Technical Report Documentation Page

1. REPORT No.

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE

Slip Form Paving in the United States

5. REPORT DATE

September 1966

6. PERFORMING ORGANIZATION

7. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

State of California
Division of Highways
Sacramento, California, U.S.A.

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

13. TYPE OF REPORT & PERIOD COVERED

12. SPONSORING AGENCY NAME AND ADDRESS

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Summary

This paper presents a broad review of the history and development of equipment and procedures now being used in the United States to place Portland Cement Concrete paving by slip form methods. Early experimental trials were started twenty years ago, but development was slow until less than ten years ago. In the past five years, use of these methods has accelerated rapidly.

Today there are some seven different manufacturers producing slip form paver machines, operating on considerably varying principles, but all of them possessing the ability to produce quality results when properly handled. Concurrent development of high production, very mobile central mix plants, and other related equipment have increased production quantities to a much greater extent than was dreamed of only a few years ago.

This new equipment, with its more sophisticated electrical and mechanical components, has given the contractor and field engineer numerous problems to solve. A need for accuracy in constructing subgrade under the pavement, uniformity of the concrete mix, installation of reinforcing steel, compaction of the mix, and adequate pavement smoothness are a few of these problems. With well-trained and experienced personnel, contractors are conquering these problems and are providing a result which is superior in quality to that realized under previous conventional methods and at costs which are estimated to range from 20 cents to $1.00 per yard less than they would be today if these new methods and machines had not been developed.

17. KEYWORDS

18. No. OF PAGES:

21

19. DRI WEBSITE LINK

http://www.dot.ca.gov/hq/research/researchreports/1966-1967/66-51.pdf

20. FILE NAME

66-51.pdf

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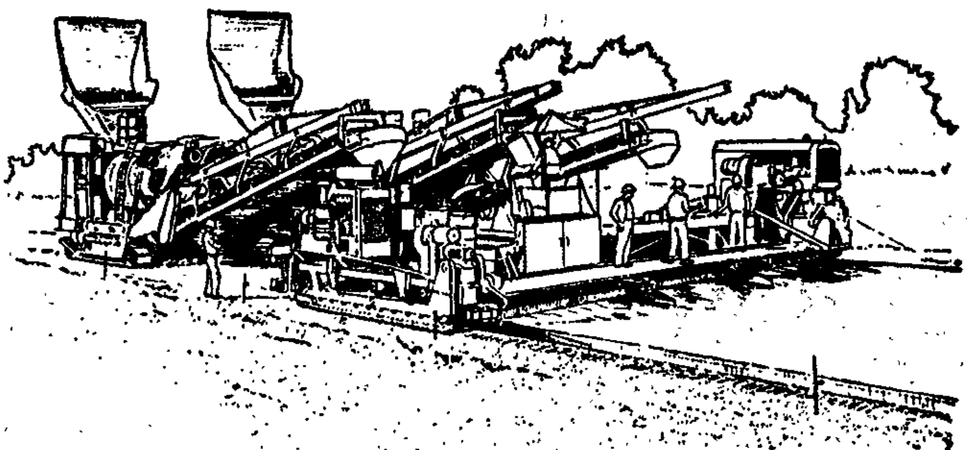

FOR PRESENTATION TO

FIFTH WORLD MEETING

INTERNATIONAL ROAD FEDERATION

LONDON, ENGLAND-- SEPTEMBER 18-24, 1966

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SLIP FORM PAVING IN THE UNITED STATES

Introduction

With annual expenditures for highway construction in the United States reaching $7 billion this year and with costs of labor, materials and equipment steadily rising, a real challenge has been placed on the shoulders of the team composed of highway engineers, highway and heavy construction contractors, and equipment manufacturers to develop new and improve old methods of construction in order to give the traveling public the greatest return for the funds invested in new highways.

A review of cost indexes for various types of construction during the past few years indicates that this team has done a very respectable job. Unit prices for highway work have generally increased at a considerably lesser rate than most other categories of construction. During an 8-year period in which over-all construction costs in the United States rose approximately 30%, the unit prices for highway work showed only about a 10% increase and the cost for surfacing items remains almost no higher than it was eight years ago. This favorable cost picture for surfacing of highways is realized for several reasons, but a very important one relates to the subject of this paper -- the development of slip form methods of placing Portland Cement Concrete pavement.

It might now be said that slip form methods of concrete paving have "come of age". To date, some 25 of our 50 states have permitted slip form methods on at least one project. Altogether, nearly 70 million square yards of slip-formed pavement has been placed on various Interstate, primary and secondary routes throughout the United States. This nearly ten thousand lane miles of concrete highway pavement can be said without question to be the finest and most economical ever built. It has been conservatively estimated that some $34 million has been saved to the highway taxpayers because of slip form developments.

It is the purpose of this presentation to review the history of the development of slip form paving, briefly describe the most commonly used equipment, discuss various procedures, techniques, and to summarize the benefits.

In the preparation of this paper the author has drawn heavily on the knowledge and experience of others, both written and verbal. There is attached a list of reference publications but in addition, I have reviewed the subject with numerous engineers, contractors and equipment manufacturers, both informally and in connection with various meetings of professional or industry organizations. I would particularly refer to a report prepared by Mr. L. S. Spickelmire, our Assistant Construction Engineer, and me, for inclusion in a German concrete yearbook soon to be published by Bundesverband der Deutschen Zementindustrie--E.V., Germany. Mr. Spickelmire gathered an enormous store of valuable information in the preparation of this report and I have drawn heavily on this information and his thorough knowledge of the subject.

It will be noted in the following text that trade or manufacturers' names are given for the various slip form paving machines. This infers, and properly so, that these firms played an important part in the development of slip form paving to its present state of art. I have not mentioned, however, for several reasons, the names of many fine contracting firms in California and other states whose ingenuity and willingness to experiment have also contributed very materially toward today's high quality product.

History: Development and Description of Slip Form Pavers

To many, the term slip form paving refers only to a method of placing Portland Cement Concrete pavement without the use of side forms to retain edges. It will be seen, however, in the discussions of development of various types of equipment that slip form paving has become an entirely new approach and connotes a great deal more than mere absence of side forms.

Undoubtedly, the most distinctive characteristic of slip form paving methods, other than the manner in which the pavement edges are formed, is the process by which a pavement surface is shaped to final cross section and profile. There are, in fact, five different processes by which slip form pavers establish the upper plane of a pavement and they characterize the type of paver used. With one exception, each process is essentially different from any used in conventional side form paving. Some of the significant features of these five processes will be described in connection with the chronology of slip form paver development which follows. They are illustrated by the schematic diagrams appearing in Figures 1 and 2.

It is reported that credit for the idea of slip form paving should go to three engineering employees of the Iowa State Highway Commission and dates back to 1946.

Except for some experimental work, no actual pavement was placed until three years later when Mr. James W. Johnson, an Iowa testing engineer, arranged for construction of a one-half mile section of highway, 6 inches thick and 20 feet wide placed in two 10-foot wide slabs. This first project was performed by day labor but another similar size job was done later in the same year by contract. These two projects, though crude in comparison to today's operations, did conclusively indicate the feasibility of the methods.

Quad Cities and Rex Pavers

Little more was accomplished for some five or six years, when in 1955 the Quad Cities Construction Company of Rock Island, Illinois, developed a greatly improved paver. This machine was wide enough for 2-lane pavement and propulsion was effected by two long crawler track assemblies.

Otherwise, this machine operated on the same basic principles originally developed in Iowa. These principles are similar to those explained later for the Guntert-Zimmerman machine except that screed position is not regulated by automatic controls. With the availability of this equipment, its use spread, with 28 miles of 2-lane pavement being placed in Iowa during 1955 and several other states permitting its use.

In 1958, the Rex Chain Belt Company of Milwaukee, Wisconsin, took over the interests of the Quad Cities Equipment Company and produced essentially the same machine. During the next six years, a number of improvements were effected in design and construction of this paver, such as moving the side forms from 7½-degree outward incline to vertical, adding a power-driven longitudinal strike-off blade immediately ahead of the main screed to prevent a tendency to rise on irregular piles of concrete, addition of a tamper bar at the leading edge of the main screed and an oscillating belt finisher.

During this period, improvements in procedural controls to minimize nonuniformity in concrete mixture and to lessen subgrade irregularity improved the end results. Last year the Rex Chain Belt Company introduced a completely new model with optional automatic controls for steering and grading, as well as other improvements.

Guntert-Zimmerman Paver

The second slip form highway paver was developed in California during this same period by the Guntert-Zimmerman

Construction Division, Inc., of Stockton, California. This machine was an adaptation of one used to slip form concrete lining in large irrigation canals.

The Guntert-Zimmerman paver was involved in an experimental section on one of our highways in 1956 but because of very rigid and unrealistic limitations imposed, the project was not conclusive. It was not until late 1959 that an attempt was made at a true slip form project using this machine which has subsequently been utilized by contractors on a large portion of the slip form paving in California.

The basic process utilized in the Guntert-Zimmerman paver consists of molding plastic concrete mix to desired cross section and profile under a single relatively large conforming screed. This is accomplished by maintaining a full width and 6 feet long, (3 feet on Rex Paver) dead screed at predetermined elevation and cross slope with hydraulic jacks that are actuated through an automatic control system which is referenced to offset pre-erected grade lines for each pavement edge. A concrete mix is delivered to a forward open bottom hopper and then liquified by intense high frequency internal vibration so that it flows into and completely fills the space formed by the conforming plate, the sliding side forms and the underlying subgrade.

Behind the conforming screed, an optional rotating Clary-type screed may be placed. Its function is to cut away any excess concrete and carry a slight amount of grout for filling any tears or other imperfections. This screed is followed by a finishing float.

A Guntert-Zimmerman paver was the first to utilize full automatic control. The sensing devices are actuated by use of taut piano wires which are set with precise reference to both the horizontal and vertical positions of each edge of pavement. This machine was originally constructed in two 12-foot modules for nominally paving 24-foot width pavements but could cut down to 12 feet to widen a 24-foot pavement to 36 feet. Some five years ago this machine was successfully used to pave 3 lanes at a time. Very recently, further modification has permitted 48-feet wide pavement in one pass to be a successful reality.

Lewis Paver

A second paver developed in California and known under the name of "Lewis" and manufactured by Concrete Machinery Ltd., of El Monte, is actually a modification of their side form finisher which employed two oscillating screeds suspended near the mid point of a trussed frame. In converting this machine to slip form use, flanged wheels were replaced by four independent track assemblies. A strike-off screed, vibrators, and towed V-shaped ironing screed were also added. Automatic controls were not provided, with both steering and elevation being handled manually.

After numerous modifications to the screeds and other parts, the Lewis machine has become a successful competitor to other makes. These modifications included the use of a lightweight hand drawn diagonal pipe float long enough to extend from one edge of the pavement to the other. While this only partially corrected original problems with this machine, the pipe float was successful in drifting a small roll of grout over the pavement and filling small imperfections for a more tight-knit and uniform surface appearance. For these reasons it was adapted by many contractors using other types of slip form pavers. Additional changes to the Lewis machine involved different types of towed and self-propelled secondary finishing machines to replace the full width V-type float on the paver itself.

Koering-Johnson Paver

The next equipment manufacturer to enter the slip form paving field was C. S. Johnson Company of Champaign, Illinois. This firm introduced a prototype on an Oklahoma State Highway project in the spring of 1963. This first model was actually equipped with an integrated subgrade trimmer in the front with the concrete being mixed in an on-site paving mixer and placed with a belt conveyer. This combination paving unit was equipped with a system of automatic controls for steering and maintaining the proper elevation and cross slope of screeds.

Subsequent production models have varied somewhat from the prototype and differ from other makes in several respects. The integrated subgrade trimmer has been eliminated. It may be purchased either with or without automatic controls. These controls differ from the Guntert-Zimmerman in that they utilize a single erected grade line supplemented by an internal cross slope reference rather than erected grade lines on each side. Provisions for shaping the pavement differ in that reliance is placed on successively metering through the action of several strike-off devices positioned ahead of a relatively small main screed. Operational usage of this production model to date has been very limited.

RAHCO Paver

During 1964 two additional manufacturers introduced slip form pavers: The R. A. Hansen Company of Tuloose, Washington, and the Blaw-Knox Company of Matoon, Illinois. The Hansen Company had for several years been active in producing slip form paving equipment under the trade name RAHCO for lining canal and river channels. The RAHCO paver incorporates a complete automatic control system referenced to erected grade lines at each side and an entirely different mechanical process for shaping the pavement section in lieu of the conforming screed used by Rex and Guntert-Zimmerman or the oscillating screeds by Lewis. The RAHCO utilizes an integrated strike-off screed and pressure plate arrangement that functions as an automatic pressure meter. Behind this assembly a counter rotating Clary-type screed is used to establish the final profile. The use of this paver has been somewhat limited to date.

Blaw-Knox Paver

The Blaw-Knox slip form paver, which also was initially used for canal lining, was first tried as a highway paver on a piece of Interstate Highway System in northern California. This paver compacts and shapes final pavement sections by mechanical processes that are essentially similar to those employed by Guntert-Zimmerman. The automatic controls referenced to erected grade lines at each side are also similar but the structural elements and the hydraulic and electrical controls vary quite a bit.

Other Pavers

Contractors in California and throughout the United States have been aggressive in developing their own modifications to many of these machines to improve results. A Blaw-Knox machine with contractor modification was the first to successfully pave 4 lanes at a time. This same machine recently set a record of one mile of 4-lane pavement in one day. Even though the normal shift was extended to about 12 hours, this is still a formidable record with over 7000 cubic yards being placed. The inner 2 lanes were 8 inches thick and the outer lanes 9 inches thick.

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Undoubtedly, additional manufacturers will continue to enter the field. The latest one reported is the Heltzel Steel and Iron Form Company of Warren, Ohio.

This discussion of the history and development of the various makes of pavers clearly indicates that it took a good many years to receive anywhere near general acceptance. This is probably not unusual. This kind of change required not only major retooling and investment by a large industry but also acceptance by the highway engineer charged with being certain of the quality of the finished product. This acceptance showed a big upswing in 1963 (see Figure 3) to the point where now these methods have actually been performed in about half of our fifty states and other states either have or are considering acceptance of the slip form method as an alternate procedure.

This same slip form paving equipment, with very little modification, has also been utilized considerably the past several years on airport construction. A new airport immediately outside of my home town of Sacramento, California, was paved this past spring with a Guntert-Zimmerman slip form paver. With edge thickness ranging up to 16 inches, no sloughing occurred.

Discussion of Operational Problems

The full potential of greatly improved quality and production quantities by slip form methods could not be realized without certain other related operations also being modified. The matters of subgrade accuracy, concrete production and uniformity, reinforcing steel installation, mix compaction, surface finish and pavement smoothness must be considered. A brief discussion of some of these important parts of obtaining high quality concrete pavement at low cost will be briefly discussed along with some of the problems which have arisen these past several years of changing times in this field.

The elimination of pre-erected side forms for highway paving operations has introduced a serious problem with respect to finishing of pavement subgrade. The traditional procedure with side form concrete pavement was to first get a rough grade and then compact the base material with careful shaping in the area of each form. Installation of forms was then accomplished with top of rail accurately positioned to alignment and grade. The pavement subgrade itself was then shaped and trimmed with equipment riding on the side forms. With slip form methods the lack of a continuous and precise elevation reference makes special techniques necessary to assure accurate tolerances for grade and cross section to meet the minimum thickness requirements below which penalties are normally assessed and to avoid excessive waste of materials and resultant added costs for greater than specified thickness.

The slip form method also necessitates a smooth subgrade area outside of each pavement edge to accommodate the slip form paver tracks. Roughness in these track paths has a direct bearing on the smoothness of the finished pavement.

In California and several other states, a cement or asphalt treated base is normally used under Portland Cement Concrete. The primary purpose of these treated bases is to prevent erosion or pumping at joints which creates voids between slab and base with subsequent cracking and breaking of the slab. In connection with subgrade smoothness just discussed the use of treated bases restricts the time period between mixing the materials and final compaction. This limitation practically means that regrading has to be done at the time of initial mixing and compaction.

These difficulties and requirements for smooth base have stimulated development of new types of automatically controlled subgrading machines. There are now a number of different manufacturers who have produced such machines and more are entering the field all the time. With the possibility of penalties for too thin a pavement and overruns of up to about 10% if the subgrade is at all rough the need for more accurate subgrading is readily seen.

One aspect of subgrade accuracy is the relationship to the particle size of the material being fine graded. In California we have found that the reduction from the previously used one and one-half inch maximum size to a three-fourths inch maximum size for the cement treated base aggregates has made significant improvements in grading tolerances.

Another very important requirement for successful slip form paving is the essential necessity for extremely high degree of batch to batch uniformity in concrete mix delivered at the paver. The mix must be uniformly maintained at the lowest slump at which it can be effectively compacted and finished if edge slump and pavement roughness are to be minimized. On-site paving mixers supplied by dry batch trucks were generally used in the earlier slip form paving operations. Today, however, they have been replaced in most instances by highly portable, fully automated central mixing plants.

Several manufacturers have entered the field with this type of plant which typically is equipped with twin mixers of about 8 cubic yards capacity. With the normal 50 to 60 second minimum mixing time these plants are capable of producing 600 cubic yards of paving concrete in one hour. These plants have a capability of being dismantled and moved with over highway equipment and set up again in a matter of 8 or 10 hours plus travel time and preparation of the advance site.

Proper delivery of concrete mix from hauling units, truck mixers or on-site paving mixers to the screeds of slip form pavers deserves some discussion. Regardless of the type of mixer or hauling unit, it is important to distribute the mixed concrete uniformly across the width of the pavement to maintain a reasonably uniform level of material at the paver's screeds. Segregation must be reduced to a minimum.

Various types of spreader boxes have been utilized to accomplish adequate spreading. These boxes have been variously towed by on-site mixers, pushed by pavers, and most recently towed by dump trucks.

With the use of a central mixing plant, the transfer from the mixer to the grade has been accomplished mostly with nonagitating dump trucks. Early concern for possible segregation by this method of transportation has been proven unwarranted.

A problem in slip form paving as compared to previous methods relates to the necessity for more skill in training of field supervisors, operators and mechanics to cope with the more complex highly automated equipment. The sometimes poor results obtained in the early days of slip form paving often related directly to people with insufficient knowledge and experience. Manufacturers have done a good job of providing technical people to solve problems when breakdowns occur. However, the contractors have found that they must have competent men to act immediately rather than face a costly shutdown waiting for a factory representative to reach the job site.

The proper care and maintenance of paving equipment should be obvious but it takes on more importance with the complicated hydraulic, electric and mechanical components of the modern slip form paver. Contractors have found that good maintenance programs pay and that preventive measures such as installation of independent monitoring systems to indicate malfunctions can be justified.

Adequate concrete density was a problem in the earlier experimental days of slip form paving but has been materially dissipated now that all major slip form pavers incorporate high frequency internal vibrators.

The problem of excessive edge slump is usually associated with nonuniformity in consistency of the concrete mix. It may also occur whenever concrete slump exceeds about 3 inches, when the pavement edge is mechanically disturbed through the action of too long a trailing form, erratic control of the paver, or other external agencies. It may also occur during periods of very damp weather or whenever rainfall is permitted to reach a new pavement before it has hardened. These are all problems, however, which can be solved through proper planning and operations.

The smoothness and rideability of a completed pavement is obviously one of the principal criterions for satisfactory acceptance. We have found it very desirable in California and in other states to determine compliance with smoothness requirements as early as possible. This has been accomplished by use of the California type profilograph which is essentially a 25-foot long beam with a recording wheel at the mid point and multiple support wheels at each end. It is operated over the pavement as soon as the concrete has hardened sufficiently to support the instrument, usually during the morning of the first day following placement.

A continuous chart is obtained which is analyzed quantitatively with the numerical indices derived indicating whether or not specification tolerances are met. The specification requirement of 7 inches per mile is being met with a large margin on most projects today with a possible exception of an occasional night joint. Numerous jobs have consistently averaged less than 1 inch per mile. Our specifications, however, do require grinding of the pavement surface to reduce roughness to the required 7 inches per mile.

Grinding, when required, is accomplished by cutting away high spots with concrete planers that utilize 2-foot wide cutting heads consisting of about a hundred diamond saw blades or by planers with heavy cylinder cutting heads upon which diamonds have been surface set in a spiral pattern. Bump cutting in this manner can produce a very undesirable looking surface, particularly if any amount of cutting is done in a confined area. Furthermore, the operation is relatively expensive. For these reasons, it is obvious that the best answer is to construct a smooth riding surface in the first place. In order to improve appearance in areas that have to be cut, California now requires that these areas be finished off to adjacent lane lines to present a neat, rectangular area rather than an irregular area.

The requirements for reinforcing steel, pavement dowels, and joint assemblies vary a great deal among the various states. In California we have never used reinforcing steel except in experimental sections. We have fairly recently eliminated the use of dowels and for many years have not used any expansion joints except at structure abutments. Other states requiring reinforcement have generally experienced less rapid use of slip form methods because of early problems in developing satisfactory procedures to install the steel.

The most common practice of placing reinforcement is to employ the two-lift method. By this method a stripped down slip form paver or other spreading equipment is used to spread a six to seven inch mat that is compacted by internal vibration. This mat is held to a reduced width to allow the slip form paver's side forms room in which to form the complete pavement edge. Mats of reinforcing steel are then positioned on top of the initial spread using hand methods. The steel is then tied and anchored against movement.

Following steel placement a conventional slip form paver shapes and finishes the top two inches of concrete and the edges. This two layer method has been found successful and avoids considerable problems found in earlier attempts to place steel concurrently in a single lift operation.

Final finishing operations basically follow those used with conventional side form paving operations. In California the longitudinal joints are normally formed during paving by use of a 2-inch deep polyethylene strip. Transverse joints are normally sawed, being spaced at distances varying from 13 to 19 feet and skewed in the ratio of 3/12 to the normal. Several manufacturers are experimenting with machines to place a polyethylene strip in lieu of sawing for the transverse joints and it is expected that a successful operation can be developed.

It was brought out in the Introduction to this paper that the use of slip form paving methods is providing a substantial savings to the highway taxpayer. Estimates of these savings have ranged from 20¢ to $1.00 per square yard. Our estimate of $34 million saved to date was based on a factor of 50¢ per square yard which is considered to be a reasonably conservative amount.

Table 4 is a summary of slip form paving completed in the United States during the calendar year 1965 showing quantities and costs for various types and thicknesses.

Conclusion

In summary we find that slip form methods of placing concrete pavement have progressed in a period of less than eight years from a questionable experiment to a position of general acceptance or even preference to previous methods. California and many other states now use slip form methods almost exclusively and this use and acceptance are spreading rapidly to other states and countries.

Slip form methods have proved capabilities of obtaining a smoother and more durable product. The paving contractor finds the increased production and mobility and the smaller labor force allow him to submit lower bid prices.

The future for slip form paving looks very bright. The progress made to date by the teamwork of highway engineer, paving contractor, and equipment manufacturer is bound to continue with added improvements in the years to come.

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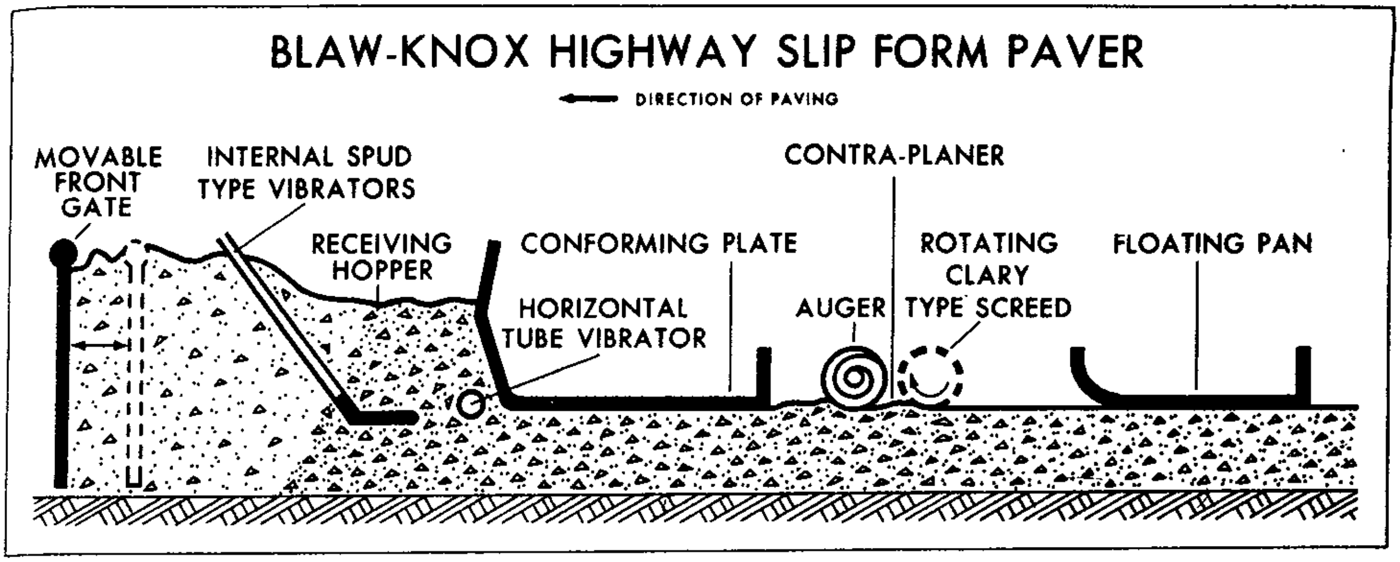

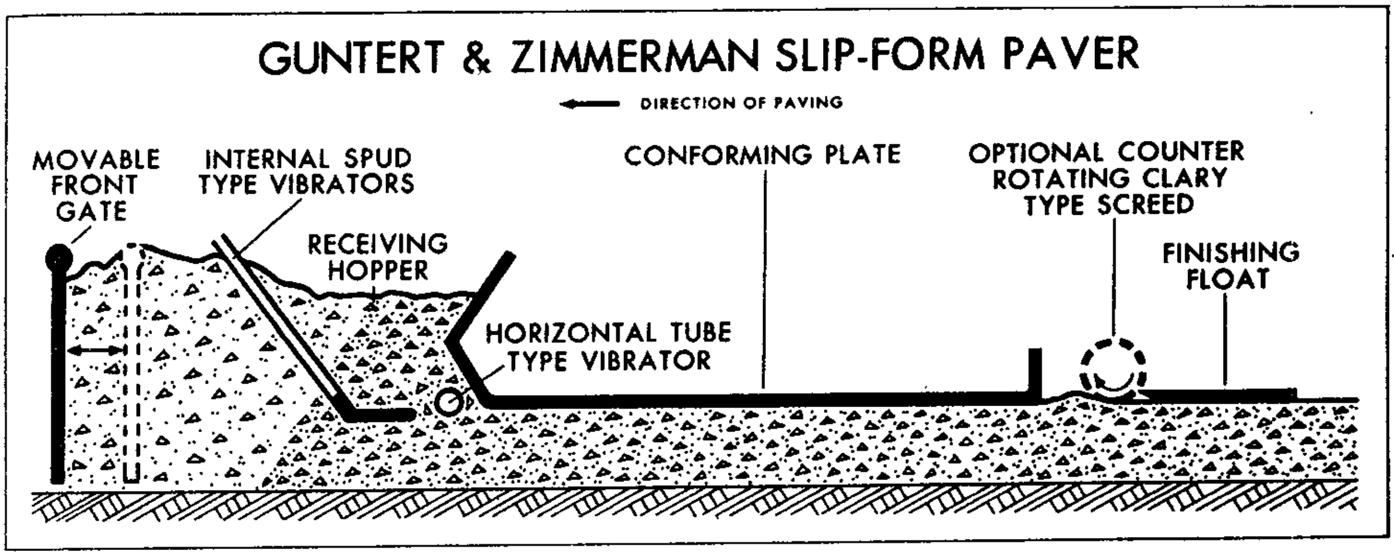

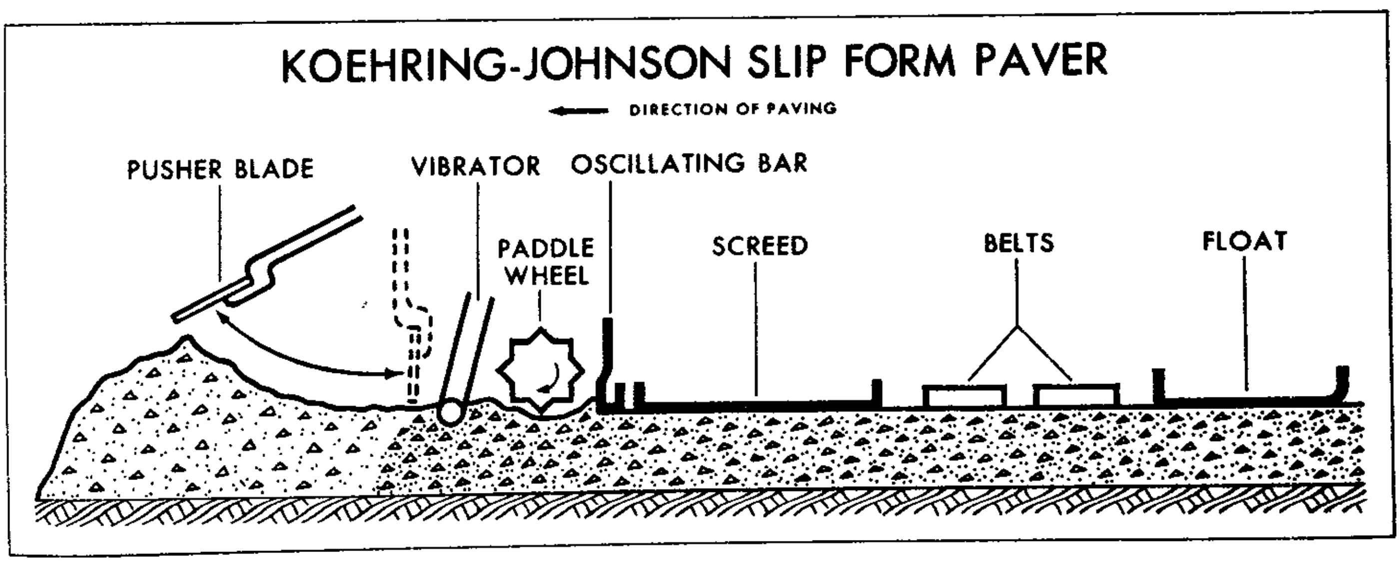

FIGURE 1 - SCHEMATIC DIAGRAM OF PAVER FUNCTIONS.......FOR BLAW-KNOX, GUNTERT & ZIMMERMAN AND KOEHRING-JOHNSON SLIP-FORM PAVERS

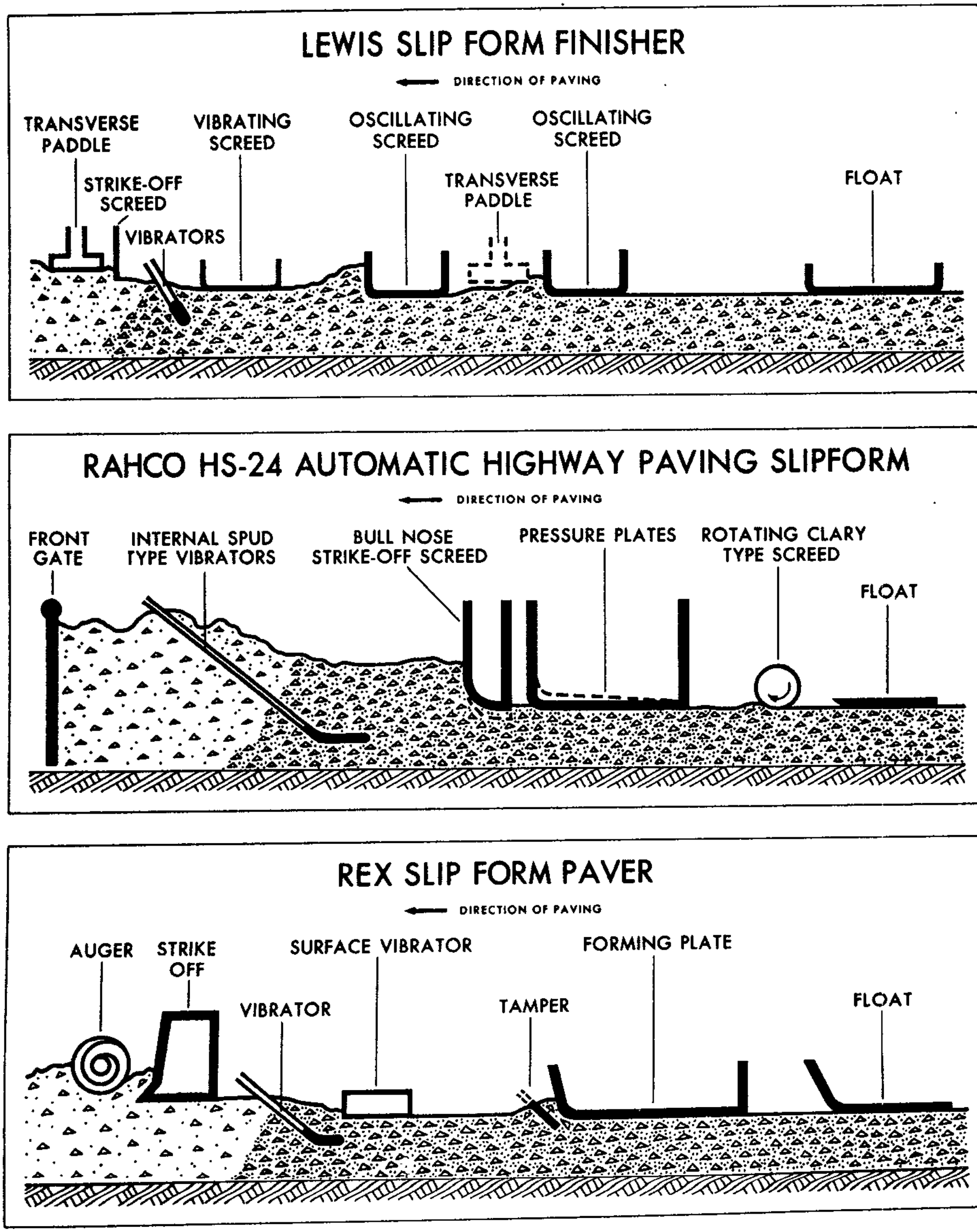

FIGURE 2 - SCHEMATIC DIAGRAM OF PAVER FUNCTIONS.....
FOR LEWIS, RAHCO AND REX SLIP-FORM PAVERS

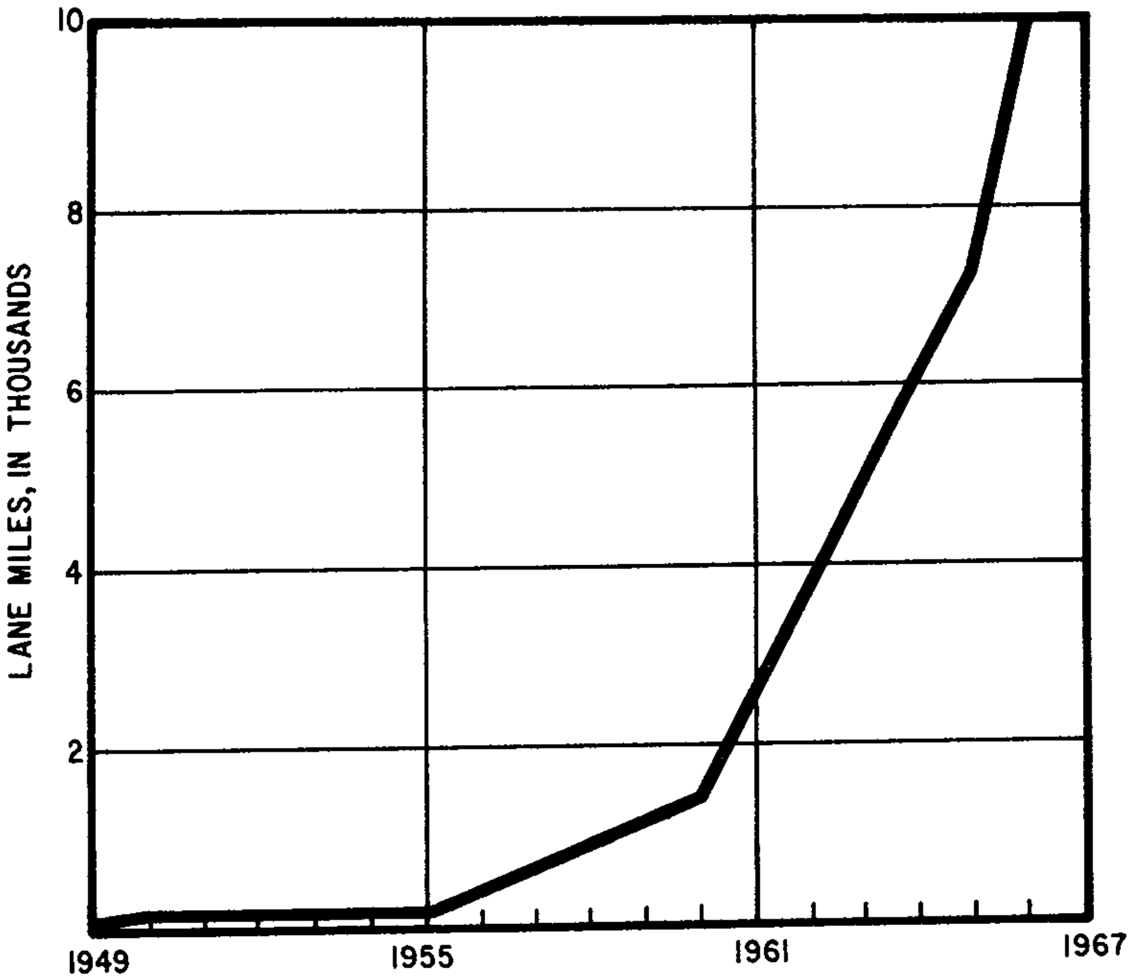

FIGURE 3 GROWTH OF SLIP-FORM PAVING

Table 4

SUMMARY OF SLIP-FORM PAVING PROJECTS BY PAVEMENT TYPE

January 1, 1965 thru December 31, 1965

Pavement Type	No. of Projects Ea.	No. of States Ea.	Total Contract Quantity SY	UNIT COST**			Total Contract Cost** $
				Highest $/SY	Lowest $/SY	Weighted Ave. $/SY	
6" URCP	38	1	1,893,053	2.44	3.22	2.72	5,142,999
6" CRCP	1	1	101,820			3.42	348,225
7" URCP	4	1	183,630	3.19	3.29	3.26	599,102
7" CRCP	2	1	13,654	5.24	4.96	5.17	70,567
0.58' URCP	1	1	197,141			3.36	662,292
0.65' URCP	2	1	184,575	4.87	4.42	4.66	861,026
8" URCP	69*	10	7,774,744	5.55	1.98	3.39	26,373,565
8" URCB	4	1	325,000	3.90	3.75	3.84	1,248,480
8" RCP	1	1	109,184			3.70	403,981
8" CRCP	5	3	1,150,694	5.16	3.79	4.61	5,302,614
9" URCP	54*‡	7	5,312,970	7.00	3.00	3.70	19,662,031
9" RCP	5	2	875,147	4.42	3.78	3.95	3,458,037
10" URCP	8	1	1,308,182	4.95	6.05	5.22	6,827,050
TOTAL	194		19,429,794	7.00	1.98	3.65	70,959,969

**Includes projects on which two or more pavement types were used.*
‡Includes an estimated number of projects for one state
***Costs include all materials and labor for constructing the pavement complete in place, excepting the cost of reinforcing steel and end anchors for continuously reinforced pavement*

ABBREVIATIONS:

(a) 6" URCP —6-inch thick un-reinforced concrete pavement
(b) 6" CRCP —6-inch thick continuously reinforced concrete pavement
(c) 7" URCP —7-inch thick un-reinforced concrete pavement
(d) 7" CRCP —7-inch thick continuously reinforced concrete pavement
(e) 0.58' URCP—0.58-ft. thick un-reinforced concrete pavement
(f) 0.65' URCP—0.65-ft. thick un-reinforced concrete pavement
(g) 8" URCP —8-inch thick un-reinforced concrete pavement
(h) 8" URCB—8-inch thick un-reinforced concrete base
(i) 8" RCP —8-inch thick reinforced concrete pavement
(j) 8" CRCP—8-inch thick continuously reinforced concrete pav
(k) 9" URCP—9-inch thick un-reinforced concrete pavement
(l) 9" RCP —9-inch thick reinforced concrete pavement
(m) 10" URCP—10-inch thick un-reinforced concrete pavement
(n) SY —Square Yard