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

L. R. GILLIS and L. S. SPICKELMIRE
Respectively, Assistant State Highway Engineer and Assistant Construction Engineer, California Division of Highways

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

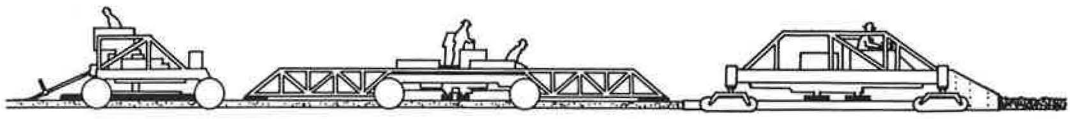

Figure 1. Multiple screed slip-form process.

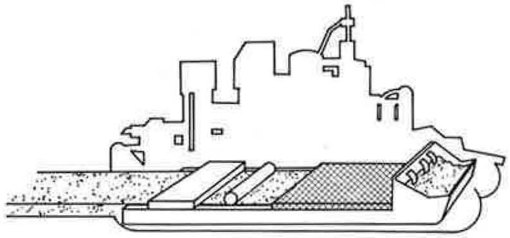

Figure 2. Conforming screed slip-form process.

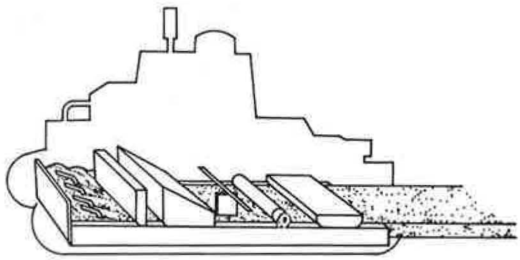

Figure 3. Pressure meter slip-form process.

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;

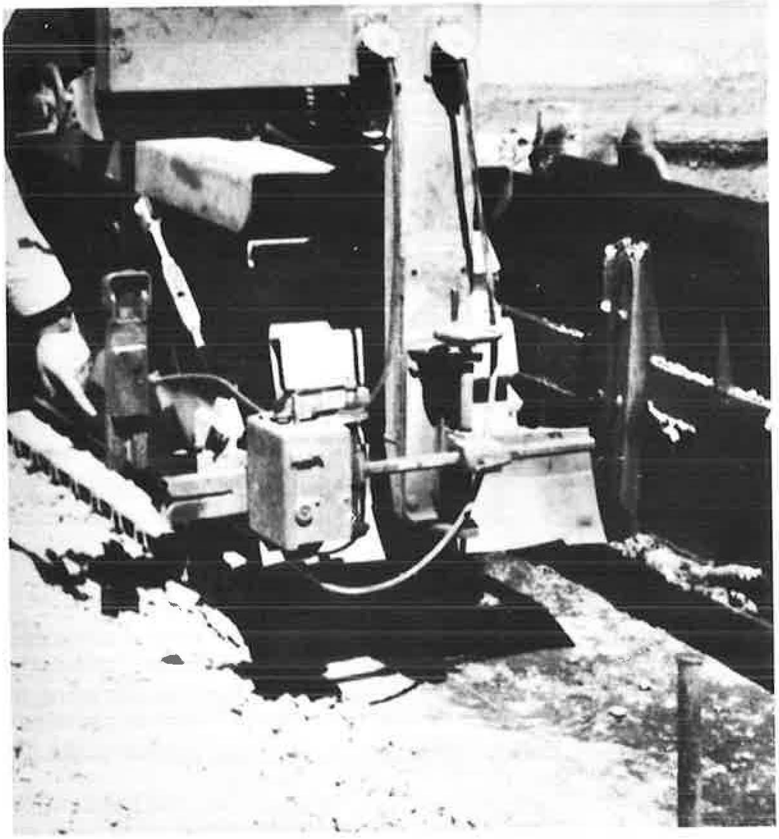

Figure 4. Grade and alignment sensors.

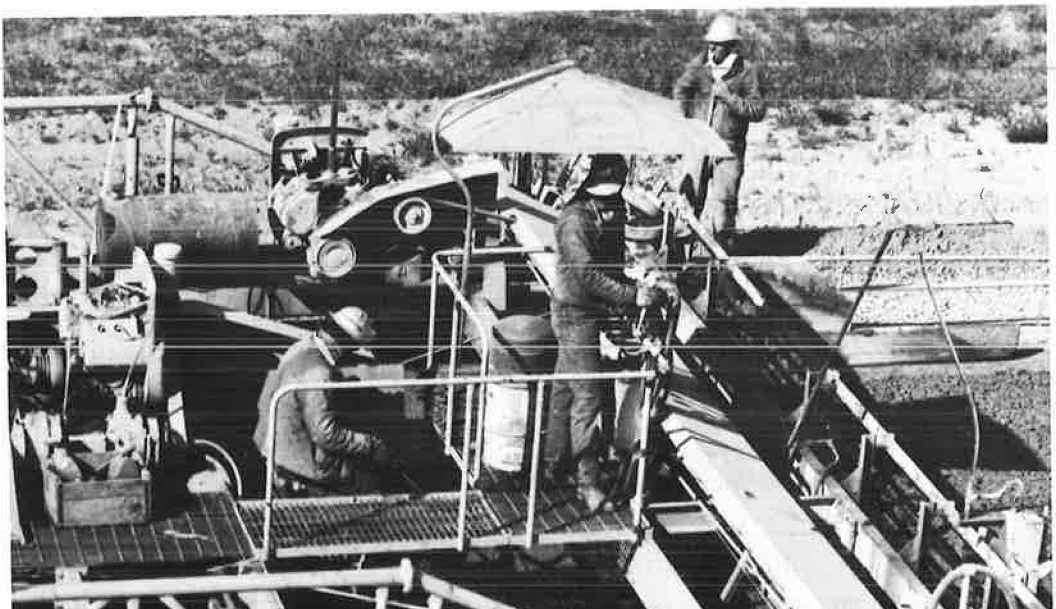

Figure 5. Plumb-bob and string line used for manual steering.

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.

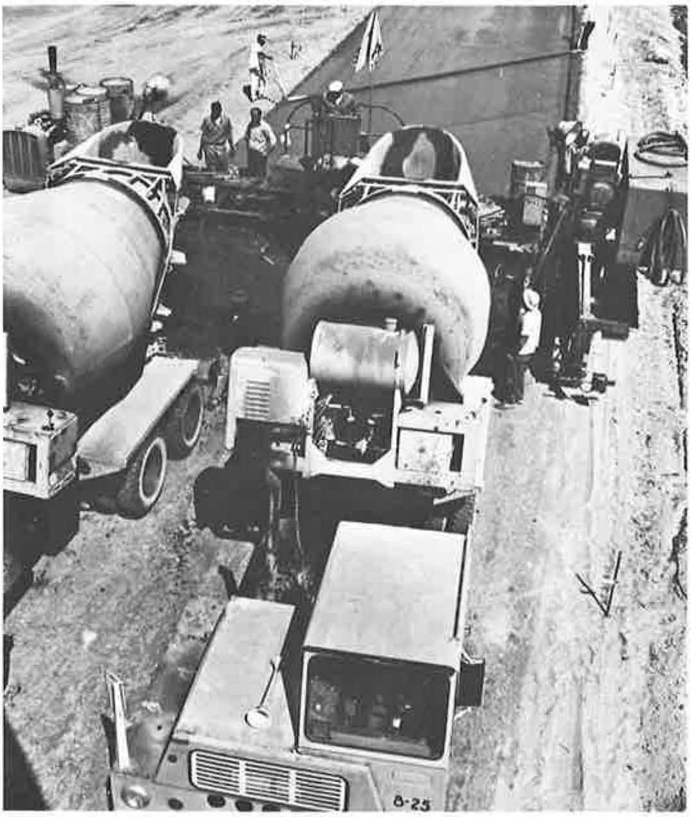

Figure 8. Tilt-drum truck mixers and slip-form paver.

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

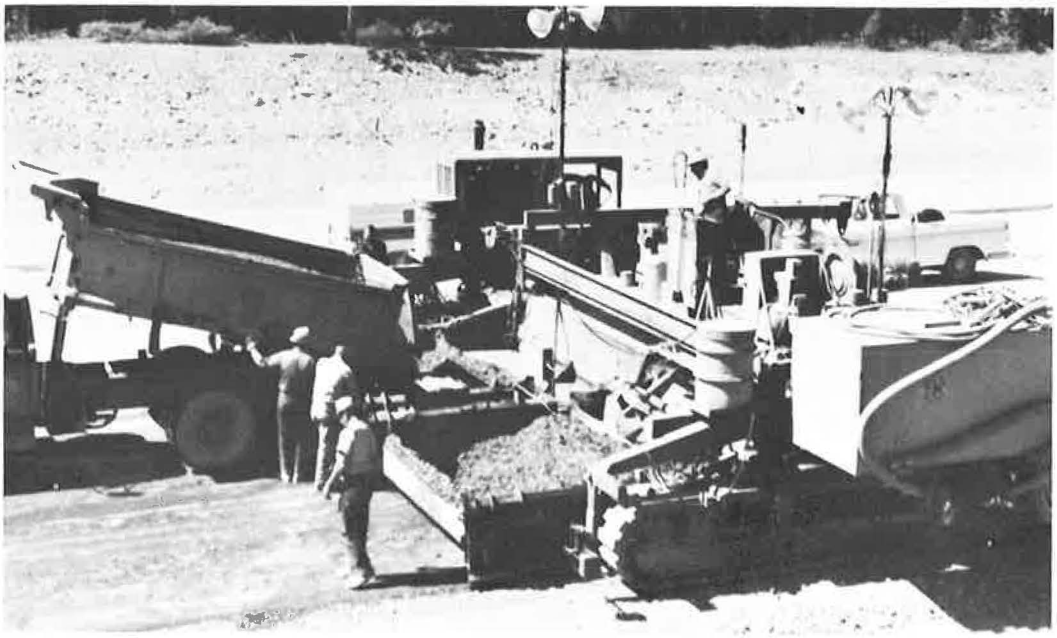

Figure 9. Sliding front plate on slip-form paver.

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.

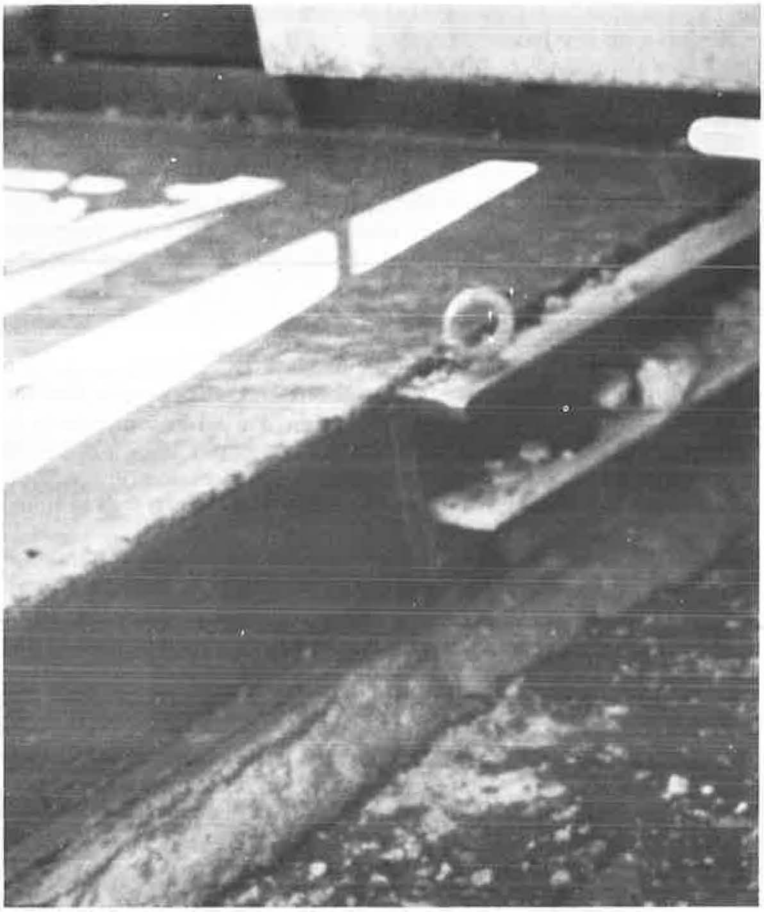

Figure 11. Pavement edge immediately behind side forms.

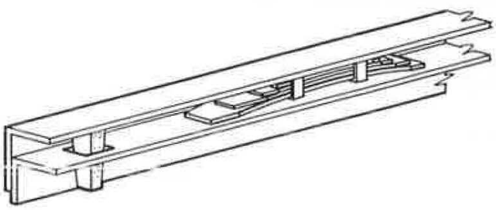

Figure 12. Spring-loaded side forms.

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.

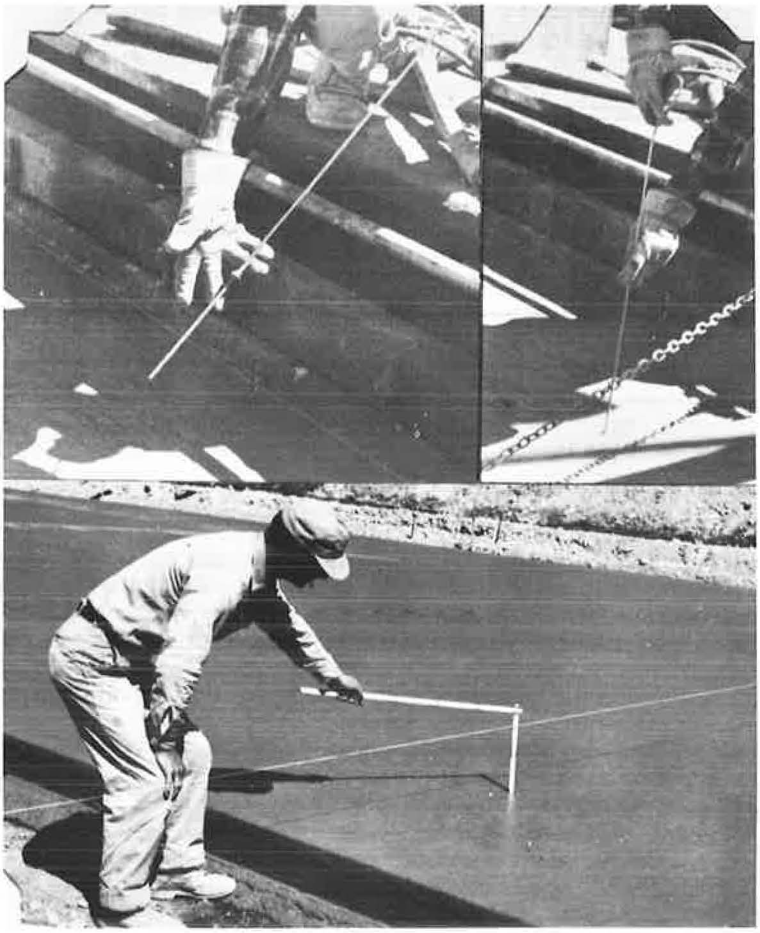

Figure 13. Pavement thickness measurement by stabbing.

FINAL FINISHING

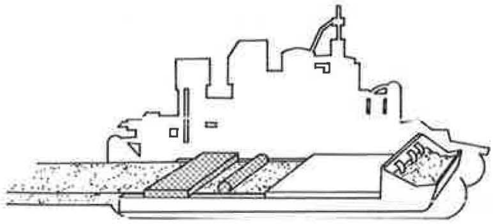

Figure 14. Rotating screed and pan float arrangement.

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).

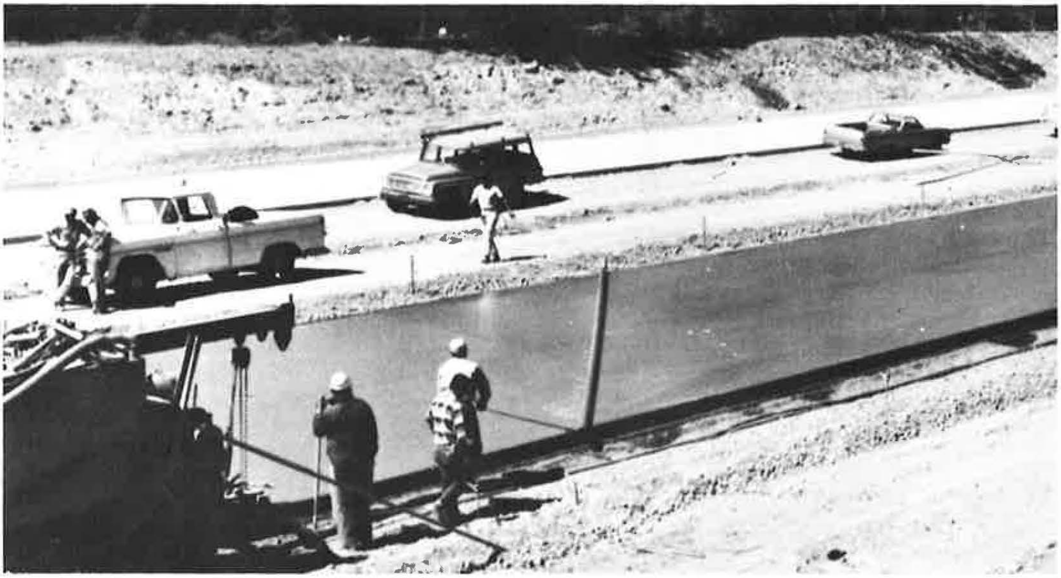

Figure 15. Pipe float procedure.

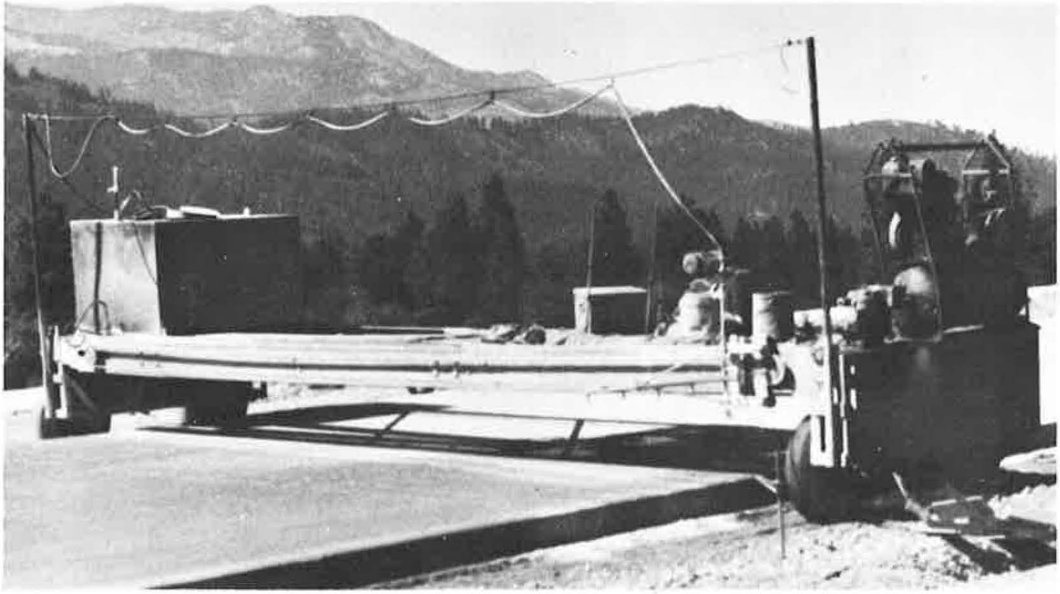

Figure 16. Curing compound application.

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

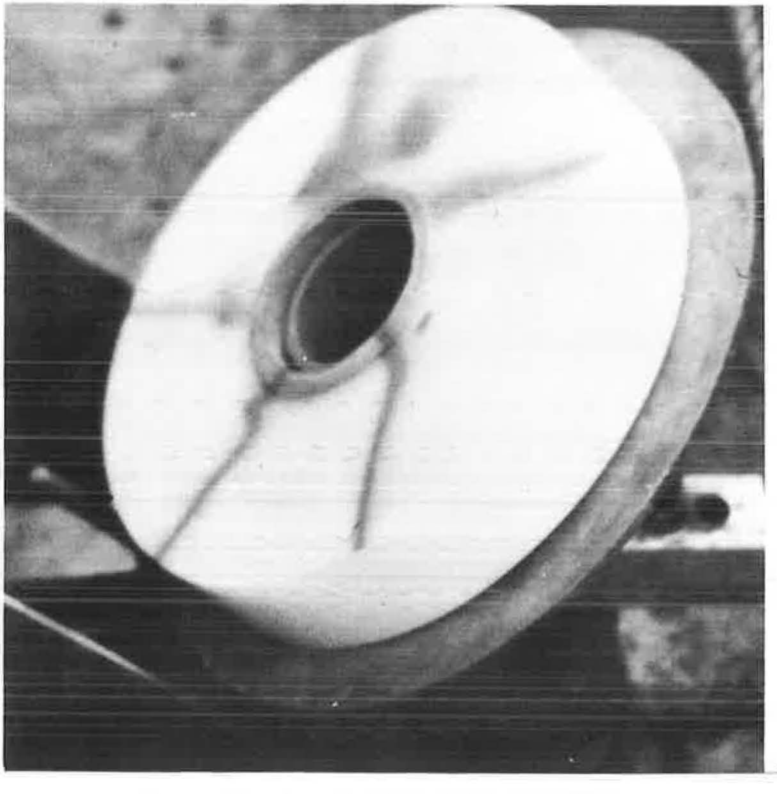

Figure 17. Longitudinal joint installer.

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

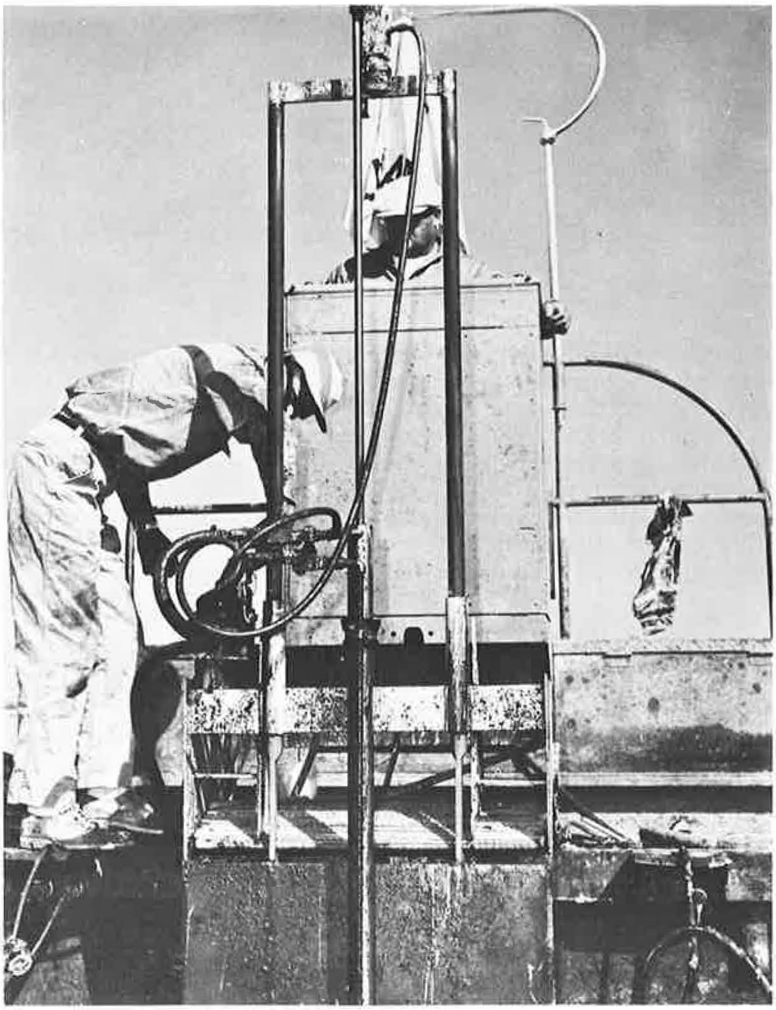

Figure 18. Tie bar installer.

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

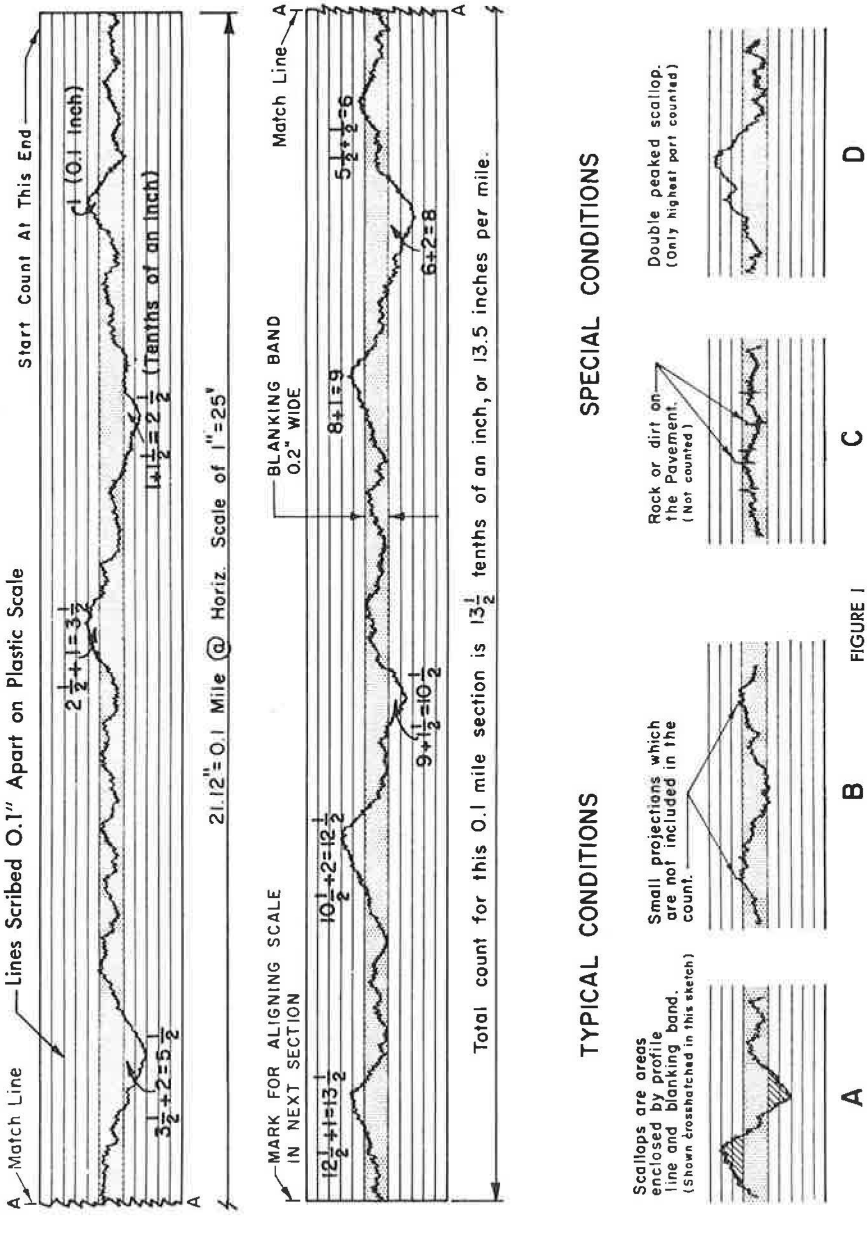

FIGURE I

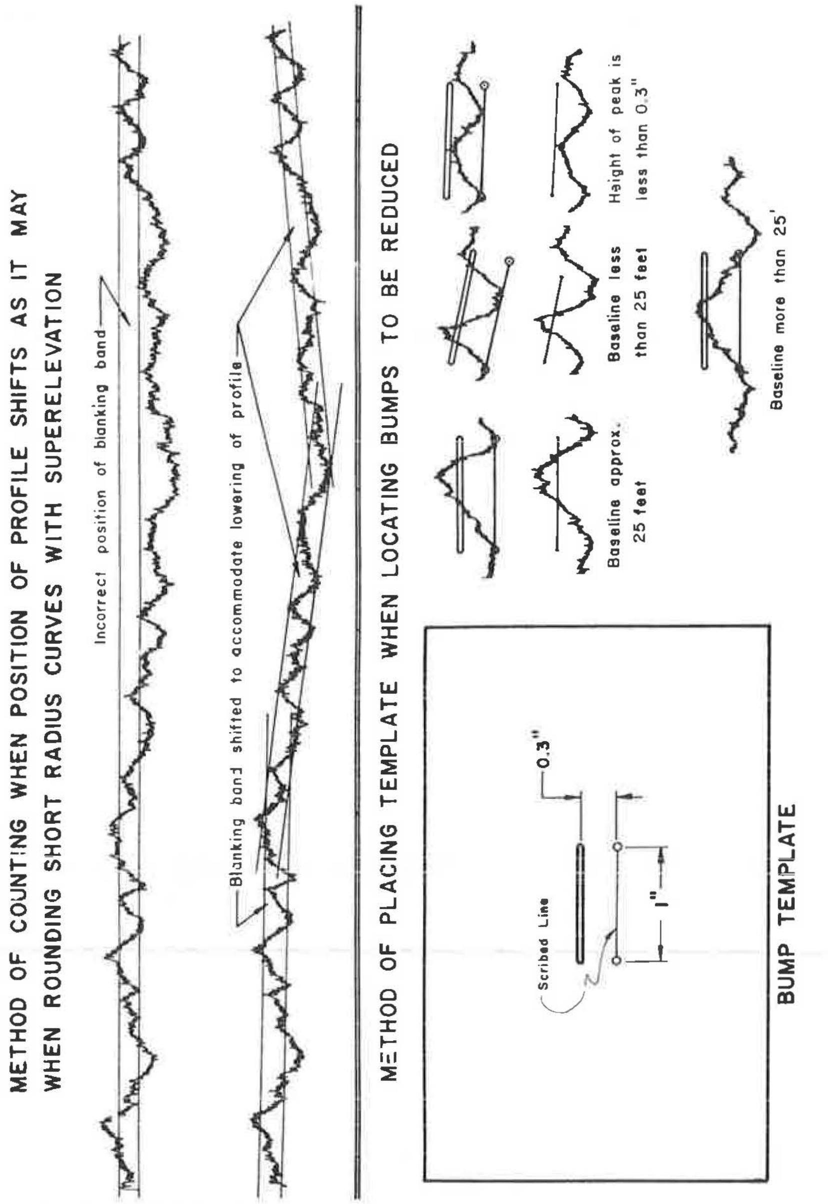
METHOD OF COUNTING WHEN POSITION OF PROFILE SHIFTS AS IT MAY
WHEN ROUNDING SHORT RADIUS CURVES WITH SUPERELEVATION
Incorrect position of blanking band
Blanking band shifted to accommodate lowering of profile
METHOD OF PLACING TEMPLATE WHEN LOCATING BUMPS TO BE REDUCED
Baseline approx. 25 feet
Baseline 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