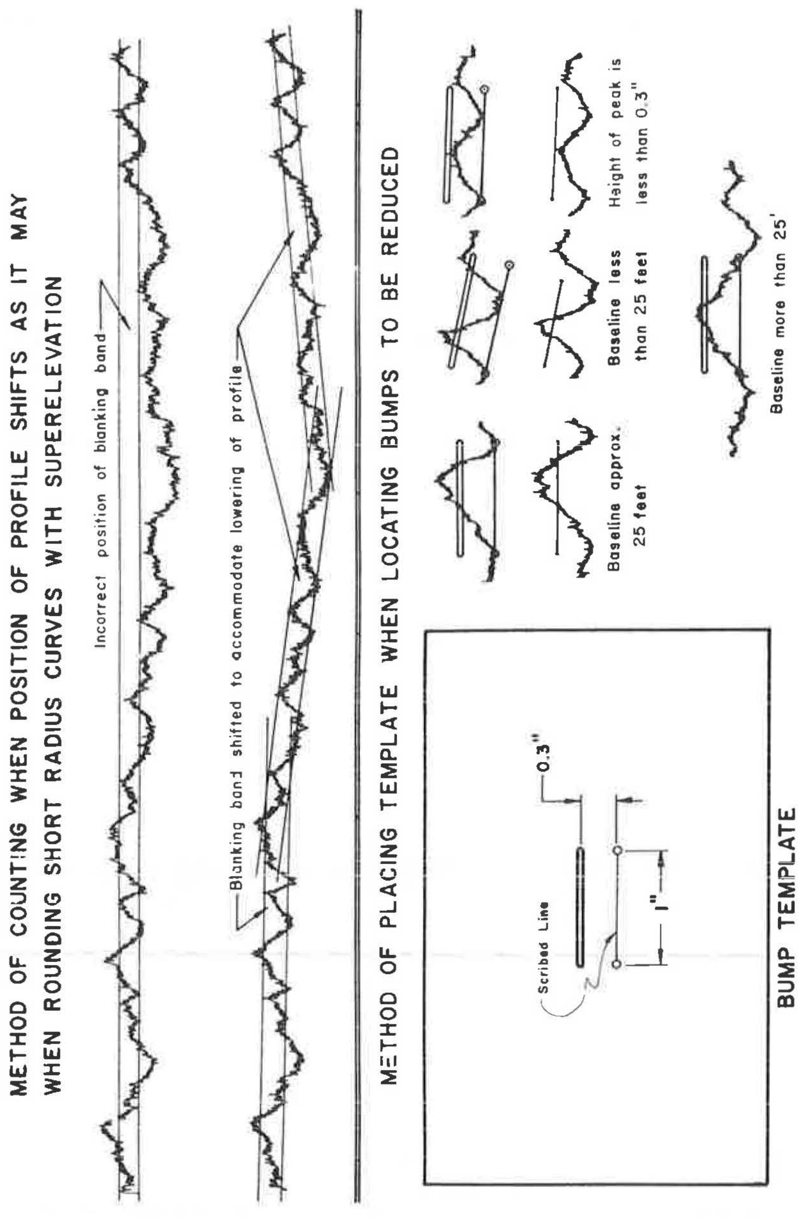
METHOD OF COUNTING WHEN POSITION OF PROFILE SHIFTS AS IT MAY
WHEN ROUNDING SHORT RADIUS CURVES WITH SUPERELEVATION
Incorrect position of blanking band
Blanking band shifted to accommodate lowering of profile
METHOD OF PLACING TEMPLATE WHEN LOCATING BUMPS TO BE REDUCED
Baseline approx. 25 feet
Baseline less than 25 feet
Height of peak is less than 0.3"
Baseline more than 25'
Scribed Line
0.3"
1"
BUMP TEMPLATE

FIGURE II

Slip-Form Paving—Construction Practices on Colorado Interstate System

ADOLPH ZULIAN, Assistant Chief Engineer, Colorado Department of Highways

Construction methods for concrete pavement are subject to a wide variety of procedures. Many new types of equipment are being developed to produce better concrete pavement faster and more economically. A recent concrete pavement project in Colorado is described briefly. The entire operation from subbase to completed roadway was accomplished in record time and involved careful job planning by the contractor.

•COLORADO has been among the pioneer states in permitting slip-form paving for concrete highways. The latest project on I-25, immediately south of the Wyoming border, was constructed with some of the newest and most modern equipment. The 16.7 mi of four-lane divided highway was completed in 40 paving days. On one 14-hr day the contractor placed 9,354 ft of 8-in. thick nonreinforced concrete pavement.

SUBGRADE

The project specified a 4-in. thickness of Class 1 granular subbase, full subgrade width. Specifications required 100 percent passing 1½ in. screen, 40 to 70 percent passing No. 4, and 5 to 15 percent passing No. 200. This material was placed with a Jersey spreader, then shaped with blades and compacted. Two inches of base course surfacing with specified grading of 100 percent passing ¾-in. screen, 40 to 70 percent passing No. 4, 30 to 55 percent passing No. 10 and 5 to 12 percent passing No. 200 was then placed by means of belly-dump trucks. This material was bladed and rolled and was purposely overbuilt about 1 in. above the grade. The contractor then used an unusual Ko-Cal base courser manufactured by Koehring (Figs. 1 and 2). It was controlled to grade by preset wires. This subgrader does not carry material ahead. The base course surfacing is the same material as used for shoulder stabilization and the overbuilt portion is pushed to the shoulder area by the machine. The subgrader does not work satisfactorily if low areas requiring an addition of material are encountered. The machine originally had only one grade guide which operated in conjunction with a pendulum and proved unsatisfactory. Another grade control unit was added to the opposite side of the machine during this construction, and excellent results were obtained even when going around curves. The problem of superelevation was easily taken care of by the extra wire. The machine was also modified by replacing the original tamping bar with a vibratory pan compactor. The speed of this subgrader (approximately 700 ft/hr) required fast action by the materials testing crews. Over 5,000 tons of subbase was placed on an average day, requiring 6 gradation, 6 P.I., 6 L.L., and 2 density tests. The placement of approximately 1,900 tons of base course surfacing per day also required 4 gradation, 4 P.I., 4 L.L., and 2 density tests. This speed necessitated fast action by the staking crews. To keep ahead of the paver operation, the subgrader was generally operated approximately 1 mi ahead. The subgrade machine followed very closely behind the wetting and rolling operation which consisted mainly of flat-wheeled vibratory compactors.

Paper sponsored by Committee on Construction Practices—Rigid Pavement.

Figure 1. Front view, Ko-Cal subgrade finisher.

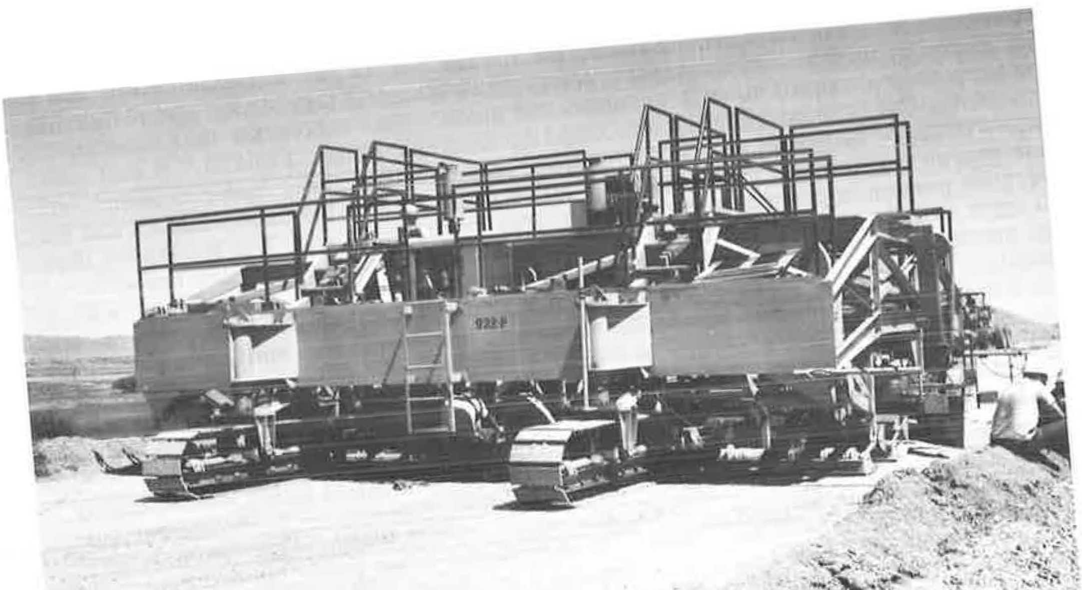

Figure 2. Rear view, Ko-Cal subgrade finisher.

PAVEMENT

A large modular type of crushing plant was used for preparation of the aggregate. This plant included a jaw crusher of the double jaw type and two cone crushers, one each set for ¾- and 1½-in. material. Production averaged 500 tons/hr and the plant could produce sand, ¾- and 1½-in. material for concrete, as well as ¾-in. base course and 1½-in. subbase material simultaneously.

Concrete was completely mixed with water in a C.S. Johnson central mix plant (Fig. 3). This plant had a capacity of 500 cu yd/hr. The two Koehring mixers had a capacity of 8½ cu yd each with a 1-min mixing time. A three-compartment, 67-cu yd storage bin provided aggregate for the mixers. Major items included three fully automatic aggregate weigh batchers, a 6,000-lb automatic cement weight batcher, 1,200-gal water tank and a 48-in. wide transfer belt. Cement was stored in a separately mounted 2,680-cu ft silo equipped with pneumatic fill pipe assemblies. The central mixing plant appeared to provide ample concrete with fewer problems than other projects where traveling mixers have been used. Also the concrete trucks did not cause as much damage to the subgrade as we have frequently encountered with traveling mixer setups.

Approximately 24 dump trucks were required to haul concrete from the plant (Fig. 4). Specifications permitted use of nonagitating trucks having smooth, water-tight bodies. Delivery was required in a thoroughly mixed and uniform mass. Discharge of concrete was required within 45 min after the introduction of the mixing water. Maximum length of haul was approximately 4 mi.

Concrete pavement was placed with a Guntert-Zimmerman slip-form paver (Figs. 5 and 6). The paver runs on crawlers and is controlled by the same preset wires used for controlling the subgrader. Average pavement placed was approximately 4,400 lin ft/day. Because of the speed of the paver, it was necessary to increase the number of stinger-type vibrators from 11 to 22. These vibrators were located ahead of the main screed. This is the first wire-controlled slip-form paving project in Colorado.

Figure 3. Concrete batching and mixing plant.

Figure 4. Dump trucks for hauling mixed concrete.

Figure 5. Guntert-Zimmerman slip-form paver.

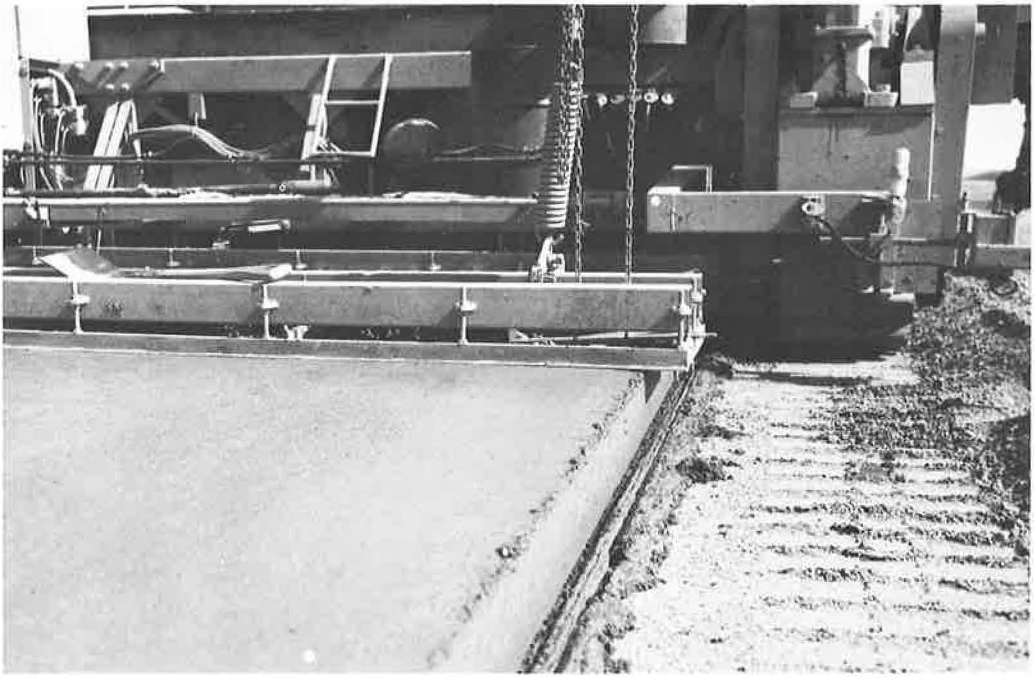

Figure 6. Rear view of slip-form paver.

Figure 7. Equipment for sawing longitudinal joint.

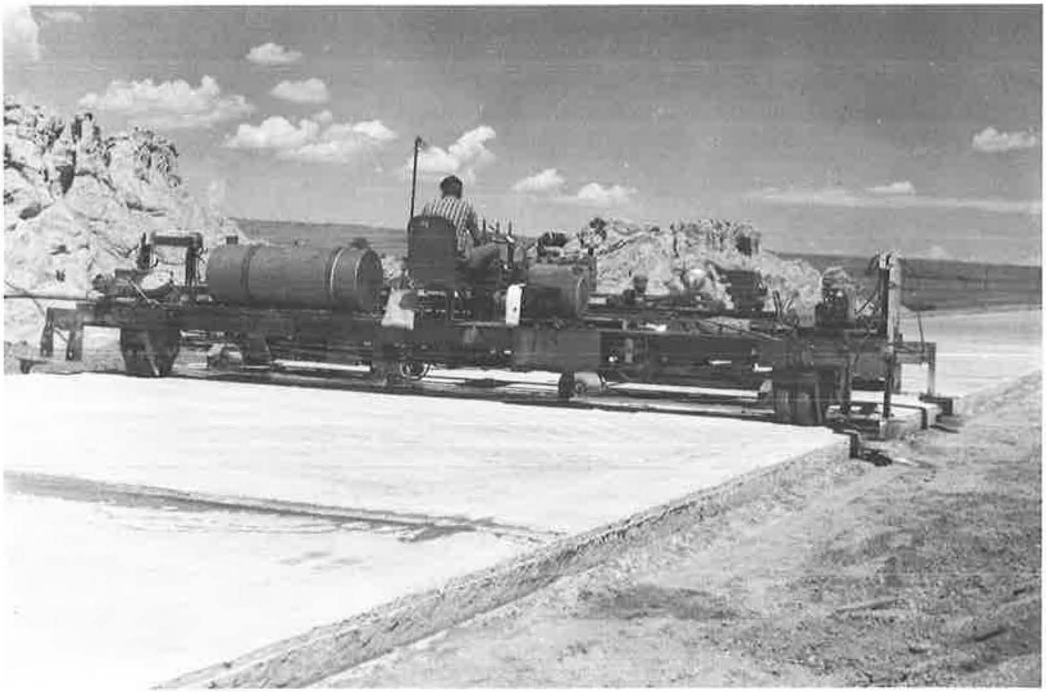

Figure 8. Equipment for sawing transverse joints.

A Clary rotating tube screed was also added to the paver together with a five-unit spray bar which was continuously in operation when the paver was moving. Vegetable-type spray nozzles were used for the spraying operation. The screed helped considerably in sealing surface voids and producing good finish. Final hand finishing consisted of straightedging and the use of paddle floats. An aluminum tube was then dragged along to provide a final finish and to seal surface voids. Texture was obtained by use of a burlap drag. Membrane curing compound was used to seal the pavement surface during the curing period.

It appears that a good specification for concrete density would be very desirable. We understand Oregon is using such a specification. The vibrators on the paver were reduced from 22 to 16 on a subsequent paving project in an adjoining state. We have found evidence of low concrete density in several test cores on different paving projects.

We are also wondering if we are working too much of the entrained air out of the concrete surface. Tests are presently under way to determine the entrained-air distribution in some concrete cores.

JOINTS

Specifications required sawed transverse and longitudinal joints, $\frac{1}{8}$ in. to $\frac{1}{4}$ in. wide and 2 in. deep (Figs. 7 and 8). The tranverse joints at 20 ft intervals are on a diagonal offset of 5 ft in the 24 ft width to reduce joint noise by permitting only one wheel to cross the joint at a time. All joints were to be filled with hot poured-type sealer meeting Federal Specification SS-S-164. During construction it was decided to omit sawing approximately 2 mi of the longitudinal joint and to place a 2-in. wide plastic strip. Accurate placement at first was difficult but was gradually accomplished. Where this strip was placed with its top edge near the pavement surface, a very neat joint resulted. If the plastic strip was placed above or below the concrete surface, a slight amount of spalling became evident. Test cores show that where the strip is properly placed, the joint was cracked cleanly through the 8-in. slab. This is not always true in the case of the sawed joints. We are permitting use of the plastic strip at the contractor's option on some additional projects to better determine its value. Its use can effect a substantial saving over the cost of sawing and sealing.

We are using ½-in. diameter, 24-in. long tie bars spaced 36 in. apart in our longitudinal joint. With a straight-line crown on the pavement we thought these bars might be eliminated. We believe they are sometimes responsible for longitudinal cracking in the lanes due to contraction in the 24-ft width. We are observing a section on which the tie bars were eliminated. There is some evidence of one slab being higher than the other through this section. A recent inspection indicates that the joint is opening more than desirable and probably will continue to do so. This leaves an opening for water to enter and can cause damage to the pavement if not kept sealed. Dowel bars have been eliminated from expansion joints but are still provided at construction joints. Approach slabs to bridges are reinforced and are tied to the concrete pavement. Normally, in continuous bridge deck construction, to avoid cracking of the bridge abutment, the approach slab is not tied to it.

Arizona's Experience with Slip-Form Paving

OSCAR T. LYON, JR., Assistant State Engineer, Arizona Highway Department

Arizona's first, and highly successful, use of the slip-form concrete paver had several noteworthy features. Profilograph readings averaged 2.5 in./mi; one ½-mi section indicated a value of 1.1 in./mi by the Hveem profilograph—the smoothest riding concrete pavement in the state. The width of the Guntert-Zimmerman machine was changed to pave both 24- and 35-ft wide roadways. Polyethylene strip was used for all longitudinal joints; in one test section it was unsuccessfully used for the skewed, transverse contraction joint. A central plant setup, using dump trucks as concrete haul units, was established.

•THE ARIZONA HIGHWAY DEPARTMENT awarded a contract in May 1963 for the construction of 6.1 mi of I-17, north of Phoenix, on a total bid of $5,056,448.90. The contract called for portland cement concrete paving, using standard forming as called for in the standard specifications. All of the paving was to be a 9-in. nonreinforced section on two roadways consisting of 3.6 mi of 36-ft wide pavement and 2.5 mi of 24-ft pavement.

In December 1963, the contractor requested the highway department to approve a change to a slip-form paving method. A cost analysis submitted reflected a $0.075/sq yd reduction in price for slip-form paving using polyethylene strips for the longitudinal and transverse joints. Sawing was to be eliminated completely. The change order, which included a central plant setup using dump trucks as concrete haul units was approved. Approval was also given to subcontract the paving to a company using a Guntert-Zimmerman paver and joint-laying machine. Work was started on Feb. 3, 1964, and was completed on April 17, 1964.

The base material on which the concrete paving was placed was specification aggregate base with the following grading: 100 percent passing 1-in. sieve; 95 to 100 percent passing ¾-in. sieve; 45 to 75 percent passing ¼-in. sieve; and 0 to 12 percent passing No. 200 sieve. The base was processed and laid with motor graders and compacted with a 16-ton pneumatic roller. Steel spikes were then placed at 50-ft intervals on each side, 4 ft beyond the pavement edge and to the elevation of the top of the base. The contractor then set stakes 16 in. above this grade at 25-ft intervals and piano wire was stretched taut between stakes on each side. The sensing units for controlling the machine followed these wires. The contractor set blue tops as grade stakes for the top of the finished aggregate base by using a string line stretched across the road from wire to wire. A LeTourneau-Westinghouse blade, Model 777, with a 14-ft moldboard was used to fine-grade the AB. A 25-ft wheelbase land plane was used for final finishing before rolling with a Galion tandem roller. A state crew checked the grade by stretching a nylon string from wire to wire. These tests were made on 25-ft stations at three points across the roadway.

Location of the concrete batch plant and the central mixer allowed by the change order resulted in a maximum haul of 6.5 mi and a minimum haul of 1.5 mi. A console-controlled plant combining five batches of 1.7-cu yd into an 8.5-cu yd mixer was used. A minimum mixing time of 55 sec was set.

Paper sponsored by Committee on Construction Practices—Rigid Pavement.

Standard gradation (square openings) for the coarse aggregates used in the paving was as follows:

Passing $2\frac{1}{2}$ in., 100 percent;
Passing 2 in., 95 to 100 percent;
Passing 1 in., 35 to 70 percent;
Passing $\frac{1}{2}$ in., 10 to 30 percent; and
Passing No. 4 sieve, 0 to 5 percent.

Gradation for the fine aggregate was as follows:

Passing $\frac{3}{8}$-in. sieve, 100 percent;
Passing No. 4 sieve, 95 to 100 percent;
Passing No. 16 sieve, 45 to 80 percent;
Passing No. 50 sieve, 10 to 30 percent; and
Passing No. 100 sieve, 2 to 10 percent.

The aggregate was produced at Union Sand and Rock Plant in the Salt River.

Specifications called for the concrete to be placed within 30 min after water was added at the mixer. Slump control was maintained by utilizing radio contact between the paver and the batch plant and through the use of the Kelly ball test on each truck load of concrete. Correlations between the standard slump cone test and the Kelly ball were continually made and recorded. It was found that a $\frac{3}{4}$- to 1-in. slump was ideal for the operation. The low-slump concrete was hauled to the paving site in dump trucks with filleted corners in the dump beds to prevent concrete from hanging in them.

The paving train consisted of four pieces of equipment: the paver, a 4-in. tubular float, a burlap drag, and a curing compound application machine. It was planned to place all joints with a polyethylene ribbon. After several days of unsuccessful attempts to place the transverse joint with this new machine, it was taken off the job and the standard procedure was used. This called for steel control joints every 60 ft with sawed joints at 15-ft intervals. These transverse joints were skewed 2 ft in 12. The steel joint material was 12-gage metal, $2\frac{1}{4}$ in. wide by 12 ft long.

The Guntert-Zimmerman slip-form paver used on these projects was used first on the 24-ft wide sections and changed on the job to finish up with the 36-ft wide sections of concrete pavement. The tubular float, burlap drag, and curing compound machine were also converted. The receiving hopper at the front of the machine was equipped with sliding gates to allow the dump truck to back into the paver while in motion. The concrete was dumped into the receiving hopper in two locations in order to load the paver uniformly. Internal vibrators followed by a horizontal tubular surface vibrator, all operating at 5,000 cycles/min, consolidated the concrete. The speed of the vibrator could be varied, depending on the consistency of the concrete. Behind the surface vibrator was the main 7-ft wide pan float. Next was an auger to distribute the concrete further, followed by a Clary screed. Behind the Clary was a second pan float, $3\frac{1}{2}$ ft wide, followed by a final pan float, 18 in. wide. No trailing forms were used in this operation.

The speed of the paver varied from 9 to 12 ft/min, but due to the limited production of the concrete plant the machine was forced to wait for concrete. Control systems were all automatic, working from elevation sensing units mounted on all four corners and an alignment sensing unit located on either of the front corners. The operator only stopped and started the slip-form paver and regulated the speed of it and the vibrators.

Hydraulic rams automatically installed the transverse tie bars every 30 in. at a depth of $4\frac{1}{2}$ in. These tied together the 12-ft lanes of pavement. The longitudinal joint was placed automatically by a device fastened to the rear of the slip-form paver. The 2-in. polyethylene ribbon was fed out from a holding reel.

The 4-in. tubular aluminum float was used to obtain final surface smoothness and was pulled back and forth longitudinally across the pavement by two finishers. An edging tool was used to true up and finish the edge. Occasional edge settlements were formed and concrete was brought from the paver to bring the edge to grade.

The desired nonskid surface was attained by a burlap drag which straddled the pavement on wheels and was pulled behind the finishing after excess surface moisture evaporated and before the concrete hardened. A self-propelled curing compound applicator also straddled the pavement and applied white-pigmented compound at the rate of 1 gal/150 sq ft of surface. The rate of application was checked at the emptying of each 55-gal drum.

The transverse joints were made by a gang saw consisting of 24 and 12 units having a total of 6 blades; each blade made a 6-ft cut. The sawing was done when the concrete was approximately 24 hr old.

Concrete test beams and cylinders were made from concrete taken from the receiving hopper of the slip-form machine. Slump and air-content tests were made periodically from this concrete. Six flexure strength beams per shift were fabricated and cured with curing compound. These were tested at 7 days at the project laboratory. Six cylinders were made each shift and buried at the point of fabrication for 24-hr curing. Four were then forwarded to the central laboratory for testing, two at 7 days and two at 28 days. The remaining two were retained at the field office for checks.

The change order required that the finished concrete pavement have a profile index, as measured with a Hveem profilograph, not to exceed a rate of 7 in./mi in any $\frac{1}{10}$-mi section. In addition, the standard specification requirement that any variation from a 10-ft straightedge of more than $\frac{1}{8}$ in. shall be corrected or removed was also in effect. An average of readings on the 24-ft wide section, which was the first placed, showed a profilograph average of 1.9 in./mi. The average for the 36-ft wide section was 2.9 in./mi. The entire 6.1 mi of pavement averaged out at a rate of 2.5 in./mi. The best $\frac{1}{2}$-mi section was on the 24-ft southbound roadway with an average rate of 1.1 in./mi.

We are well pleased with the results of this first slip-form paving job. The riding surface on these two projects is better than we have ever been able to obtain by form paving. The price advantage of the change orders of Bentson's two projects will be about $13,000.00. Supplemental specifications, covering slip-form paving with central mixing and dump truck transporting, have been prepeared and will become a part of our standard specifications when revised in 1965. Our bidding schedules will allow contractors an option between the conventional forms and the slip-form method on all future concrete pavement.

Slip-Form Paving with Mesh and Dowels in Illinois

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Respectively, Engineer of Research and Development and Research Project Engineer, Illinois Division of Highways

The first use of the slip-form paving process in constructing a portland cement concrete pavement on the primary highway system in Illinois is discussed. The pavement contains the transverse joints, dowels, tie bars, and distributed welded sire fabric reinforcement employed by Illinois in standard formed construction. Details of the construction process and the results that were achieved are described and evaluated.

• THE SLIP-FORM PAVER was developed to reduce the cost of portland cement concrete paving through the elimination of form setting. Experience with the slip-form paving process in Illinois dates back to 1952, at which time a simple, cable-drawn, sled-type device was used in lane-at-time base construction. In time, the self-propelled, full-width pavers came into use.

In the early work done in Illinois, some difficulties were experienced in obtaining a smooth surface reasonably free of excessive bumps and longer undulations. However, improvements in the equipment and in construction procedures eventually reached a stage where the average contractor could be expected to produce a base of uniform thickness and satisfactory edge alignment, meeting a surface-smoothness tolerance of ¼ in. in 10 ft. The use of the slip-form paver in base construction has become standard procedure in Illinois. Portland cement concrete bases are constructed without transverse contraction joints or steel reinforcement, and are surfaced with 2 or 3 in. of bituminous concrete before being placed in service to traffic.

In view of the reports received from other parts of the country regarding the improvement of slip-form pavers and the adaptability of the slip-form paving process to surface-course construction, the experimental paving project described here was undertaken to determine the feasibility of using the process in conjunction with the inclusion of the standard distributed welded wire fabric and dowels at the transverse joints as normally used by Illinois.

The construction project selected for the experimental work in Illinois is located north and east of Monmouth on US 34 and is identified as FA Route 9, Section 103, Project FU-21(8), Warren County.

The project is 4.7 mi long and includes 3.4 mi of single pavement and 1.3 mi of dual pavements. Embankment and subbase construction was begun under contract in 1963 and completed in 1964. All paving work was done during 1964. The research work on the project was conducted by the Illinois Division of Highways in cooperation with the U. S. Bureau of Public Roads.

SUBGRADE AND SUBBASE CONSTRUCTION

The experimental project lies in a glaciated area of moderately thick loess with level to moderately rolling topography. Moderate cuts and fills were required in some locations to establish an acceptable gradeline. Embankment and subgrade soils are predominantly of AASHO groups A-6 and A-7-6.

Embankment compaction was accomplished with a three-wheel roller, a tamping roller, and a pneumatic-tired roller. Densities obtained met the required 90 percent of standard maximum dry density. The earth subgrade was prepared to receive a subbase by blading with a Caterpillar No. 12 motor patrol.

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Subbases as used in Illinois are of the trench type, constructed 18 in. wider than the pavement at each edge and installed principally to control pumping. On this particular project, design thicknesses of 4, 6 and 8 in. were used. The 6- and 8-in. thicknesses were constructed of a dense-graded crushed stone. The 8-in. thickness was used at only a few locations where less than average support was anticipated. The 4-in. thickness was intended to be a cement-stabilized mixture in which 3½ percent of cement was added to a dense-graded crushed stone; however, the low cement content was not sufficient to provide adequate protection against freezing and thawing when the subbase lay exposed to the elements except for a curing covering of RC-2 liquid asphalt, through the winter following its construction.

The granular subbase material was laid to the required thickness by a Blaw-Knox pneumatic-tired spreader. A pneumatic-tired roller and a 10-ton tandem roller were used to compact the subbase material to the approximate grade and to the required 95 percent of standard maximum dry density. The subbase was then brought to final grade with a crawler-type subgrading machine operating on a graded track line (Fig. 1). The surface was later smoothed with a light roller.

PAVEMENT DESIGN

The pavement placed by the slip-form process in Illinois was of the standard design normally placed by the conventional forming process. This pavement is of 10-in. uniform thickness and 24-ft width. Welded wire fabric weighing 78 lb/100 sq ft is placed at a 2½-in. depth between contraction joints, and between pavement edge and center joint. Transverse contraction joints are spaced at 100-ft intervals and are formed by sawing the hardened concrete to a depth of 2¾ in. These joints contain 1¼-in. diameter by 18-in. length steel dowel bars spaced on 12-in. centers and placed at mid-depth of the slab. Longitudinal joints are also formed by sawing and contain No. 5 steel tie bars 30 in. in length and spaced on 30-in. centers, also placed at mid-depth of the slab.

Figure 1. Subgrading machine.

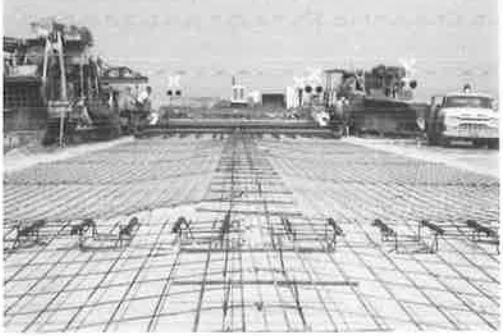

Figure 2. Wire fabric, tie bars and dowel assemblies used in unsuccessful single-lift process.

CONCRETE MIXTURE DESIGN

The paving mixture was typical of those use in Illinois. Two sizes of coarse aggregate were combined with sand, cement, water and air-entraining agent to form the mixture. The size A coarse aggregate ranged in size up to 2½ in. for the first half of the project to be constructed, and to 1¾ in. for the second half. A typical batch composition is as follows:

Coarse aggregate (size A), 1,340 lb;
Coarse aggregate (size B), 1,300 lb;
Fine aggregate, 1,775 lb;
Cement, 7.98 sk; and
Water, 34.0 gal.

Slumps of the concrete mixtures on the project ranged between 2 and 2½ in., and air contents ranged between 5 and 5½ percent.

CONCRETE PLACEMENT

Paving Operation

Two methods of slip-form paving were tried by the contractor. The initial method,

Figure 3. Sled attachment on Rex slip-form paver used in unsuccessful single-lift process.

Figure 4. Rex slip-form paving train.

which involved a single-lift process, was unsuccessful because of insufficient drive power of the equipment and was abandoned after a few hours' trial. The second method, a two-lift process, proved to be successful and was used through the remainder of the project.

The initial and unsuccessful method involved the use of a single Rex slip-form full-width (24-ft) paver. A sled-type attachment was mounted on the front of the paver to set the welded wire fabric in place at the required $2\frac{1}{2}$-in. depth. The fabric, tie bars, and dowel-bar assemblies were placed on the finished subbase in advance of the paving operation (Fig. 2).

Concrete was mixed in a traveling mixer operating on the shoulder and was placed between the wings of the paver in front of the strike-off. As the paver moved forward, the fabric was to slide over and into the sled mechanism to the required depth (Fig. 3). The driving mechanism of the paver did not have sufficient power to move the paver forward in a satisfactory manner with this arrangement, and it was soon abandoned in favor of a two-layer process.

The two-layer process involved the use of a paving train that included two Rex slip-form pavers operating in tandem (Fig. 4). These pavers travel on crawlers, and depend on the smoothness characteristics of the paths along the subbase to provide the required surface smoothness of the pavement. Initially, concrete was supplied to the two pavers by a Koehring 34-E dual drum mixer. Later, this mixer was supplemented with a Multifoote single-drum mixer.

The lead slip-form paver was used only as a concrete spreader. The hydraulically operated screed of this paver was adjusted to place a $7\frac{1}{2}$-in. thickness of concrete 23 ft, 6 in. wide. In the leveling operation, the screed moves forward and backward horizontally for 5 ft.

At the rear of the lead paver is a device that includes a rotary steel drum for distributing tie bars across the longitudinal joint. Tie bars were inserted on four equally spaced grooves (30-in. spacing) along the circumference of the drum (Fig. 5). Dowel-bar basket assemblies were staked in place on the subbase in advance of the paving operation at 100-ft intervals where transverse joints were to be sawed in the hardened concrete.

Sheets of welded wire fabric reinforcement were carried to the freshly laid first lift of concrete and placed in position immediately following passage of the lead paver. Four men were required to carry the individual sheets of reinforcement onto the concrete. Initially, some difficulty was experienced in keeping the fabric reinforcement from becoming displaced during the final finishing operation of the second paver. Bending the outermost longitudinal wires of each sheet of fabric to hook onto the preceding sheet remedied the condition. Numerous checks made on the depth of fabric placement as the work proceeded showed that the fabric lay within $\frac{1}{2}$ in. of the planned depth of $2\frac{1}{2}$ in. below the pavement surface.

The final $2\frac{1}{2}$-in. course of concrete above the wire fabric sheets and the 3-in. gaps along the pavement edges were placed by a second, more fully equipped, Rex slip-form paver following closely behind the lead paver. This machine spread, consolidated, and finished the concrete in one pass. A metal indicator attached to the paver to follow a stringline offset from the track line was used to guide the paver (Fig. 6).

Between spreading and final extrusion, the concrete was consolidated by a surface vibrator mounted on the paver, operating at a frequency of 3,500 rpm. The vibrated concrete was tucked into the extrusion meter by means of tamping bars. The extrusion meter is a plate, 42 in. wide and 24 ft long, adjusted to the crown of the pavement. The tamping bars work slightly below the surface of the concrete to prevent large pieces of aggregate from tearing the completed surface. The vibrators and tamping bars set ahead of the extrusion meter are shown in Figure 7. The concrete surface was given a belt finish by a 2-ft wide oscillating belt mounted immediately behind the extrusion meter.

The second paver included 48 ft of trailing forms of 10-in. depth on each side set 24 ft apart and held together by truss-frame braces. These forms held the concrete in place at the edges a sufficient time for testing of the surface with a 10-ft straightedge and for accomplishing whatever hand-floating operations appeared to be necessary to give a smooth surface (Fig. 8). A wet burlap drag attached to the last truss-frame brace completed the finishing operation.

Curing of the newly laid pavement was accomplished with impermeable paper placed as soon as the concrete hardened. The surface of the pavement was wet immediately before the paper was placed. The curing paper remained in place for a period of not less than 72 hr from the time the surface was covered.

At locations where contraction joints were to be sawed, the curing covering was removed temporarily immediately before sawing and replaced immediately thereafter. Contraction joints were sawed directly over the dowel bar assemblies perpendicular to the pavement surface. Sawing was performed not earlier than 6 hr nor later than 30 hr following paving. Premature cracking occurred at only two locations before sawing was accomplished. Most of the sawing was done the morning following the paving operations. All sawed contraction joints were cleaned, dried and sealed before opening the pavement to traffic.

Manpower and Production

Paving operations, inclusive of batch-truck operation and the curing and joint-sawing operation, required 42 to 46 men when using one mixer, and 52 to 57 men when using two mixers. The average hourly production was about 97 ft with one mixer and about 129 ft with two mixers.

Figure 5. Tie bar placer of lead paver.

Figure 6. Second Rex slip-form paver.

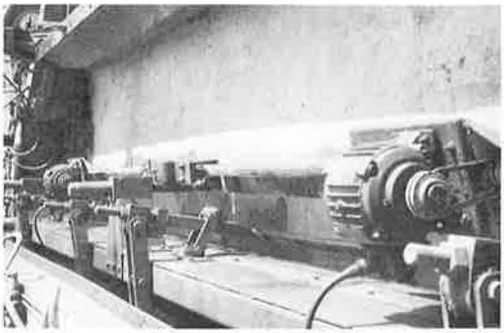

Figure 7. Tamping bars and surface vibrators.

Figure 8. Finishing operations behind second paver.

Surface Variations

Illinois specifications require that surface variations do not exceed $\frac{1}{8}$ in. in 10 ft when measured in the wheelpaths with a 10-ft straightedge. Grinding is required where variations exceed this amount. Analysis of the data obtained in surface variation measurements on the project indicated an average of about 11 variations over $\frac{1}{8}$ in. in 10 ft/wheelpath miles. This value is not inconsistent with values obtained on projects paved by normal procedures in Illinois.

Roughometer Readings

Surface smoothness tests with the Illinois BPR-type roughometer showed an overall section average roughness index (R. I.) of 75, which places the pavement at the bottom of the "very smooth" category (75 or less) by Illinois standards. This figure is somewhat better than the average for all concrete pavements constructed in Illinois by standard procedures. It is of interest that the R. I. readings decreased from the lower 80's to the lower 70's as the paving operations progressed. This improvement is attributed to the experience and skill acquired by the contractor as the work progressed.

Miscellaneous Observations

The maximum vertical grade traveled by the pavers was 4.0 percent. A few locations of low-degree horizontal curvature and slight superelevation were also encountered. In no case did any of these features create problems.

The pavement edges formed in the process were considered to be generally satisfactory, although slight slumping was noted at various times. No slump was observed where slump-cone measurements did not exceed $1\frac{1}{2}$ in. However, the surface of the concrete placed at this consistency did not finish well and appeared to have an open texture, especially where the mixture contained coarse aggregate up to $2\frac{1}{2}$ in. in size. The problem was lessened when a change was made to a coarse aggregate of $1\frac{3}{4}$ in. maximum size. Noticeable slumping of the edges occurred whenever the slump approached 3 in. At the few locations where excessive settling of the concrete at the edges occurred, a correction was made by staking 2- by 10-in. by 10-ft planks along the side affected.

Transverse construction joints were formed at the end of each day's operation by means of a header board with holes for dowel bars. Dowel bars, $1\frac{1}{4}$ in. in diameter by 18 in. long and spaced on 12-in. centers, were installed through the header boards. To facilitate positioning of the paver for the next day's operations, $\frac{3}{4}$- by 10-in. boards were inserted along the side of the last 20 ft of trailing forms. This caused a slight reduction in pavement width in the vicinity of the construction joints.

In a few locations it was necessary to provide a longitudinal construction joint with tie bars where local roads were to intersect the main pavement. This was accomplished by inserting bent tie bars with cardboard sleeves at the required spacing as the paver moved along. In these few instances, the tie bars were located on top of the wire fabric reinforcement. The alternative of driving the tie bars into the concrete edges after the paver had passed caused slumping and was abandoned.

FINDINGS

It was evident from the work on this project that, with the exercise of reasonable control, the slip-form paving process can produce pavement that is true to line and grade, of specified thickness, and of satisfactory surface smoothness. It was also evident that the slip-form process is applicable where welded wire fabric and doweled, sawed transverse joints are included in the construction.

A comparison of the costs of the slip-form process with the costs of conventional paving was not a part of this study; however, it was evident that the slip-form process offers the opportunity for some reduction in cost by the omission of form setting, without adding appreciable cost elsewhere.

A Contractor Looks at Slip-Form Paving

WALFRED E. SWANSON, Vice President and General Manager, Roberts Construction Company, Lincoln, Nebraska

This paper covers the contractor's experience with early bidding and construction, agency acceptance, and job quality. It discusses efficiency, production capabilities, captial equipment and labor involved. It reviews the competitive position of slip-form paving.

•AS CONTRACTORS, we must acknowledge a debt of gratitude to a few hardy engineers, construction men, and equipment designers in Iowa and Illinois for the early pioneering and development work in connection with slip-form concrete paving during the late 1940's and early 1950's. A great deal of credit must be given to personnel in the Iowa State Highway Department for permitting its use and assisting in the development of slip-form paving methods on some of their 6- and 7-in. unreinforced concrete secondary roads during those years. It was during this same period that the Quad-City Equipment Company of Rock Island, Ill., made the initial developments and improvements on their first slip-form paving machines which ultimately became the first commercial machines on the market available to contractors. In 1958, the Rex Chain Belt Company of Milwaukee took over the rights and interests of the Quad-City Equipment Company and began producing slip-form pavers under their own name. Since that time many improvements have been made and at least three other equipment manufacturers have entered the field; today contractors have a choice of several types of slip-form pavers in a competitive market.

The Colorado Department of Highways and some of its far-sighted and progressive engineers were quick to recognize the potential advantages and economies of the slip-form method of concrete paving on the basis of their observation and inspection of the early operations in Iowa. In 1955, they modified their specifications to permit the use of the slip-form method on all concrete paving projects, and since that time the choice of paving methods has been left entirely with the contractor. As a result, since 1956 almost every concrete paving job of any consequence has been constructed using the slip-form method. This highway department led the way nationally and was very cooperative with the contractors in developing and improving the slip-form method of concrete paving on their primary and Interstate highway systems. Results showed that most of the slip-form concrete paving projects built between 1956 and 1958 were equal to or better in quality and riding surface than those constructed by conventional methods with forms and a complete train of paving equipment. In addition, the economies of this new method were becoming apparent; definite savings in cost varied from \$0.20 to \$0.40/sq yd as reflected by comparative bid prices.

There were times when the number of visiting engineers, equipment manufacturers, highway officals, and contractors from other states almost outnumbered our own paving crews on these early paving projects. Colorado had set the pattern for use of slip-form paving methods on all primary and Interstate concrete paving projects, which was soon followed by many neighboring states, initially Wyoming and New Mexico, during the later 1950's. This new method of paving had by then been proven and was being accepted in several states, and the ultimate end for most conventional types of formed concrete paving operations could be forecast with reasonable assurance within 10 yr or by 1969.

As is true with any new method of work involving new types of equipment, the bidding by contractors on early slip-form paving projects was on the conservative side and did

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not reflect the greater savings which are now being obtained by highway departments and contracting agencies all over the country. As contractors, we had to learn how to utilize and work with new equipment and procedures, train and develop new crews, and overcome some of the usual inertia and resistance to change within our own organizations. This also applied to some of the inspection and engineering personnel within the various state highway departments and other engineering or contracting agencies for whom we were working.

Many of the early slip-form concrete paving jobs had their full share of problems and headaches. Furthermore, in a few instances, some jobs were constructed in part with marginal or even substandard finishes and riding qualities. An inspection of the first slip-form paving job performed by any contractor would show that he had more than his share of problems during the first mile or two, and that following this initial apprenticeship period, each succeeding mile showed definite and continued improvement. This same observation can still be made for a contractor's first slip-form job today, except that with the improved equipment and a larger backlog of experienced engineering and construction personnel, the problems are fewer and the results are usually better. In general, most of the state highway departments and other contracting agencies were quite tolerant and cooperative with the contractor's organizations on their first jobs. We were all learning and developing together as an engineering and construction team. The equipment manufacturers also deserve much credit for their valuable assistance and efforts during these early periods. An analysis of the tough competitive bid prices, the high quality of work, the excellent riding surfaces, and the savings in cost, which are now being obtained throughout the areas where slip-form paving methods are being used by experienced contractors, is ample proof that the early trials and tribulations, plus a very commendable cooperative effort between the contractors and the state highway departments, were well worth while.

ACCEPTANCE AND USAGE

The acceptance or permissive use of the slip-form method for concrete paving on Federal-aid primary and Interstate highways has not been adopted by all of the state highway departments as yet. However, the use of this method has made remarkable progress since Colorado's first Interstate slip-form project in 1956. During these past 8 yr, at least 26 additional states have approved this method as an alternate on some or all of their concrete paving projects. The remaining states are studying the system and some are either seriously considering it or are on the verge of advertising for bids on their first slip-form paving projects during late 1964 or in 1965.

Late in 1962, the Oklahoma Turnpike Authority modified its specifications to permit the use of slip-form concrete paving as an alternate bid for 22 paving contracts on 64 mi of the Southwestern Turnpike (now known as the H. E. Bailey Turnpike) extending from Oklahoma City to Wichita Falls, Texas. All 22 contracts were successfully bid, accepted, and constructed using the slip-form alternate. Due to the excellent paving results achieved in 1963 on the turnpike, the Oklahoma State Highway Department has since opened up its bidding on both primary and Interstate concrete pavements to permit the use of the slip-form method. Needless to say, the slip-form method is now being bid successfully and used by the contractors on practically all of their current concrete paving projects, both plain and reinforced. The Oklahoma Turnpike Authority has stated that the use of the slip-form method on the turnpike "saved them from 35 to 45 cents per square yard on the concrete paving." This permitted them to obtain a very high quality of paving within their engineering construction estimate, which is essential to a project financed through the banks and sale of bonds on the open market. Those contractors and state highway departments and other contracting agencies that have developed a backlog of experience in the slip-form paving field, have demonstrated that this method will reduce the final cost of concrete paving without any reduction in its quality. For public construction agencies, this means that there is a better chance of keeping construction costs within estimates for individual paving projects as well as paving programs. Insofar as the public or taxpayer is concerned, they will benefit by obtaining additional mileage of concrete paving for the same money or the same mileage for less money.

QUALITY OF PRODUCT AND RESULTS

After a contractor has constructed his first slip-form project, he should have solved most of the major problems connected with this system of paving. He should become more proficient with each succeeding job and develop his own trade secrets for handling particular job problems relative to such variables as bases, aggregates, mix designs, unusual climatic conditions, grades, transitions, curves, ramp construction, multiple lane construction, plain or reinforced sections, and many others. The experienced contractor can now meet any current concrete paving specification with the slip-form method if he is given the opportunity.

There are still wide differences in specifications for concrete pavements, and there is much to be done in developing uniform requirements and standards throughout the many individual highway departments and other contracting agencies. The new "Guide Specifications for Highway Construction" as published by AASHO in 1964 is a definite step in the right direction to help standardize specifications and eliminate some of the current inequities and unreasonable requirements in some state specifications. Many joint cooperative committee meetings were held with personnel from the Associated General Contractors of America and the American Road Builders Association to review and discuss most sections of the Guide Specifications before they were published. These joint meetings are continuing, and it is hoped that personnel from the newly organized American Concrete Paving Association will be represented on future joint committees on the specific area of concrete paving, and in particular the slip-form method. As contractors, we believe there is merit in utilizing "end result" specifications to a greater extent. Such specifications were largely responsible for the initial impetus and ultimate success of slip-form paving operations on the primary and Interstate highways in Colorado. This was in line with the department's fundamental policy that construction methods should not be written into the specifications, but rather that an end result should be required. Specifications for the quality of concrete and smoothness tolerance of the finished surface were not changed.

EFFICIENCY OF OPERATIONS

The contractor as an individual, and the construction industry in general, are recognized as comprising one of the last strongholds of the American free-enterprise system where initiative and ingenuity are prime factors and are rewarded accordingly. Contractors are constantly searching for more efficient methods, procedures, ideas, and equipment to be used in bidding and in the performance of their construction operations. The slip-form method of concrete paving is an outstanding example. One slip-form paver takes the place of from three to four conventional concrete paving machines in a normal paving train which includes such items as spreaders, finishers, float finishers, and belt and burlap drag machines. Furthermore, we are of the opinion that a better quality of concrete is obtained with this new method, as the possibility of overworking and overfinishing the pavement is greatly reduced. In addition, an average of 10,000 to 12,000 lin ft of steel paving forms and the equipment necessary for their continuous rehandling each day are eliminated. This method also results in a substantial savings in skilled and unskilled manpower. The overall savings in labor will average between 20 and 30 men, of which about 30 percent would be skilled.

With a substantial reduction in the amount of equipment and manpower required for a slip-form operation over the conventional paving operation, the job management problems are greatly reduced. The entire operation is simpler and is confined within a shorter working length, and all elements can be controlled and supervised more effectively. The overall efficiency of a slip-form paving operation is far greater than can ever be obtained from a conventional paving operation with all of its equipment and large crews which must be spread out over at least double the working length required for the slip-form method.

PRODUCTION CAPABILITIES

The slip-form method of concrete paving is quite versatile and is readily adaptable to all types of operations and conditions. This is an important factor from a contractor's viewpoint as it gives him more flexibility in his bidding and work programs. This method of paving can be utilized on small as well as large projects with any thickness of paving from as little as 5 in. to as much as 12 in. The slip-form paver can accommodate and place concrete from any type of source such as concrete pavers fed by dry-batch trucks, transit-mixed concrete, or wet batch from ordinary dump trucks or dump-cretes fed by a central mix concrete plant. With its variable travel speed and vibration controls, most slip-form pavers can accommodate a wide range of average concrete productions from as low as 80 cu yd to as high as 400 cu yd/hr. Based on a paving slab 8 in. thick and 24 ft wide, these concrete production figures can be translated into travel or paving speeds of from approximately 130 to 600 lin ft/hr. From these figures it is quite evident that the current mile-a-day target is well within the range of slip-form pavers, and has actually been exceeded in many instances.

The slip-form paving method has further proven its versatility by its ability to handle mesh reinforcement in concrete pavements. The first of such applications was performed by Roberts-Western in two test sections, each ½ mi long, on I-25 south of Denver, Colo., in 1958. On this project, the mesh was fed directly into the front of the slip-form paver by means of a sled type of mesh placer attached to the paver which was designed and manufactured by the contractor. Similar applications have been made in other states. Currently, there are several Interstate projects in Oklahoma and Iowa where mesh is being installed in 9-in. thick concrete pavements by means of two slip-form pavers. The first slip-form paver, or spreader, spreads the bottom 6-in. lift of the slab to permit placing of the wire mesh. The second slip-form paver follows immediately behind and places the top 3 in. and the outside edges of the concrete slab. This has proven to be a very efficient operation. Other types of machines and methods for handling slip-form paving with mesh reinforcement are currently in the development or trial stages.

CAPITAL EQUIPMENT INVESTMENT

Contractors are vitally concerned with the amount of capital investment required for equipment spreads necessary to perform paving operations. The slip-form method shows up very favorably in this respect. For the average paving project, a conventional spread of paving machines, including forms and the related handling equipment, will require an average investment of from $200,000.00 to $250,000.00. Equipment necessary to perform these same placing operations by the slip-form method will require an average investment of under $120,000.00 or less than one-half. Because of the smaller amount of equipment required on the project, the field repair and maintenance problems are also reduced by a corresponding amount. These two factors obviously have a direct bearing in reducing the contractor's cost of operations which in turn is reflected in his bidding. The reduced equipment requirements inherent in the slip-form method of paving should develop a more favorable ratio of earnings to capital investment, which from a business and management point of view, is desirable. There are now several equipment manufacturers in the field who are aggressively trying to obtain a segment of the slip-form method equipment business. This means that contractors now have a choice of several types of equipment in a competitive market. Such a market encourages the development of better equipment, which in turn will benefit the slip-form method and slip-form contractors.

MANPOWER AND LABOR REQUIREMENTS

The reduced manpower requirements of the slip-form method of paving has many advantages beyond that of lowering the contractor's direct costs. For projects located in sparsely populated or isolated areas, it alleviates the problems of manning the job with an adequate number of unskilled and semi-skilled personnel. Most contractors have a nucleus of skilled workmen who will follow them around the country to most of their projects. In highly unionized areas, the smaller working force will normally result in fewer union difficulties and problems for the contractor's management. In areas of very high labor rates, the reduction in unit labor costs is much more apparent than in the lower labor rate areas. In other words, we can be even more competitive with slip-form methods in the higher labor rate areas.

COMPETITIVE POSITION

As paving contractors, we are vitally interested in our competitive position in order to bid and perform work successfully. Maintaining adequate markets for concrete paving work is also essential if we are to continue in business. The slip-form method of concrete paving helps to achieve both of these objectives because the basic costs and bid prices are lower. In addition, the overall operations are more efficient on almost all types and geometric designs of concrete pavements including the following:

1. Main line pavements usually 22, 24, or 25 ft in width (in some cases, even as wide as 36 ft) and of any thickness from 5 to 12 in.;
2. Most ramps with uniform widths of 14, 16, and 18 ft, including both straight and curved sections (curved sections currently limited to those with a working radius of at least 300 ft);
3. Sections of pavement with certain types of integral curb (some sections, however, still subject to the unrealistic limitations imposed by geometric designers in engineering offices); and
4. Multi-lane construction such as 36 or 48 ft in total width.

As the result of improved paving efficiencies, lower costs, and lower bid prices, the overall market for concrete paving should increase. Also because of improved efficiencies and greater economies, concrete paving should now receive more favorable consideration when alternate types of paving are being selected for particular projects or programs.

CONTRACTOR'S SUPERVISORY PERSONNEL

How do the contractor's supervisory personnel react and make the transition from the conventional to the slip-form method of paving? As far as our company is concerned, the transition was made without any difficulty. In most cases, the slip-form method was accepted with enthusiasm, even by some of our senior foreman and superintendents who had been paving with forms for over 25 yr. After the first experience with slip-form methods, no further selling is needed within a contractor's organization. Other contractors have reported similar results and experiences.

A CHALLENGE

Speaking on behalf of most of the slip-form paving contractors in this country, I can make the following statements with respect to the slip-form method of concrete paving.

1. We can meet and comply with any current concrete paving specifications or requirements as far as end results are concerned.
2. We can produce quality concrete paving more efficiently and economically than by any other current method.
3. We can place concrete paving at any desired rate of speed up to 600 lin ft/hr, to accommodate a wide range of production from current concrete plants.
4. A wire grade control system is not considered essential for obtaining smooth pavements with slip-form pavers if the base courses are constructed and fine-graded to the proper tolerances. Electronic grade control systems should be utilized in the fine-grading and trimming operations of the base course underlying the concrete paving.
5. Universal acceptance and use of the slip-form method of concrete paving will result in more miles of paving for the same dollars and an increasing market for concrete pavements.

A FORECAST AND A HOPE

As contractors, we are predicting that the slip-form method of concrete paving will become the accepted standard for all highway departments and contracting agencies in the United States by 1970. There will, of course, be some minor exceptions. According to information received from some of the equipment manufacturers, they are already exporting slip-form paving equipment to Europe and South America, where this method is also beginning to attract attention and is being accepted.

As contractors, we are looking forward to the day when we can actually say—"Goodbye Forms."

Slip-Form Today and Tomorrow

HAROLD J. HALM, Paving Bureau, Portland Cement Association

The latest slip-form paving developments and techniques are discussed and illustrated. Among these are the compatibility of slip-form pavers with central-mixed concrete and the most recent technique of using two slip-form pavers to construct concrete pavements having mesh dowel designs. New equipment and recent modifications to current slip-form pavers are also described in order to present the latest results of research and development by all slip-form manufacturers.

Equipment manufacturers, contractors, and highway engineers predict that within a few years slip-form paving will be the standard method of concrete pavement construction. In only 15 years, the slip-form paver has proved itself.

•THE SLIP-FORM TECHNIQUE is no longer experimental. The acceptability and advantages of this method of concrete pavement construction have been proven. The future looks bright. The most significant breakthrough has occurred this year with the use of slip-form in several states where mesh dowel designs are required. Slip-form had not generally been accepted in states employing mesh dowel designs. However, in the past construction season, Oklahoma and Iowa awarded Interstate contracts which permitted the contractor to use slip-form equipment with pavements having a design of mesh and dowels.

The first project was constructed in Oklahoma on I-40 by Brooks and McConnell Construction Co. of Oklahoma City. Two Rex slip-form paving machines were used in tandem to pave 5 mi of dual 24-ft wide, 9-in. thick concrete pavement (Fig. 1). The lead slip-form paver struck off the 6½-in. bottom course of concrete dumped on the grade in front of the machine by a Koehring dual-drum and a tribatch mixer (Fig. 2). The frame of the lead slip-form machine carried the mesh, which was simply pulled off by laborers and dropped into place on the surface of the bottom 6½-in. course (Fig. 3). Offsets, 2 in. thick, were attached to the inside of the sliding forms. This 2-in. reduction in width on each side permitted the second slip-form paver to clear the edges of the bottom course with ease.

The rear machine was a conventional Rex slip-form paver (Fig. 4). A dual-drum paver deposited concrete on top of the mesh in front of the second paver. The 2½-in. top course, plus the filled-out bottom course, was thoroughly vibrated and extruded to a smooth 9-in. thick, full 24-ft wide pavement (Fig. 5).

A similar project was constructed in Iowa on I-80 by the Fred Carlson Construction Co. (Fig. 6). This was the first Interstate slip-form paving in Iowa. Although Iowa pioneered slip-form paving and has more than 1,000 mi of slip-form concrete pavement, this was the first project requiring mesh reinforcement. The only differences between the Oklahoma project and the Iowa project were the following.

1. Iowa's pavement was 10 in. thick.
2. Oklahoma used a sand-asphalt subbase; Iowa used a crushed stone subbase. The Iowa contractor had to stabilize the crawler track path to eliminate tearing up the subbase in front of the tracks of the second slip-form machine.
3. In Oklahoma, the mesh was carried on the frame of the first machine; in Iowa it was stacked along the right-of-way and carried in from the shoulder.

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Figure 1. Two Rex slip-form pavers in use on I-40 in Oklahoma.

Figure 2. Koehring dual-drum and tribatch mixers placing concrete in front of first slip-form paver on I-40.

The Quad City Construction Co., the pioneer of slip-form paving in Iowa, developed its own spreading device coupled with a new Rex slip-form paver and central mix plant to pave its contract on I-80 in eastern Iowa (Fig. 7). A 45-ft section of heavy specially shaped form was fastened to the front corners of the slip-form machine (Fig. 8). A split, reversible screw spreader mounted on crawler tracks and guided by the 45-ft form sections struck off the concrete for the first course. The crawler-mounted screw spreader was self-propelled and could move forward or backward within the 45-ft length of guide forms.

This operation required close coordination between dumping the central-mixed

Figure 3. Mesh carried by front paver.

concrete and operating the screw spreader and slip-form paver. It permitted the contractor to strike off the concrete for a full 24-ft width and kept the distance between the first and second course of concrete to 45 ft or less.

The mesh was laid out on the subbase ahead of the paving operation (Fig. 9). Laborers passed the sheets of mesh over a series of bars on the screw spreader so that the mesh was placed directly on the struck-off first lift of concrete. A total of 21 mi of four-lane divided Interstate pavement was placed in Iowa in 1964 by this method.

Oklahoma to date has had nine projects requiring mesh and dowels built with the slip-form paver. Five contractors have built these nine jobs totaling 37 mi of four-lane Interstate pavement. Of special interest is the progressive reduction in unit cost as contractor experience was gained for this type of construction. This 9-in. pavement, including mesh and contraction joints at 61.5 ft, was first bid in September 1963 at \$4.37/sq yd. The last four jobs were all less than \$4.00/sq yd, with the lowest at \$3.78.

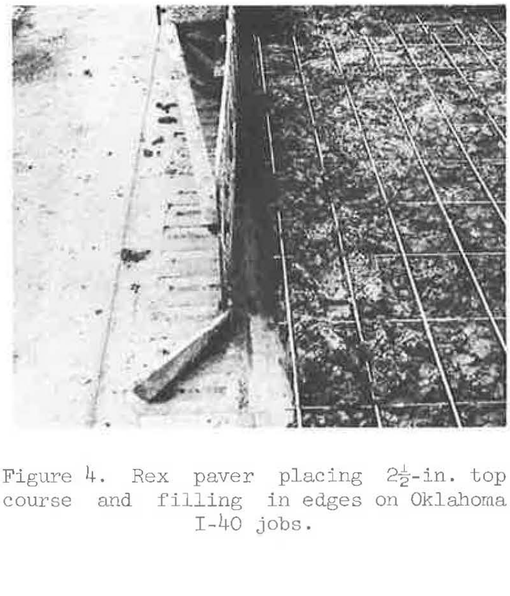

Figure 4. Rex paver placing $2\frac{1}{2}$-in. top course and filling in edges on Oklahoma I-40 jobs.

The versatility of slip-form is becoming more apparent. The Peter Kiewit Sons Co. paved not only the main line but also the ramps on one of its projects in Wyoming this past summer, using a Rex slip-form paver (Fig. 10). A Guntert-Zimmerman slip-form paver was also used in Wyoming to pave ramps on I-25. Roberts and Western Co. successfully placed integral-curb ramps with its Rex machine on an interchange of the Pioneer Expressway near Lawton, Okla.

Texas is having success with slip-form on the state's continuously-reinforced Interstate projects. Texas contractors are building a smoother pavement with slip-form methods than they were able to obtain with formed construction.

The only airfield paving to use slip-form pavers in this country was at Hillgrove Airport in Providence, R.I., in 1958, when the circular parking apron was paved. The apron is 1,300 ft long

Figure 5. Finished slab on twin slip-form project, I-40.

and 300 ft wide, 8 and 10 in. thick. France has had more experience with airfield construction for multiple-lane paving using slip-form paving equipment. Last summer at a completely new airport project near Brest, France, the Rex slip-form paver was used to pave multiple lanes for the main runway, the secondary runway, taxiways, and parking aprons. A Guntert-Zimmerman slip-form paver was used to pave a new taxiway at Orly Airport, Paris. These machines had previously been used successfully on highway pavements in France.

It is no longer an uncommon sight to see a 36-ft wide pavement being slip-formed in one pass without side forms. Contractors using the Guntert-Zimmerman slip-form paver like the cost savings of being able to make one pass rather than two on a 36-ft pavement (Fig. 11). Many of these pavement designs have the two outside lanes 9 in. thick and the inside lane 8 in. thick. The 1-in. difference is built into the cement-treated subbase and subgrade. These 36-ft slip-form pavers are compatible with 34E pavers, central-mixed concrete hauled in conventional dump trucks, and, most recently, truck-mounted mixers carrying 7½ cu yd and capable of discharging in less than 60 sec (Fig. 12). These truck-mounted mixers (ready-mix trucks) are designed to handle low-slump paving concrete.

Figure 6. Paving I-80 in Iowa with two Rex slip-form pavers.

Figure 7. Device developed for paving I-80 project in Iowa.

Figure 8. Special 45-ft length of form to guide crawler-mounted screw spreader.

Figure 9. Placing mesh on first lift of concrete.

The electronic control devices have resulted in grade accuracy and surface smoothness never before attained. At the same time, overruns are kept to a minimum. The same guide wire can be used to trim the subgrade, finish the subbase, and control the pavement elevation.

Some of the excellent riding pavements being built with the slip-form are constructed without the aid of trailing side forms or without hand finishing behind the machine (Fig. 13). One of the main advantages of slip-form paving is that the concrete is confined into its final form at high densities within a comparatively small space and requires only a minimum, if any, manipulation of the surface of the slab behind the slip-form. Any additional working of the surface of the slab behind the slip-form machine only produces a less durable concrete surface.

There are now several new manufacturers entering the slip-form paver market. The trend is toward some form of automatic guide wire control and machines capable of up to 36 ft.

The Koehring-Johnson slip-form paver has been under development for several years. In 1963, an experimental model paved a city street project in Green Bay, Wisc., and a 4½-mi highway project in Oklahoma (Fig. 14). As a result of this experimental work, the machine was redesigned and a production model will soon be available. This production model was tried out on several test slabs at the L. S. Johnson plant in Champaign, Ill., in late 1964 (Fig. 15). The paver has electronic controls for alignment, surface elevation, and cross-slope, all controlled from a single wire.

The R. A. Hanson Co., having considerable experience with slip-form canal lining and concrete pipe equipment, developed a slip-form paver which operated in California

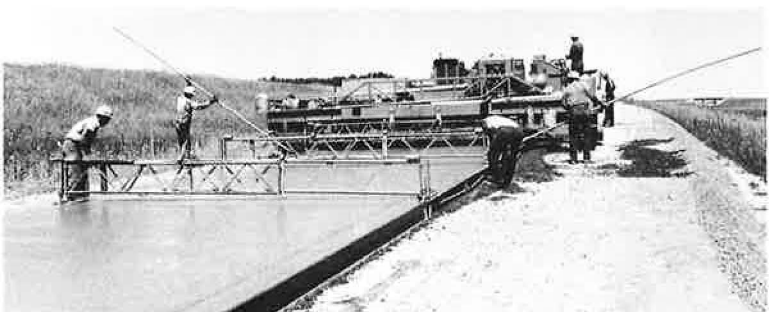

Figure 10. Ramp being paved in Wyoming with Rex machine.

Figure 11. Owl Slip-Form Concrete Co. paving I-10 in southern California with 36-ft Guntert-Zimmerman paver.

Figure 12. Central-mixed concrete hauled in dump trucks feeding 36-ft Guntert-Zimmerman slip-form paver.

Figure 13. Twenty-four-foot Guntert-Zimmerman paver operating in California with pipe drag in lieu of conventional hand finishing.

Figure 14. Koehring-Johnson experimental slip-form operating in Oklahoma in 1963.

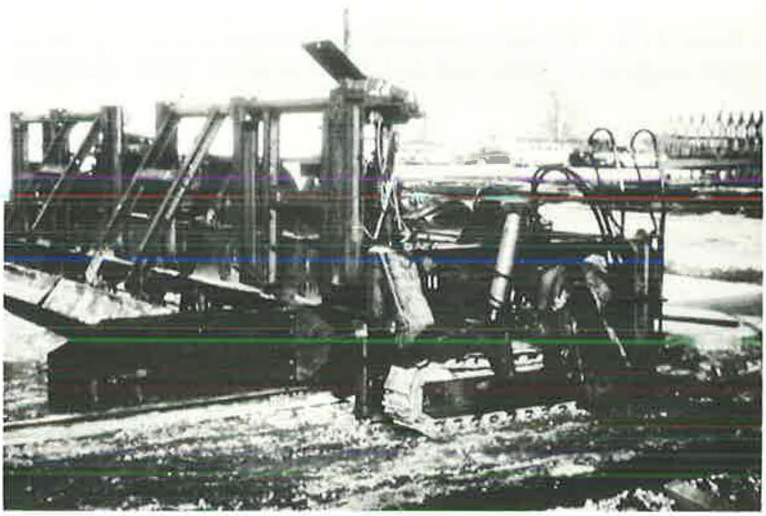

Figure 15. Koehring-Johnson production model on test pavement.

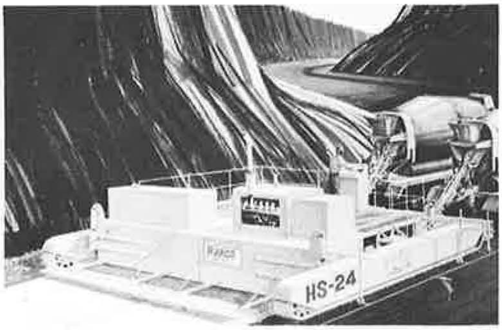

Figure 16. Drawing of HS-24 slip-form paver used in California.

Figure 17. Blaw-Knox slip-form paver operating on ditch invert in southern California.

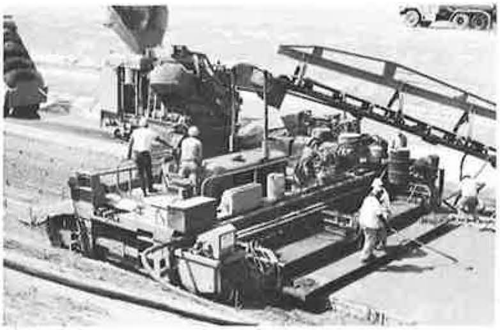

Figure 18. Rear view of Blaw-Knox paver.

this past construction season (Fig. 16). The Hanson paver, known as the HS-24, uses airtrol automatic control for grade and level.

Another slip-form paver, which was introduced for the first time in California this past season, is manufactured by the Blaw-Knox Co. (Figs. 17 and 18). Blaw-Knox has four slip-form pavers in California. These machines have placed both 24- and 36-ft pavements. The machine, according to the manufacturer, can be converted to 12, 24, 36 or 48 ft in about 4 hr. It has a paving speed of up to 20 ft/min and a traveling speed of 60 ft/min.

The slip-form future looks bright indeed. Complete automation is removing the element of human error to produce smoother, more durable concrete pavements at greater economies than ever thought possible.