HIGHWAY RESEARCH BOARD
Bulletin 132

Concrete Control and Construction

National Academy of Sciences—
National Research Council
publication 422

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1956

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HIGHWAY RESEARCH BOARD

Bulletin 132

Concrete Control and Construction

PRESENTED AT THE

Thirty-Fifth Annual Meeting

January 17–20, 1956

1956

Washington, D. C.

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Contents

Quality Concrete for Highway Construction With Central Mixing Plant

GLENWAY MAXON, Consulting Engineer
Milwaukee, Wisconsin

Central mixed concrete, delivered to job by new agitated truck bodies, offers great opportunity for fast placement, new methods of quality control, and versatility in respect to placing concrete in bridges and the numerous other structures as well as the slab itself.

The method is fundamentally old. Figures will show work in Ohio during 1921.

The first large scale operation along modern lines was the concreting on one section of the Ohio Turnpike in 1954.

There were two large scale operations in 1955 and numerous smaller operations where only part of the concrete was central mixed.

Improvised plants such as stationary truck mixers, and stationary pavers permitted the use of equipment already available. This was affected on the Garden State Parkway widening, June 1955, and odd parts of US 14 in Ohio near Ravenna, such as bridge approaches, intersections, and the like.

The need is shown for new equipment including a spreader to convey and deposit the concrete evenly across a full 25 foot width of pavement. Portable, or semi-portable, concrete mixing plants are also needed which can be transported in parts for rapid travel and erection. These plants should incorporate complete facilities for automatic weighing, recording and testing.

It is proposed that the heavy media method of testing for cement content be enlarged to test the first, middle, and last parts of the concrete as discharged from the central mixing plants to measure uniformity of mixing.

In respect to placing concrete in the slab a device should be tried for consolidating by using both pressure and vibration in order to successfully place concrete of one inch or less slump.

With the added flexibility and speed, central-mixed concrete may well improve quality and reduce cost of concrete in our country's new highway program.

● CENTRAL-MIXED concrete for use in the construction of highways has a great future in reference to economy, rapidity, and quality. By grouping the manufacturing elements of batching and mixing, the opportunity for higher production rates and less costly inspection are available.

The design of equipment for easy inspection, should be paralleled with simple and quick testing methods. Tedious testing methods, frequently lead to their curtailment or are carelessly applied.

All personnel should be made cognizant of the ways and means for controlling quality of the concrete for it takes team work to insure the best concrete between the forms. (Figures 1 and 2).

Concrete has been placed in road construction by non-agitated delivery from central mixing plants as far back as 1913. (Figure 3).

Flexibility of Central Mix

Central mix plants can quickly switch from Class A to Class B concrete and can further batch out and mix concrete for precast, and prestressed concrete where water content is at a very minimum. Isolated placements of widened intersections, curbs and gutters, culverts, retaining walls, maintenance buildings, etc., can all be served with concrete from a central mixing plant without disturbing the set up for slab con-

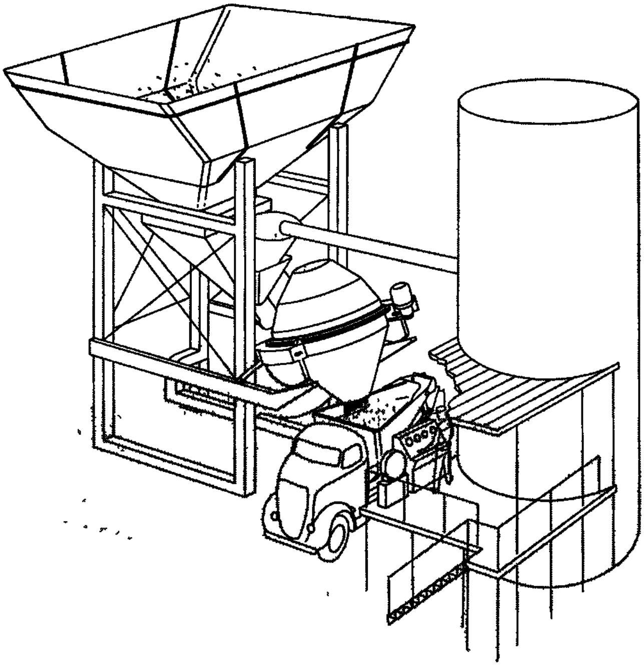

Figure 1. Diagram of elements. Plant - operator and test floor - Agitor delivery.

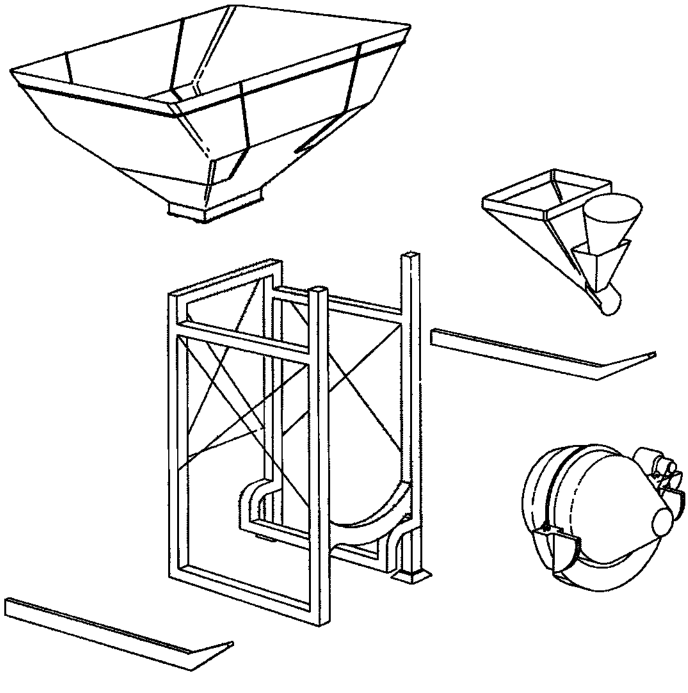

Figure 2. Diagram of elements. Exploded view of plant.

Figure 3. Highway job in Ohio, Columbiana Lisbon Road, September, 1921.

struction. Concrete for these can be placed when weather or subgrade conditions make slab placement impractical. (Figures 4 and 5).

Control

Automatic control of weights, of aggregates, water, cement, and the mixing of these can all be viewed by one operator and checked by one inspector. Today, mixing plants with plug-in electric connections can be quickly moved. The set up costs are not much greater than the set up of present day batching equipment. Tear down and new set up should be made within two weeks with plants designed with that in mind. (Figure 6).

Recording

For projects for government work, and where required in airports, expressways, etc., devices for recording the amount of cement in each batch can be had for an additional $5,000., and for another $7,000., devices for recording aggregate may be included. With central mixing, moisture control is comparatively easy, particularly if the operator can be located at the discharge end of the mixer, where he can look within the drum and by experience determine the slump of the concrete before discharge. (Figure 7).

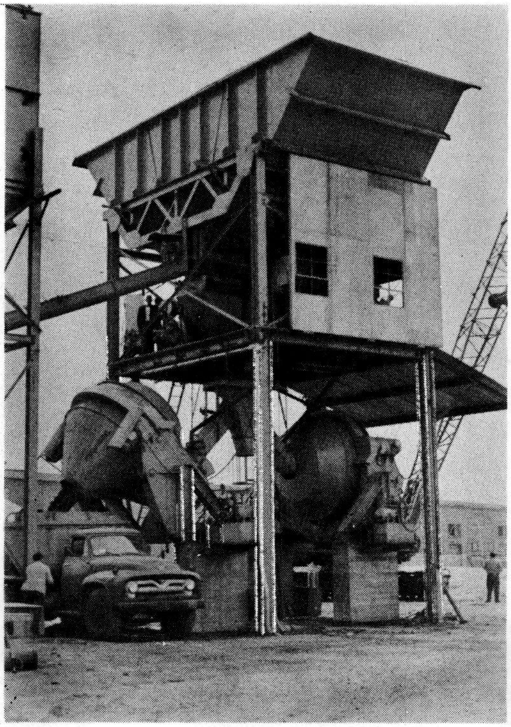

Figure 4. 4 cu. yd. mixer and dumpcrete. New Jersey Turnpike Extension.

Speed of Mixing

In mixing concrete in a mixer of this type there are numerous methods of speeding up the cycle. Material for 4.4 yards of concrete can be placed in this mixing drum in the course of 15 seconds. At the same time, the water injection should be speeded up

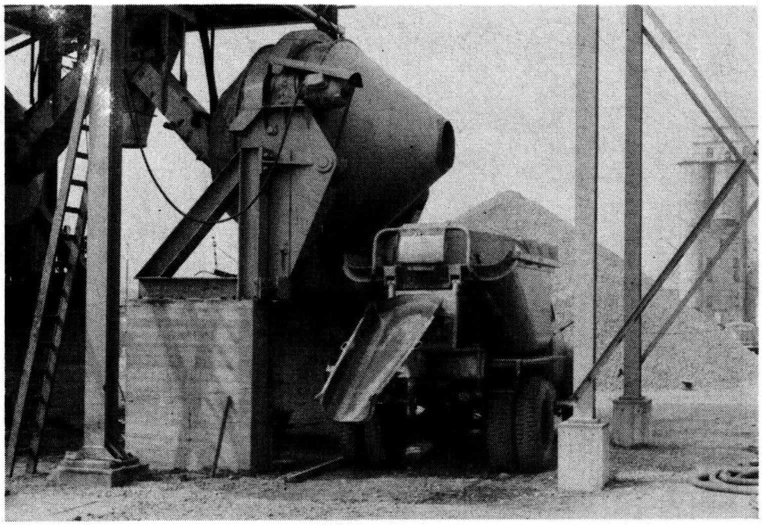

Figure 5. Brewster mixer, New Jersey Turnpike Extension.

by applying pressure, very possibly injecting it from the opposite end of the drum or from both ends. Mixing time, after all the ingredients are in, should not be more than one minute and fifteen seconds. Complete tilting to discharge, and return for the next load requires fifteen seconds. With such a cycle, this mixer can turn out 150 yards

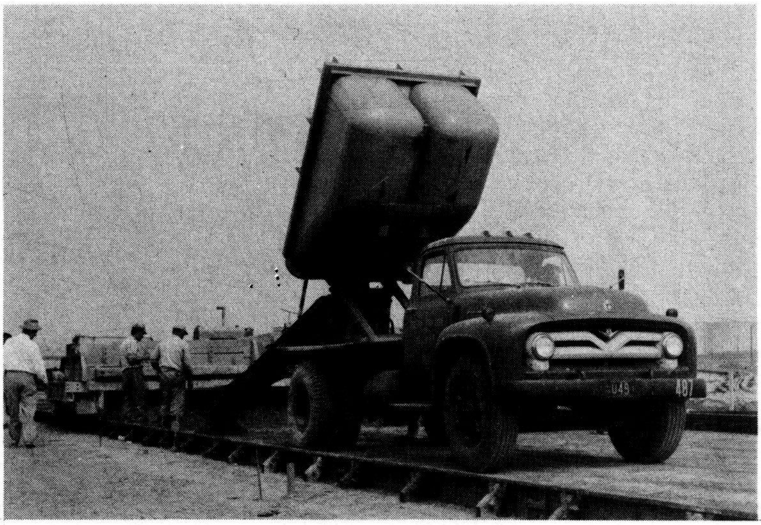

Figure 6. Placing concrete from Brewster plant, New Jersey Turnpike Extension.

per hour, a quantity sufficient to build 225 feet of 24 foot pavement 9 inches thick. It is possible that this cycle can be somewhat speeded up. In any event, it has the approximate capacity of two 34-E pavers. The tilting mixer has a record for reliability which is not surpassed.

Placing and Spreading on Slab

The placing of concrete on the slab entails no serious problem. It is possible now to mix and place the equivalent concrete of several pavers at one location without taking

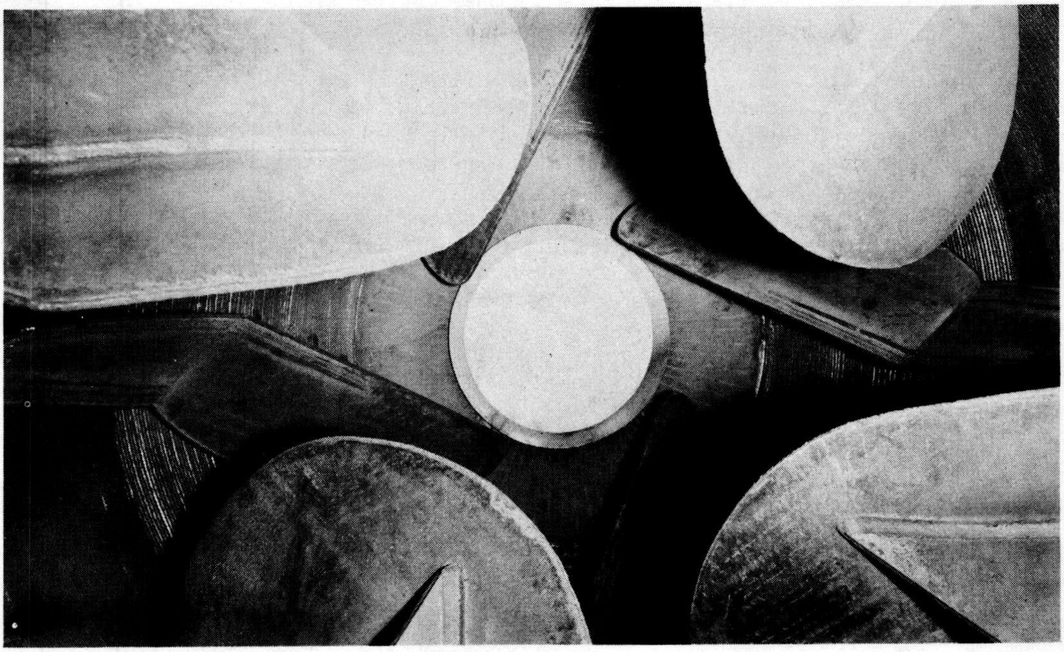

Figure 7. Inside of mixer.

up much room on shoulders. (Figure 8). Where the slab has width wider than that which can be spouted from a non-agitated high discharge concrete body, a conveyor

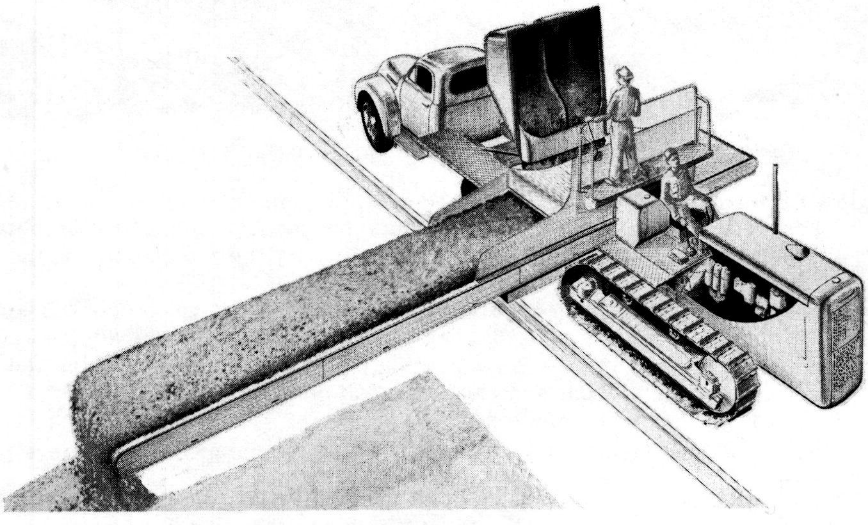

Figure 8. Shuttle belt conveyor. Mounted on Caterpillar D-8 for spreading concrete on 25-foot widths.

can be provided for moving concrete to the far side. Such a conveyor is shown in the figure. This conveyor was developed by W. D. Winkelman Company. (Figures 9 and 10).

Placing Auxiliary Concrete

The instruments for placing concrete on bridges, curbs, gutter, retaining walls, and interchanges, are similar to those used now with the stationary mixers, pavers, or truck mixers. Where pavers are used for mixing concrete for the slab, the same may be set up as stationary mixers for placing the miscellaneous concrete. (Figures 11 and 12).

Testing and Inspection

At the present time there are no widely used methods for testing the degree of mix of fresh concrete. A simple mixer efficiency test is much to be desired. The heavy media method of determining cement content, together with an easy means of determining the amount of segregation of various portions of the batch, is needed. Some of the expense of making compressive and flexural strength samples might be transferred to mixer tests. If these mixer tests are shown to have a relationship with seven and twenty-eight days strengths, their use would be of value to both the contractor and contracting officer in quality control as mixed, rather then attempting correction after a month in place.

Even though tests of fresh concrete may not tell the whole story, a diagnosis should

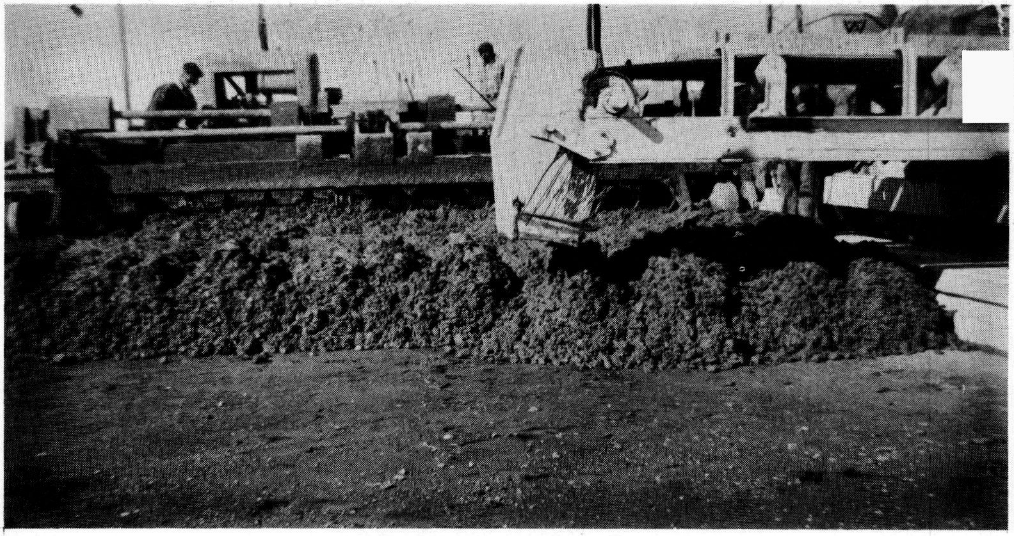

Figure 9. Spreading dry concrete, Plattsburg Air Base.

be made before failure, rather than holding an autopsy some 28 days too late. The cooperation between the contractor and the engineering inspector can best be obtained by simplifying the job of inspection at the time we simplify the job of manufacturing the concrete.

When 700 psi, is called for in flexural strength it is imperative to check frequently for errors in batching and mixing. Daily checks of material should be augmented by daily checks of mixer efficiency. I am suggesting one method of check using the heavy media method of separating cement and sand in fresh mortar.[1]

The ball penetration test takes much less time than the slump cone.[2] (See Figure 13 for variation of this method.) The Chace Air Meter can be carried in one's pocket.[3]

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[1] A Method for the Determination of the Cement Content of Plastic Concrete by W. G. Hime and R. A. Willis published January 15, 1955, by the Research & Development Division of the Portland Cement Association. (See brief description in Appendix.)
[2] See ASTM Specification - 55.
[3] The Chace Air Meter has been used quite successfully by Howard, Needles, Tammen & Bergendoff on bridge approaches and slab work on the New Jersey Turnpike extension from the Newark Airport to the Holland Tunnel. It is manufactured by L. M. Chace,

With it, one man can make a test for air content in the course of ten minutes.

Continued sampling and testing, instructing labor and management of the reasons for testing, together with simplifying the methods of testing, are steps to improving and controlling quality. Management and the people working are just as proud of good work as any skilled employees in the quality manufacture of shoes or automobiles. We make a grave mistake when we don't strive to cultivate their interest. The sidewalk inspec-

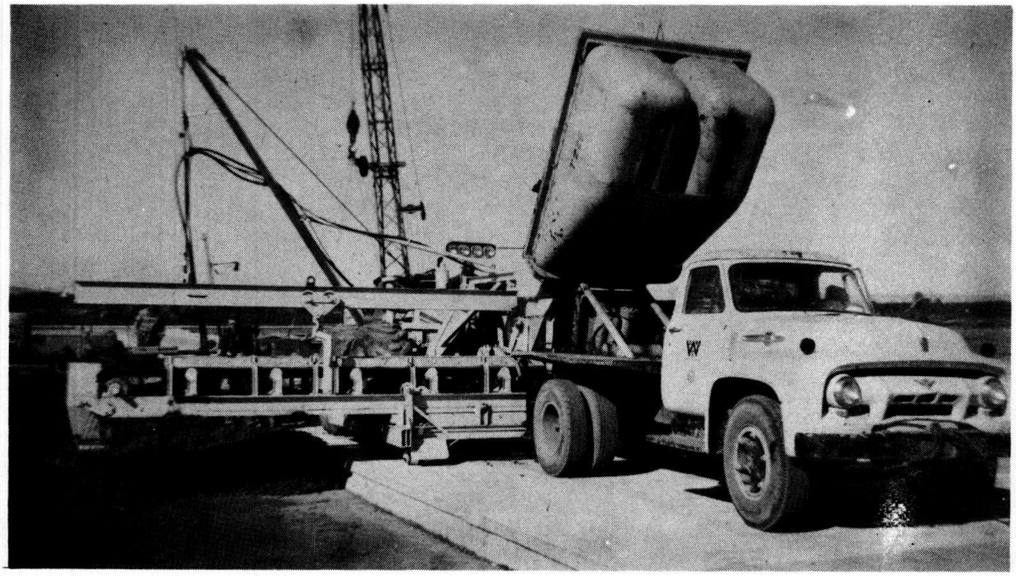

Figure 10. Plattsburg Air Base. Dumpcrete depositing in hopper, (Note ''Tourna-Dozer'' to which belt conveyor is mounted).

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[3] (footnote continued)
North Bridgton, Maine. A small sample of the mortar is taken and placed in a cup immersed in alcohol and agitated to remove the air. The drop in the gage is then compared to the chart, which had previously been computed with the aid of the standard meter.

tion holes on building projects affects the pride of the workman within. A group trip of visitors through a factory has a salutary affect on the workers. The pride of quality

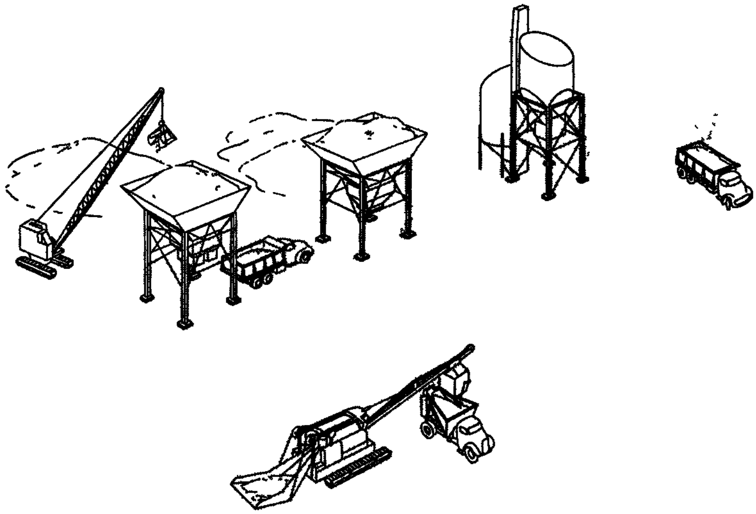

Figure 11. Bins, trucks and paver - AGITOR delivery.

should be in evidence on the company's bulletin board, and should be displayed as prominently as that of safety records. Quality control for highway concrete means 5,000 psi. compressive strength concrete, 700 psi. flexural strength, and the designed air

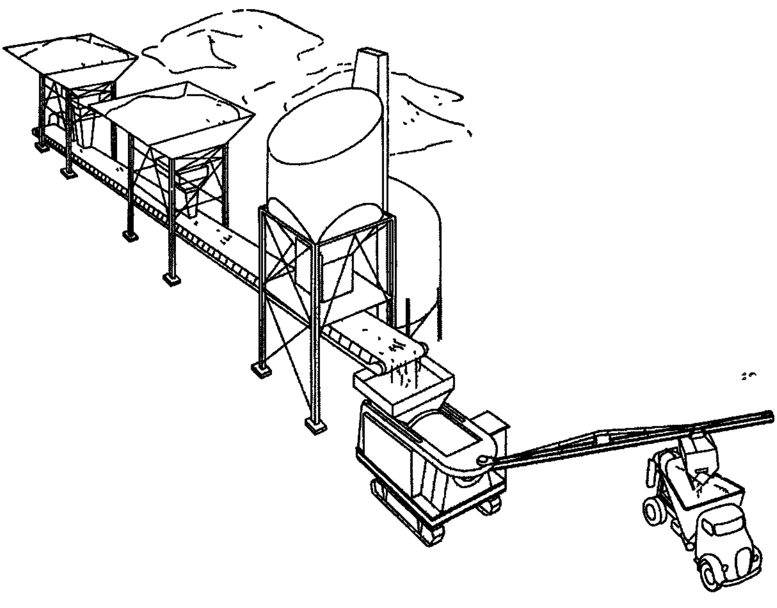

Figure 12. Bins, belt conveyor, paver - AGITOR delivery.

content; also not far in the future, the manufacture of no slump 7,000 to 8,000 psi. concrete for prestressed members.

Quality control should lead to better uniformity. There should be no variation of 20 percent. Equipment can be designed to control the strength within a variation of 10 percent, and to control other qualities which are required to be uniform.

The Heavy Media Method has been put to use by the New York State Department of Public Works.

The tests were carried on by Ralph Hollweg, structural supervisor of District No. 10 during the summer of 1955. M. E. Goul is District Engineer. Their operations cover Nassau, Suffolk, and counties in Greater New York. The tests were made by Cellini under Hollweg's supervision. The laboratory room is about 10- x 12- ft. In the tests I viewed about ten of us crowded into that room and still left room for testing. Both Cellini and Hollweg spoke well of the method. I took five stereo photographs showing: separation through 30 mesh screen, drying in skillet, dried sand and cement, with centrifuge in background, filling centrifuge test tubes, test tube with cement and sand separated. (Sand floating on heavy media.)

Placing Dry Concrete

No great progress has been made towards consolidating dry harsh mixes in pavements. Means of combined pressure and vibration should be explored. These methods

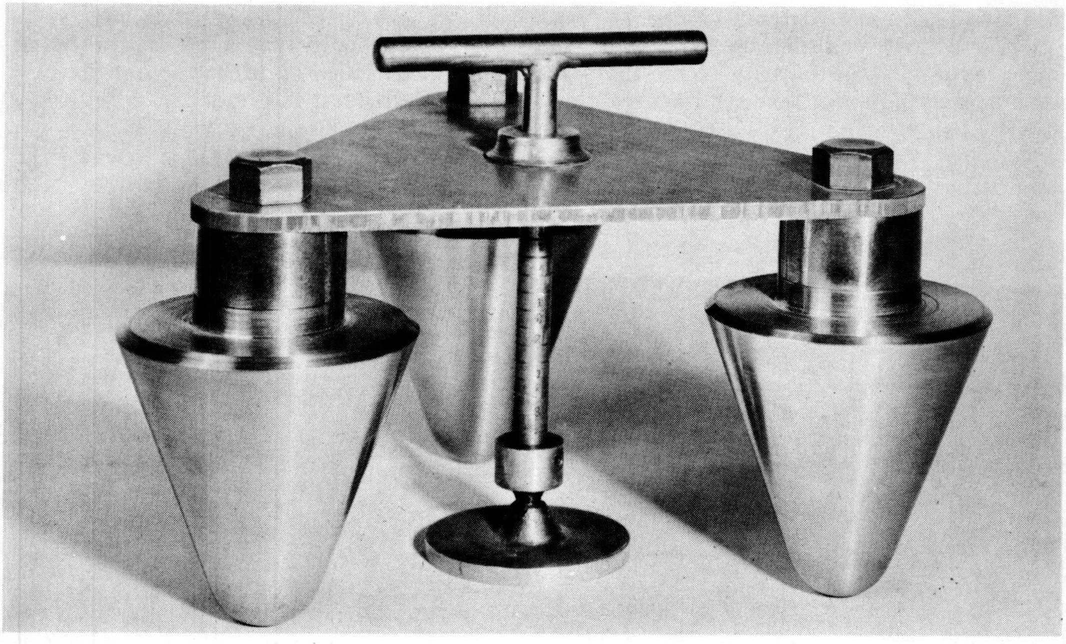

Figure 13. Three point penetration tool, similar in principle to Kelly Ball.

have proven of great value in the manufacture of concrete products. The very old method of hand-tamping with a square tamper might be emulated by machine methods, vibrating the tampers as pressure is applied. If such machinery be devised, there is no reason why 0 to 1-inch slump concrete cannot be placed without voids or honey combing as economically as the 3-inch to 4-inch slump concrete now prevailing.

In conclusion, the design of equipment, the planning of work, and systematic inspection, are items which must be correlated for mass production and quality control of concrete roads.

Appendix

The Hime-Willis test for cement content can be made within 1 hour 15 minutes. Several tests can be processed simultaneously. The elapsed time for three tests should not be more than 1 hour 45 minutes. That is all that would be required to check cement distribution in the mortar from first, middle, and last part of the mix.

1. In field tests - samples of approximately 50 lb. are taken from the mix.
2. A representative part of about 4 lb. is taken from the sample. Its exact weight is recorded.
3. The sample is wet sieved in a beaker through 30 mesh sieve. The minus 30 in the beaker is then collected after decanting the water and placed in a skillet.
4. The contents are dried, broken up and weighed.
5. Two samples of 25 grams each are taken and introduced into two 50 ml. graduated centrifuge test tubes.
6. The tubes are filled while stirring to 50 ml. mark with a mixture of acetylene tetrabromide and carbon tetrachloride of specific gravity less than cement and more than sand.
7. The tubes are placed in a centrifuge and spun for several periods of 3 minutes each, stirring in between periods.
8. The volume of the cement content is read and recorded.
9. By comparing the cement content to the weight of the dried sample and then comparing to laboratory mixes a transfer in contents can be computed from the volume of the cement layer to sacks per cubic yard in the concrete being tested.
10. By checking the yield of the entire mix and taking three samples, front, middle, and rear, the cement content can be checked, the cement distribution determined and the stone and sand contents computed.
11. The test can then be a continual check on the aggregate scales. Flexural beam samples might well be taken from the same batch. Continued uniform cement distribution, and uniform flexural strength being the desired result in the quest of better quality control.

Note: Items 10 and 11 are suggested by the author.

Self-Propelled Machines for Unformed Concrete Slab Construction in Illinois

ROBERT H. TITTLE, Engineer of Construction
Illinois Division of Highways

Early in the 1940's the Illinois Division of Highways started a program of rehabilitating old existing 18-foot concrete pavements by widening the slabs to 22 feet and 24 feet with concrete, correcting vertical and horizontal alignment at certain locations with concrete base course, and resurfacing the entire project with bituminous concrete. A satisfactory method of placing the widening without forms was developed soon after this program was started which resulted in substantial savings to the state.

A machine had already been built in Iowa to construct one lane of concrete pavement without forms. It was felt that a method might be developed where the full-width base course could be built without forms. With this in mind, we encouraged the contractors on our projects to investigate and study the possibility of developing this new idea. It required a certain amount of promotion on the part of the Division of Highways to convince the contractors of the benefits to be derived from money spent by them in constructing such a device.

There have been many important improvements in road-building equipment in recent years. One of the latest developments is this entirely different type of concrete paver or finishing machine. This equipment, which has been developed on several of our projects during the past four construction seasons, places concrete base course without the use of the conventional side forms. The machines employ the use of slip forms which eliminate the costly operation of handling and setting forms.

The first machines constructed were cable-drawn and were rather simple in design. The experience gained with the cable-drawn machines confirmed our opinion that it was possible to build concrete slabs economically without forms. It was also conceived that better results and more efficient operations would be possible with self-propelled machines. Several of these machines have been built and used with good results.

This paper covers the development of these machines and the results which have been obtained with their use.

The fact that the contractors are willing to finance the building of their machines certainly indicates that the new type of construction is more economical than conventional methods. The machines are capable of laying full-width slabs which are uniform in thickness and have straight edge alignment. The edges stand vertically with very little slumping. Compression tests made on cores removed from the base course indicate strengths comparable to concrete placed by other methods. It is possible to lay concrete slabs without forms meeting a surface tolerance of ¼-inch in 10 feet. With further development of this machine, it may be possible to meet the requirements of ⅛-inch in 10 feet which is specified for concrete pavements.

A motion picture covering the development of this equipment and also showing the construction of several of our projects will be presented in conjunction with the paper.

● THERE have been many important developments in road building equipment in recent years; possibly the greatest progress has been made with earth-moving equipment. The size and mobility of earth-moving equipment have been developed to such an extent that production has been increased tremendously on the average road construction project. This has had a definite effect on the cost of road work as grading prices are actually lower today than in the earlier days of road building.

Asphalt paving equipment has changed considerably in recent years with larger hot-mix plants and the development of several efficient asphalt finishing machines that eliminnate the need of hand finishing. Concrete paving equipment has also been developed to increase production and reduce the need of so much hand labor. Among some of the modern developments are the 34-E dual drum paver, concrete spreaders, surface vibrators, and the longitudinal float. These changes have made it possible to increase production and produce smoother riding surfaces.

An entirely new and different type of concrete paver or finishing machine was developed in Iowa in 1949 that incorporated the use of slip forms in lieu of staked-in-place steel forms. The machine was given wide publicity and created considerable attention at the time; however, very little has been heard of this machine since that date.

Illinois was at that time facing the problem of rehabilitating many miles of old concrete pavement. We felt that such a machine might eventually simplify construction operations where it is necessary to construct full-width concrete base course at different locations to improve vertical and horizontal alignment on the existing highways. It was apparent that these projects offered an excellent opportunity for further research and development of this new and novel paving equipment. Any irregularities in the surface of the new concrete base course would not be detrimental, as they would be covered with 3 inches of bituminous concrete.

Realizing this opportunity, the Illinois Division of Highways felt obligated to highway engineering and industry to encourage the contractors to explore this new method of paving. With a certain amount of promotion and encouragement, the contractors responded beyond our expectations. They spent considerable sums of their own money to build self-propelled slip form pavers and subgrading machines. This equipment has now been used in several states outside of Illinois and has attracted the attention of many engineers and contractors over the country.

PAVEMENT REHABILITATION

Early in the 1940's the Illinois Division of Highways started a program of rehabilitating old existing 18-foot concrete pavements by widening the slabs to 22 feet and 24 feet with concrete, then resurfacing the entire width with 3 inches of bituminous concrete. During the early years of this program steel forms were used to construct the 2-foot and 3-foot widths of concrete widening on each side of the old 18-foot pavements. However, this method of construction proved to be an expensive and slow process.

It was soon realized that a faster method of building the concrete widening must be used in order to complete the large program facing Illinois. To accomplish this result, the method of widening without forms being used in our neighboring State of Wisconsin was investigated. This method appeared so promising that the contractors were encouraged to develop it in Illinois. In a short time a very satisfactory method was being used for this type of construction. Production was greatly increased and in one case a contractor placed more than 17,000 feet of 2-foot widening on one working day. Without its adoption it is doubtful that Illinois could have completed so many miles of widening each year. This method of placing concrete widening without forms has had a direct influence on contract costs and it has resulted in substantial savings to the State.

Many of the widening and resurfacing projects include certain locations where it is necessary to correct the vertical or horizontal alignment of the existing pavement to meet present-day standards. It is the practice at these locations to remove the old concrete pavement and construct a new concrete base 22 feet or 24 feet in width and resurface the entire project with bituminous concrete in order to have a uniform surface throughout. The length of these relocations vary from about one thousand feet to as much as two or three miles. Originally the contractors used regular steel pavement forms and finishing machines to construct the full-width base course. In addition to the cost of setting forms, considerable equipment had to be moved from one location to another, which was costly and this cost was reflected in the unit bid prices.

Since we had been successful in our program for widening pavement without forms it was felt that with the proper encouragement the contractors might be able to develop a method for building full-width base course without the use of forms and finishing machine. As mentioned above, the Iowa State Highway Commission had already done some experimenting with this type of construction building one lane at a time. It was felt that even if the surface of the concrete base was not perfect it could be corrected with the bituminous concrete surface course.

With these thoughts in mind the problem was discussed with several contractors. Late in 1951 it was decided to revise our specifications to permit the construction of full-width base course without forms. Only one concession was made in the special provisions—the surface

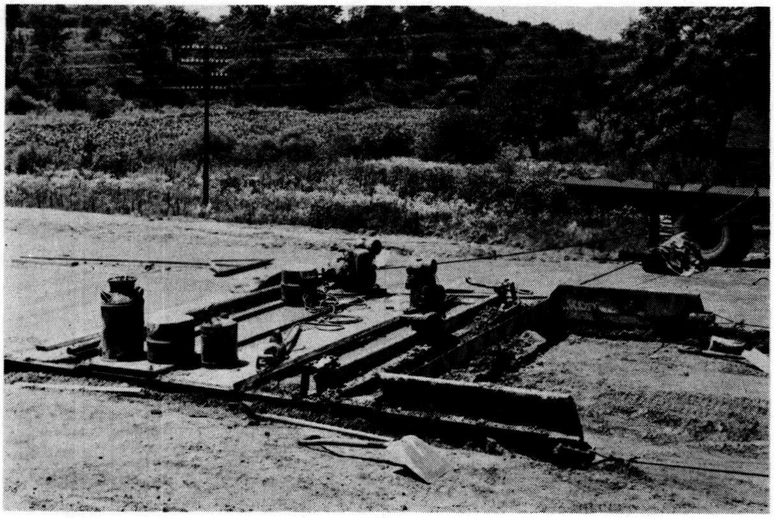

Figure 1.

tolerance requirement was changed from 1/4-inch in 10 feet to 3/8-inch in 10 feet. The requirements for the thickness of the concrete base course and the quality of the concrete were not changed.

DEVELOPMENT OF CABLE-DRAWN SLIP-FORM PAVERS

This revision in the specifications created considerable interest among the contractors and engineers; however, it still required a certain amount of promotion on the part of the Division

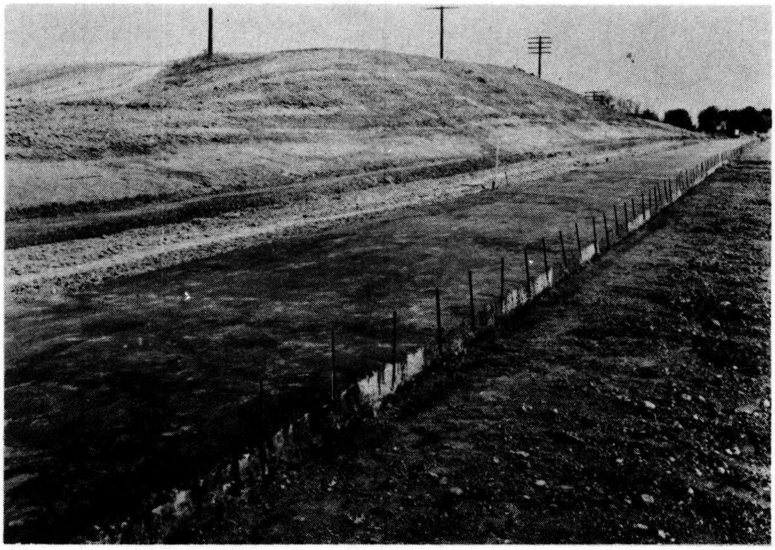

Figure 2.

of Highways to convince the contractors of the benefits to be derived from the money expended by them in constructing a device to build full-width base course without forms. Early in 1952 one of our contractors decided to attempt to construct 1,004 feet of full-width base course involved in a grade revision, without the use of forms. After considerable planning and several conferences it was decided that it would be easier to build the base course in two operations, one lane at a time. The machine as finally developed is shown in Figure 1. The machine consisted of two runners 25 feet in length, spaced 11 feet apart to construct the 11-foot lane of concrete. A strikeoff was located near the forward part of the machine to level the concrete and form the crown of the base course. It was followed by a vibrating screed attached to the runners immediately back of the strikeoff. The machine was pulled forward by a single steel cable op-

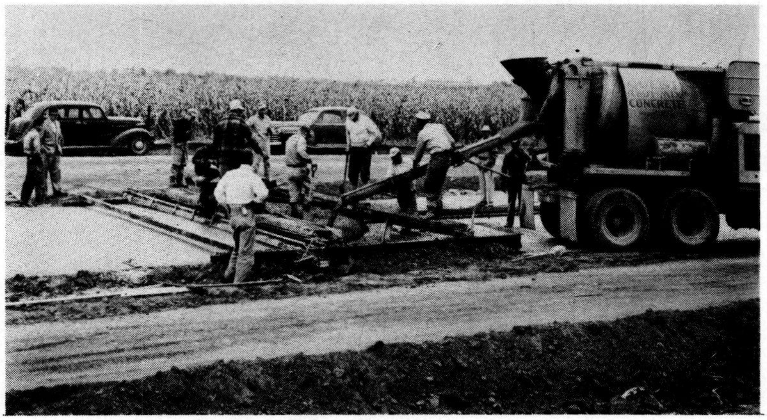

Figure 3.

erated from a winch on a truck. The concrete was deposited on the subgrade in front of the strikeoff and as the machine was pulled forward, it molded the concrete into a single lane of base course and did a creditiable job in the first attempt to construct full-width base course without forms.

Cores taken from the concrete slab constructed in this manner proved to be of good average thickness and the quality of the concrete compared favorably with concrete finished by other

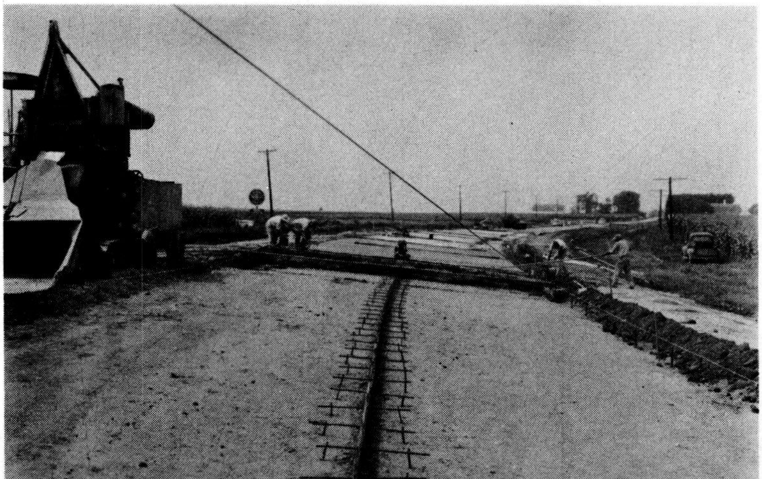

Figure 4.

methods. Following the construction of the base course, the bituminous surface was constructed and today it is impossible to locate this section of the road from general observation because it has the same appearance and riding qualities as the rest of the project.

Several important lessons were learned from this project. The installation of the tie bars across the centerline joint presented quite a construction problem as shown in

Figure 2. The construction of the second lane also had to be delayed until sufficient strength had been attained in the concrete placed in the first lane. It was realized from this experience that it would be more desirable to construct the full-width base course in one operation.

A second machine was built by another contractor later in the 1952 construction season. It was used on a 1,100-foot length of 22-foot width base course. This machine was very similar to the first machine so far as strikeoff, vibrating screed and length of runners were concerned; however, it provided for the construction of the full-width base course in one operation. This machine was also pulled by a single cable from a winch on a truck. The contractor placed the entire length of base course within the time limit of one average working day. This machine is shown in Figure 3. The construction of a full-width base course in one operation was proved more efficient by this machine; however, it was found that the single cable pull would not produce a straight edge alignment. It was decided that the machine should be pulled by separate cables from two winches to give better alignment control.

During 1953 two more machines were built in Illinois for the construction of full-width slabs without forms. One machine was similar to the second machine previously

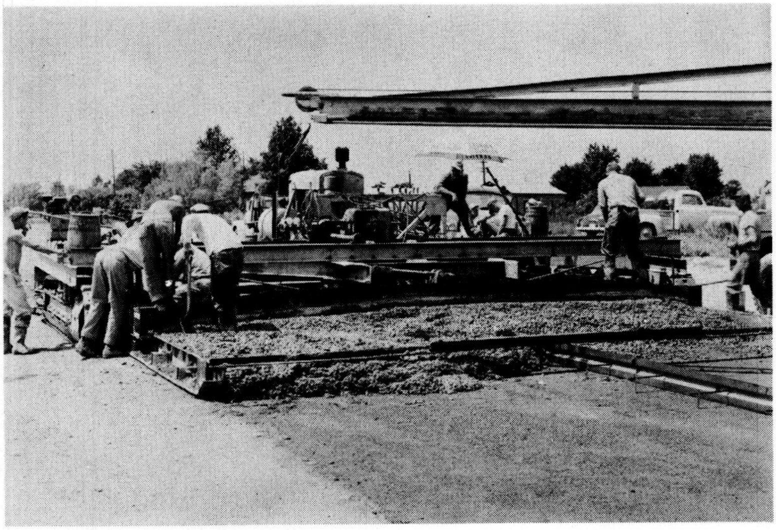

Figure 5.

described except that it was pulled by two cables—one attached to the front of each slip form. The two cables as expected permitted better edge alignment control. This machine actually built 10,384 feet of base course during the 1953 construction season. On one project it was used to construct the base course on two superelevated curves, which proved to be somewhat of a problem; the operation, however, was successful. Figure 4 shows the machine in operation.

DEVELOPMENT OF SELF-PROPELLED SLIP-FORM PAVERS

The experience gained with the cable-drawn machines confirmed our opinion that it was possible to build concrete slabs economically without forms. It was also conceded that better results and more efficient operation would be possible with a self-propelled machine; however, it was estimated that the cost of building such a machine for experimental purposes would amount to a considerable sum. It was considered doubtful that the contractors would care to make such an investment on experimental equipment.

Evidently there was a greater interest in this type of construction than we had anticipated because one contractor decided that he could and would build a self-propelled machine capable of meeting our requirements. This machine was built during the early month of 1953 and completed $3\frac{1}{4}$ miles of base course without a single mechanical failure.

This self-propelled machine shown in Figures 5 and 6 consisted of a regular concrete finishing machine with an additional vibrating screed placed between two oscillating screeds; the entire unit was mounted and attached to a pair of slip forms 30 feet in length. This unit was mounted on the inside of a power unit with two caterpillar tracks approximately 8 feet in length. The heavy duty power unit was capable of propelling the slip forms forward at several slow speeds or at high traveling speeds. It could also be operated in reverse. When constructing the concrete base course, the machine operated at a speed of 3 feet per minute. The concrete was deposited on the subgrade in front of the machine as shown in Figure 5, and as the machine moved forward, the concrete was struck off and the surface finished with the two oscillating screeds and the surface vibrating screed. The concrete was confined between the slip forms for a period of at least ten minutes. The machine was used successfully in placing 3.25 miles of 24-foot base course in 1953 and 3.39 miles of 22-foot base course in 1954, both having a thickness of 9 inches.

This machine actually laid as much as 1,044 feet of 24-foot base course 9 inches thick in one working day; however, there was no attempt to set a record and it was

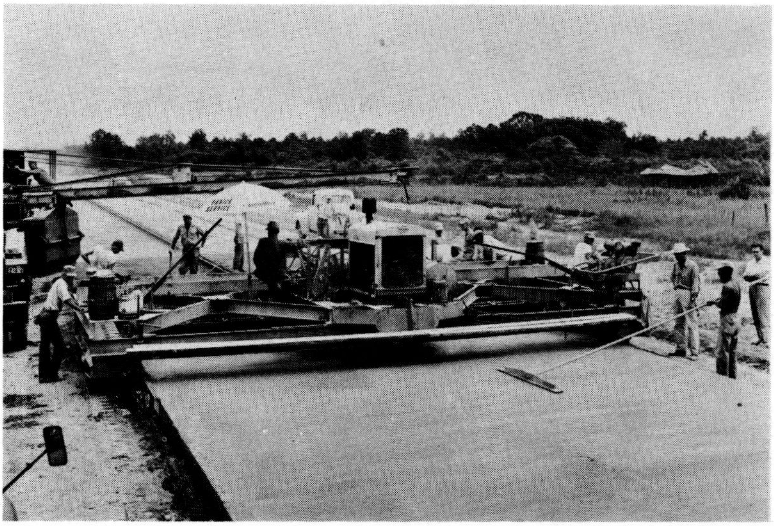

Figure 6.

evident that the machine would take care of as much concrete as could be produced by a 34-E dual paver. The edges of the concrete slab were straight in alignment and vertical with very little evidence of slumping. The concrete slab met the surface tolerance requirement of $\frac{3}{8}$-inch in ten feet.

The development and operation of the first self-propelled machine created considerable interest in Illinois and elsewhere. Another contractor decided that he would build a self-propelled machine incorporating his own ideas. The machine was placed in operation by this company on a contract early in 1954 to build 1.84 miles of 24-foot base course 9 inches thick. This machine is shown in Figure 7.

This machine also utilized the basic principles of modern pavement equipment but differed in some respects from the first self-propelled machine. The supporting framework for the engine, the adjustable strikeoff, the vibrating screed and the oscillating belt are mounted on permanent slip forms 22 feet in length. Temporary 16-foot slip forms are attached to the permanent slip forms making a total length of 38 feet, thereby lengthening the time that the concrete is confined within the forms. A burlap drag which performs the final surface finishing on the slab is mounted on the steel framework which holds the ends of the slip forms in line.

The caterpillar tracks which provide the forward motion are 22 feet long and extend for the full length of the permanent slip forms. These tracks are actually a part of the slip form unit. The plate at the inside edge of the caterpillar track forms the edge of the concrete slab. The tracks travel on the subgrade adjacent to the concrete slab and this portion of the subgrade is finished as accurately as though steel forms were to be

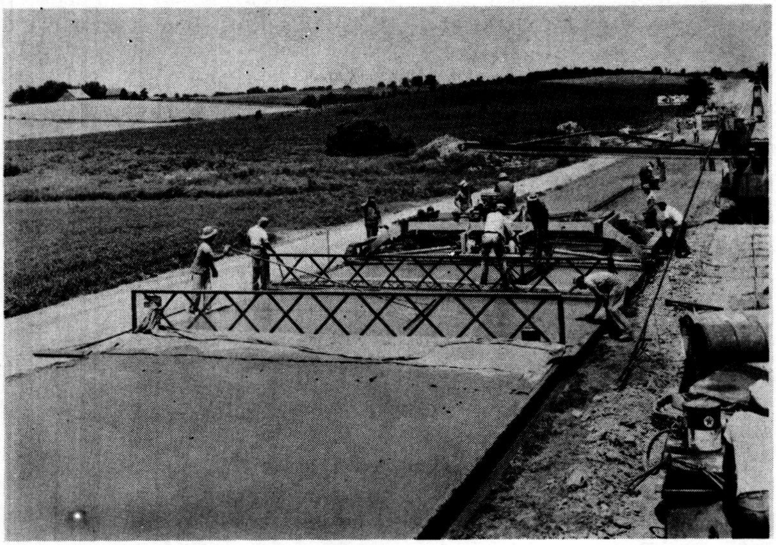

Figure 7.

placed. This accurately prepared subgrade permits the machine to hold a regular and true profile for the upper edge of the concrete slab.

In 1955 this contractor built several new machines incorporating a number of improvements. The machines are heavier in design and are adjustable to 20, 22 and

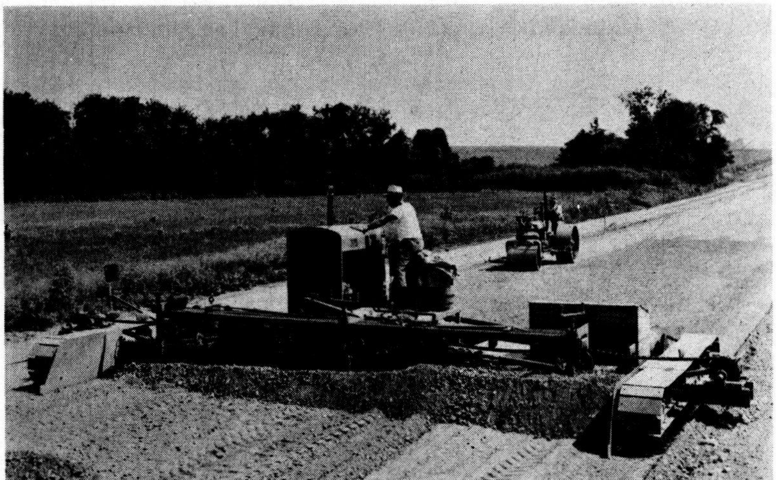

Figure 8.

24-foot widths and will construct concrete slabs having thicknesses of 7, 8, 9 and 10 inches. Tamper bars and internal tube vibrators have been mounted on the front of the machine to consolidate the concrete. A front view of this machine is shown in Figure 9, and Figure 10 shows the back view of the equipment and the finished base course. The machine can be operated at several speeds; however, a speed of approximately $2\frac{1}{2}$ feet per minute appears to give the best results.

DEVELOPMENT OF SELF-PROPELLED SUBGRADE MACHINES

One of the problems which faced this type of construction was an economical and accurate method of building the subgrade. Realizing this, one contractor developed

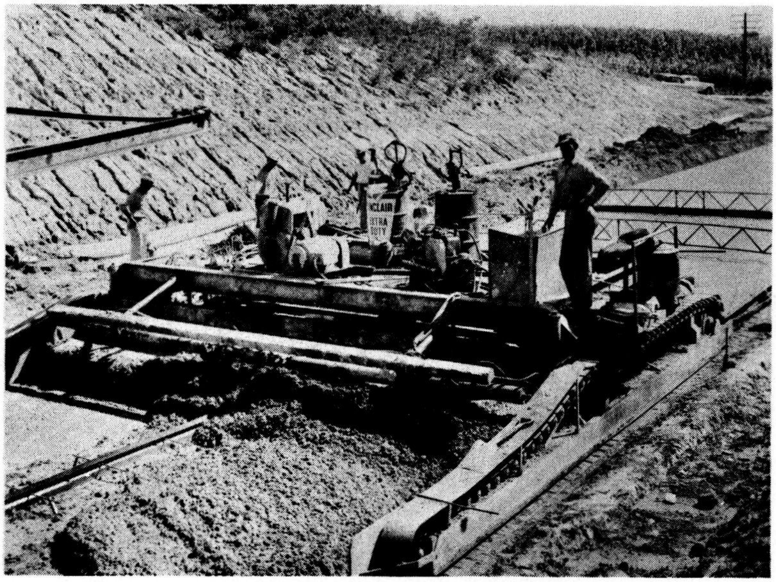

Figure 9.

the heavy duty self-propelled subgrade machine shown in Figure 8. The machine operates on caterpillar tracks and it consists of a transverse cutting blade set to cut the

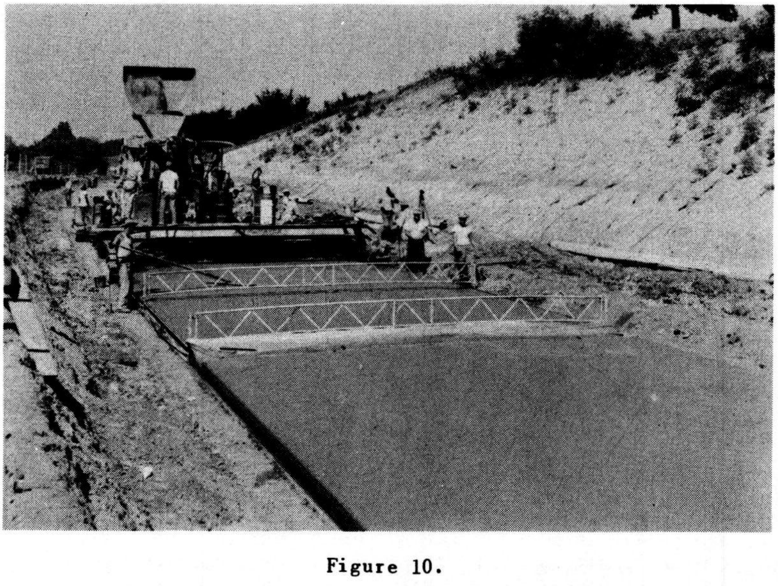

Figure 10.

subgrade to the proper crown profile. Another contractor converted a conventional power subgrader for this purpose by replacing the wheels with caterpillar treads and using chain drives to propel the machine. A front and back view of this equipment is shown in Figures 11 and 12.

The subgrade on which the tracks of the machine travel is accurately hand finished to the proper elevation. As the subgrade machine moves forward, it cuts the subgrade to the true elevation. When the paving machine, which also has caterpillar treads,

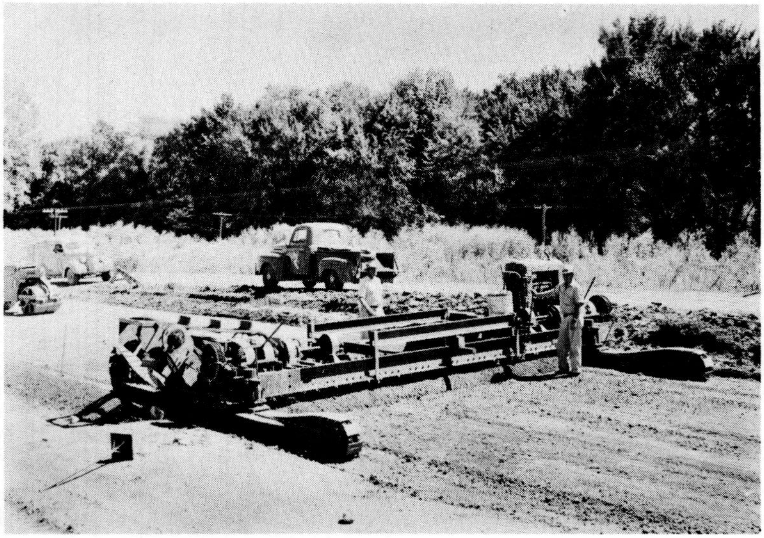

Figure 11.

moves over the same path, a uniform thickness of concrete slab is produced. The surplus subgrade material is carried to the shoulder by a conveyor belt. The machines construct an accurate uniform subgrade requiring almost no hand work. The self-

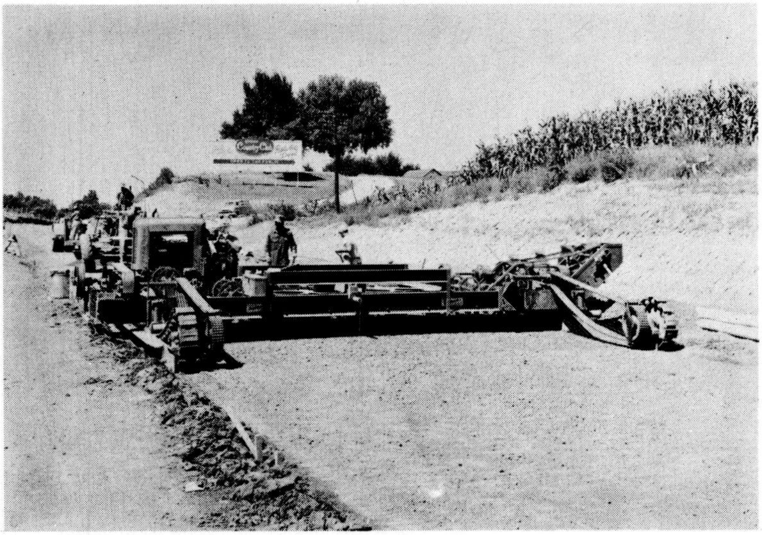

Figure 12.

propelled machines were a big improvement over the mechanically-drawn templet previously used in this type of construction. When the contractors exercised reasonable care in preparing the subgrade, the amount of overrun in concrete was reduced to less than 5 percent of the theoretical quantity.

SURFACE VARIATIONS

In order to encourage this type of construction, our specifications for base course were revised by increasing the permissible surface variation from 1/4-inch in 10 feet to 3/8-inch. We now feel that base course constructed with a slip form paver can be built to 1/4-inch tolerance, so we have recently changed back to that requirement. The following data was taken from projects which permitted a 3/8-inch variation:

NUMBER OF VARIATIONS

Length feet	1/8 inch	1/4 inch	3/8 inch
1,300	10	4	0
650	5	1	0
2,050	26	7	0
2,850	24	7	0
2,875	28	7	0
3,349	182	44	5
9,900	97	32	3

CORE STRENGTHS

As mentioned in the first part of this paper, cores have been taken from the finished concrete slabs on a number of projects and the quality of the concrete compares favorably with concrete finished by other methods. We have run a number of compression tests on these cores and the following are some of the results:

Number of Cores	Age	Average Strength psi.
16	20 to 28 days	4,168
35	4 months	4,515
14	5 months	5,367
13	6 months	5,658
17	10 months	6,060

The concrete used to construct the base course conformed to the following composition and consistency limits:

Cement used per cubic yard. . . . . 5.6 to 5.8 bags
Water used per bag of cement. . . . . 4.9 to 5.3 gallons
Slump. . . . . $1\frac{1}{2}$ to 2 inches
Air content . . . . 3 to 5 percent
Coarse aggregate furnished in two sizes.

COSTS

Complete cost data is not available; however, our estimating department has made a tentative analysis of one project. In constructing this project, which consisted of 6.1 miles of 24-foot 9-inch thick base, the contractor used 23 men and 2 foremen on the subgrading and paving operations. The equipment consisted of a 34-E dual drum mixer, self-propelled subgrade machine, self-propelled slip form paving machine, motor patrol, one pneumatic roller, one steel-tired roller, 2 water trucks, and 2 service trucks. An average of 120 lineal feet of concrete slab was laid per hour on this project and the best day's run was 1,525 feet. The common labor rate was $2.10 per hour and the computed labor cost (excluding plant batching and hauling costs) was found to be $0.20 per square yard.

CONCLUSIONS

The fact that the contractors are willing to finance the building of their machines certainly indicates that the new type of construction is more economical than conventional methods. The machines are capable of laying full-width slabs which are uniform in thickness and have straight edge alignment. The edges stand vertically with very little slumping. Compression tests made on cores removed from the base course indicate strengths comparable to concrete placed by other methods. It is possible to lay concrete slabs without forms meeting a surface tolerance of $\frac{1}{4}$-inch in 10 feet. With further development of this machine, it may be possible to meet the requirements of $\frac{1}{8}$-inch in 10 feet which is specified for concrete pavements.

Much has been accomplished through the effort of the Division of Highways to stimulate interest among the contractors to develop the new equipment. A total of 21.4 miles of concrete slabs has been completed by this method on state projects during the last four construction seasons. It is felt that the new equipment has passed beyond the experimental stage and is now in the development stage.

Use of the Kelly Ball for Field Measurement Of Concrete Consistency

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Highway Physical Research Engineers
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The Kelly Ball test is a simple field method for determining the consistency of plastic concrete. It is made by measuring the penetration of a 30-pound metal "ball" into the surface of the concrete. This test can be made on the concrete in place and can be made easier and faster than the slump test. The results of tests reported in this article show good correlation between the slump test and the Kelly ball penetration test.

● THE ASTM standard slump test[1] has been used for many years as a measure of the consistency of fresh concrete in the laboratory and on the job. As a laboratory procedure it is reasonably satisfactory. In the field, especially on paving work, it has several disadvantages and the most serious of these is the time required to make the test. Others are the necessity for careful selection of samples and the close attention to details of the technique required to obtain reasonably accurate results.

Realizing the disadvantages of the slump test as a field control method Professor J. W. Kelly, of the Department of Civil Engineering of the University of California, developed a penetration device that is rugged and portable. This test was recently made an ASTM Tentative Standard (C 360-55 T).

Professors Kelly and Polivka of the University of California give the following account of the development of this test in an article published recently (5):

"The test was developed in the Engineering Materials Laboratory of the University of California at Berkeley as an outgrowth of an attempt to devise a simple test for workability of concrete. Workability is an elusive property, and early trials with various balls showed little correlation with the more elaborate tests in laboratory use. However, it was observed that static ball penetration correlated rather well with slump and it became apparent that the penetration test measured some property similar to slump, a property which had been termed 'consistency' but which is now called merely 'slump' in ASTM C 143. It is the significant property which is measurable in the field for practical purposes.

A 6-inch ball was considered to be the smallest that would integrate the resistance to penetration over several pieces of aggregate, and a 30-pound weight was found to be the lightest that would penetrate reproducibly the stiffest mixes of plastic concrete. This combination of area (or displaced volume) and force has been found applicable even to harsh concrete containing 2½-inch aggregate and having a nominal slump when wet-screened of 1½ inches. The apparatus has also been used on mass concrete containing 0 to 6-inch crushed aggregate by making the penetration test only on areas which had been found by probing to be free from the larger pieces of aggregate. A 20-pound weight on a 6-inch ball has sometimes been used for lightweight concrete.

Penetration tests have been developed independently in other countries. A static test used in Spain employs a weight on a spherical tip and having a flared edge so that the plunger will not sink too deep into wet concrete. The German Committee on reinforced concrete has adopted an impact test suitable for stiff mixes or mixes of low cement content; it consists in dropping a 33-pound plunger having a 4-inch hemispherical tip 8 inches onto the surface. In England, the Wigmore consistometer employs a metal ball set on the surface of a concrete sample which is vibrated on a table.

The static ball test was introduced to field use by E. L. Howard, Testing Engineer, Pacific Coast Aggregates, Inc., San Francisco. His experience with the variety of mixes used in ready-mixed concrete was so successful that it encouraged the authors

[1] Standard Method of Test for Slump of Portland-Cement Concrete, ASTM designation: C 143-52.

to report the test to ASTM Committee C-9 at its San Francisco meeting in 1949. Howard has continued to contribute to its field development, and is convinced that it will eventually replace the slump test.

Many other organizations have adopted the ball test, and hundreds of balls are in use throughout the country. The California Division of Highways has adopted it as a standard for field use on pavement construction. At least two other state highway departments, North Carolina and Colorado, are using it extensively. The Waterways Experiment Station, Concrete Division, U.S. Army Corps of Engineers, has adopted it as an alternative standard."

Kelly Ball Apparatus

The apparatus is popularly known as the "Kelly ball." It is made by machining into a hemisphere, one end of a solid right cylinder 6 inches in diameter and 4⅝ inches in height. It is fitted with a graduated vertical rod ½ inch in diameter which serves as a measuring scale and a handle. The vertical portion of the rod is graduated in ½-inch units with each inch numbered. The ball is guided by a stirrup or frame which also serves as a reference line in the measurement of the penetration of the ball into the plastic concrete. The zero on the graduated handle coincides with the top of the frame when the apparatus rests on a level rigid surface. The weight of the ball and handle is 30 pounds. The sketch of the original apparatus is shown in Figure 1.

Modification of the Kelly Ball

The Kelly ball equipment used by the Bureau of Public Roads differs from the original in the following details:

1. To prevent the reference frame from tilting, the bearing area of each foot of the frame (originally specified as 1½ square inches) was increased by the addition of semicircular bearing plates of 5-inch diameter (area approximately 9¾ square inches). The clear distance between the feet was maintained at 9 inches as originally specified (see Figure 2). This change is included in the ASTM Tentative Method C 360-55T.

2. To facilitate reading the depth of penetration of the ball, a vertically movable pinch clamp was fastened to the graduated handle. This is clamped at the top of the handle before making the test and is lowered to make contact with the top of the frame after the ball has penetrated the surface of the concrete. The apparatus is then removed from the concrete and the penetration reading is made reading the position of the clamp on the rod. This makes the test procedure more convenient for the operator and avoids any possible delay in the concreting operation.

Use of the Kelly Ball

Plastic concrete can be tested with the Kelly ball after placement in the forms and prior to any manipulation or in suitable containers such as tubs, pans, wheelbarrows, or buggies.

In making the test, the surface of the concrete is smoothed and leveled quickly by the use of a small wooden float or screed. The surface is worked as little as possible to avoid formation of a mortar layer. During the test, the adjacent concrete should not be vibrated, jarred, or agitated.

The ball is held vertically by the handle in very light contact with the leveled concrete surface and with the zero on the rod coincident with the top of the frame. The handle is then released and the depth of penetration of the ball into the concrete is estimated on the graduated rod to the nearest 0.1 inch. (see Figure 3). A minimum of three readings should be taken from a batch or location. No correction is made for any slight settlement of the feet of the frame. The test requires less than ½ minute to perform, which allows the operator sufficient time to work where the concrete is being discharged from the mixer without delaying the placing and finishing operations.

Experience has indicated that the minimum depth of concrete tested should be 6 inches for a maximum size of coarse aggregate of 2 inches or less. When larger coarse aggregate is used, the minimum depth should be three times the nominal max-

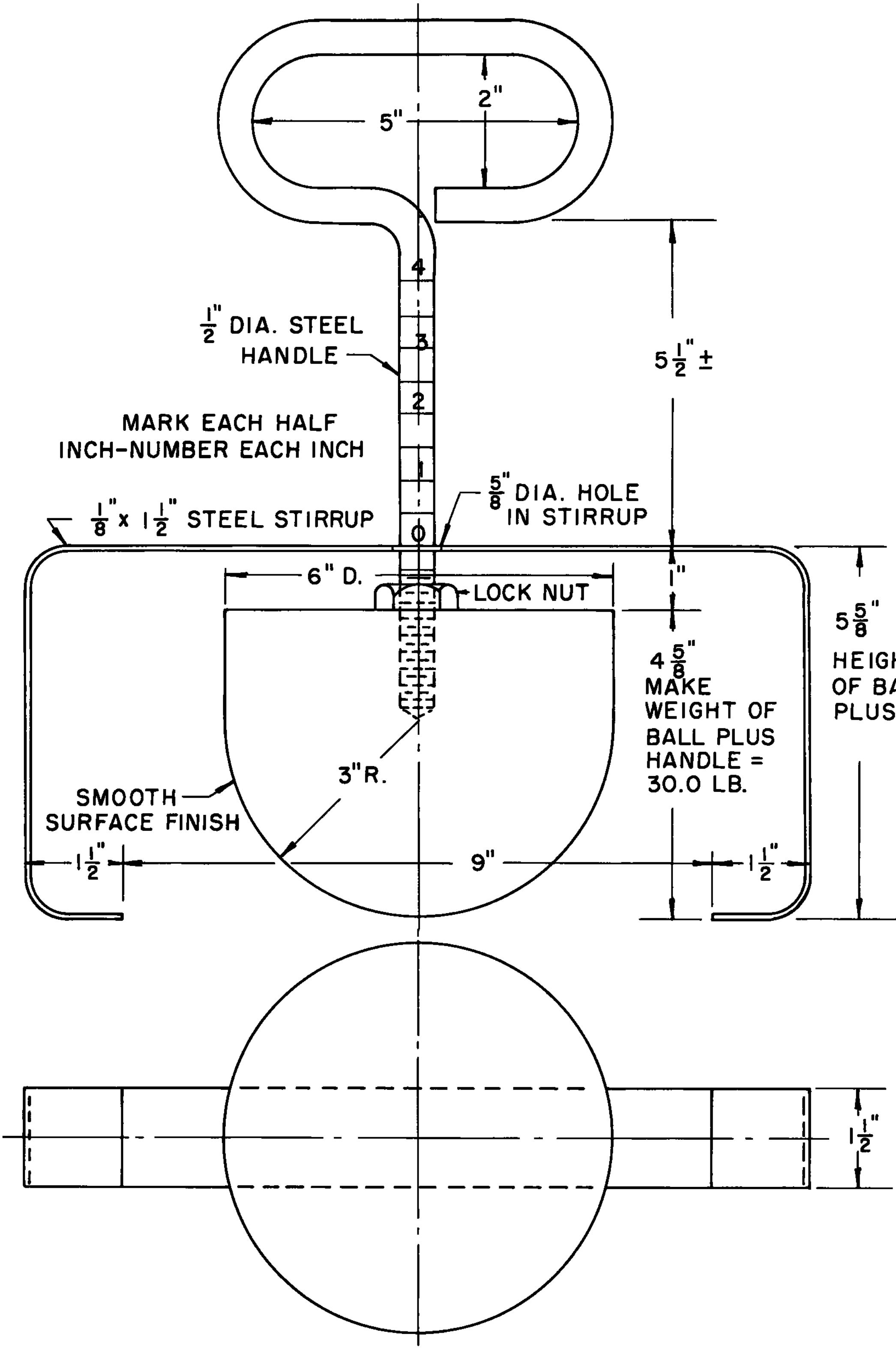

Figure 1. Ball-penetration apparatus for consistency of concrete.

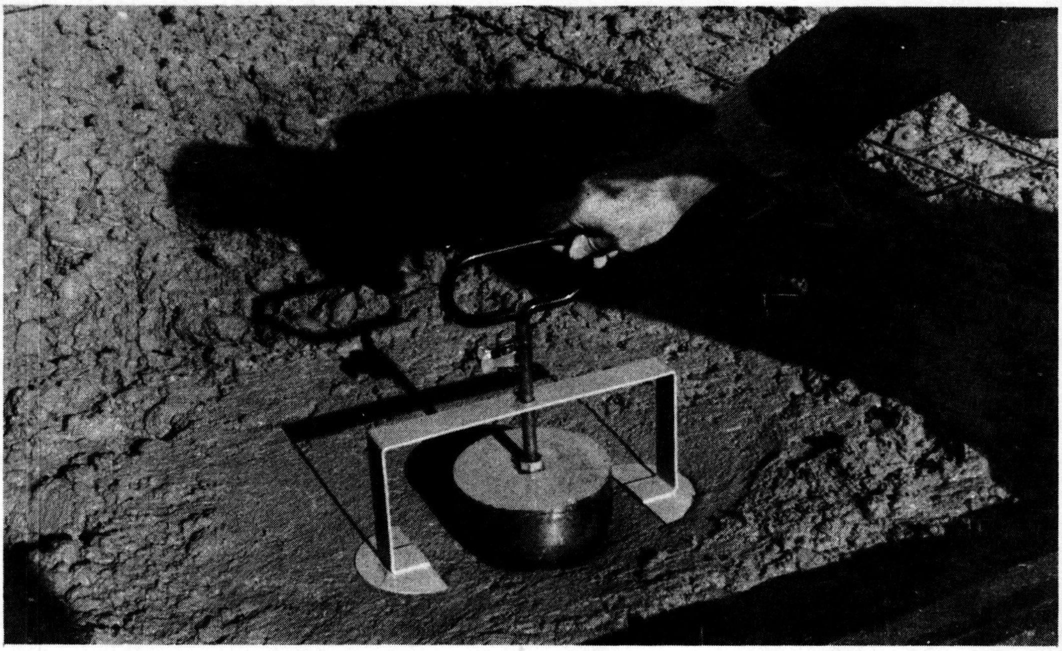

Figure 2. Kelly ball penetration test as used in the field.

imum size of coarse aggregate. When testing concrete placed inside forms, as in piers, walls, etc., a minimum horizontal distance of 9 inches from the face of the form to the point tested should be maintained to avoid boundary effects. For concrete discharged on the subgrade in pavement work, no test should be made nearer than 9 inches to the form edge of the leveled surface of the concrete. For a second test in the same batch of concrete the foot of the stirrup should be at least 6 inches from the point where the foot rested in the first test.

TABLE 1

CORRELATION OF KELLY BALL PENETRATION TEST AND SLUMP TEST FOR CONSISTENCY OF CONCRETE

Field Tests — Project No. 1

Kelly ball penetration		Slump
Individual	Average	
Inches	Inches	Inches
2.5-2.4	2.4	4.7
2.8	2.8	4.0
3.7	3.7	4.4
2.7	2.7	4.3
2.3-2.5	2.4	3.7
1.7-1.9-1.5	1.7	2.3
3.7-3.1	3.4	4.1
1.4-1.4-1.1	1.3	0.7
2.5-2.6-1.9	2.3	3.9
1.8-1.0	1.4	1.7
2.6-2.8	2.7	3.7
2.0	2.0	3.3
1.4-1.6	1.5	2.6
3.2-3.4	3.3	4.5
1.1-1.2-1.2	1.2	2.3
2.7-3.5-2.6	2.9	4.7
4.2-4.7-3.7	4.2	5.3
2.2-2.2-2.4	2.3	3.7
Average [a]	2.4	3.6

Coarse aggregate - Gravel, 2-inch maximum size.
Cement content = $6\frac{1}{2}$ sacks of cement per cubic yard.
Air content = 5 percent.

[a] Ratio of penetration to slump = 1 to 1.5.

Field Tests Using Kelly Ball

A limited number of tests were made on several paving projects to correlate Kelly ball penetration readings with the corresponding slumps. The concrete used on the first of these projects contained $6\frac{1}{2}$ sacks of cement per cubic yard, 2-inch maximum size gravel, and about 5 percent air. Batches were selected so that tests could be made without delaying the progress of the work and so that some adjustments could be made in the water content and consistency of the batches. The concrete was discharged on the subgrade in a pile 8 to 10 inches in height. A sample for the slump test was taken and thoroughly remixed in a pan. The Kelly ball penetration test was made on the concrete in place on the subgrade prior to any manipulation. The top surface of the concrete was leveled with a wood float, the apparatus set on that surface, and the penetration read. The water content of the concrete was varied in order to obtain a greater range in consistency. Usually 2 or 3 Kelly ball penetration readings were made for comparison with the reading of each slump. The test data taken over a two-day period are tabulated in Table 1 and are shown graphically in Figure 4 (A). The average penetration was 2.4 inches, the average slump was 3.6 inches, and the ratio of penetration to slump was 1 to 1.5.

The concrete on the second project had the same cement content and the same max-

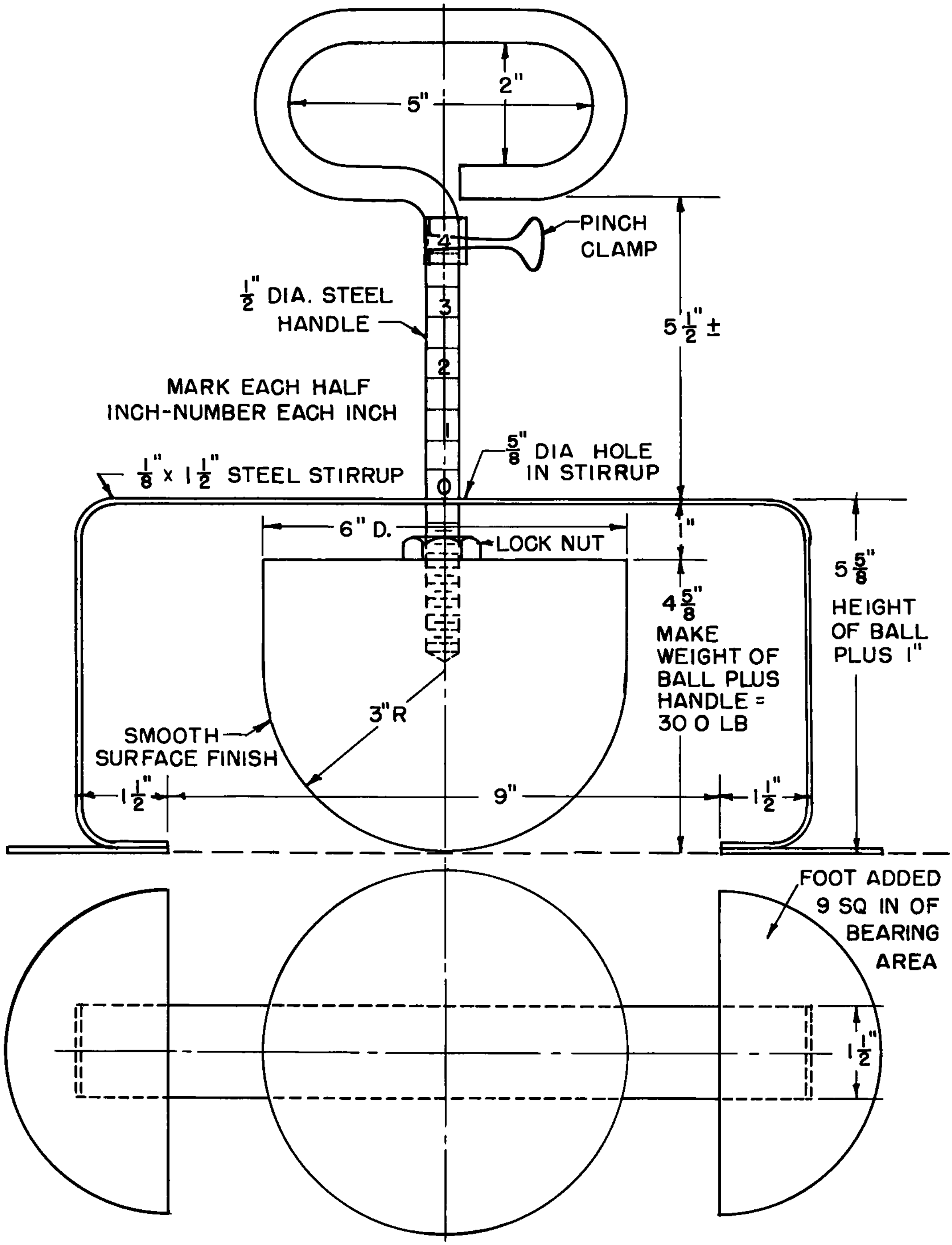

Figure 3. Ball-penetration apparatus for consistency of concrete Bureau of Public Roads modification.

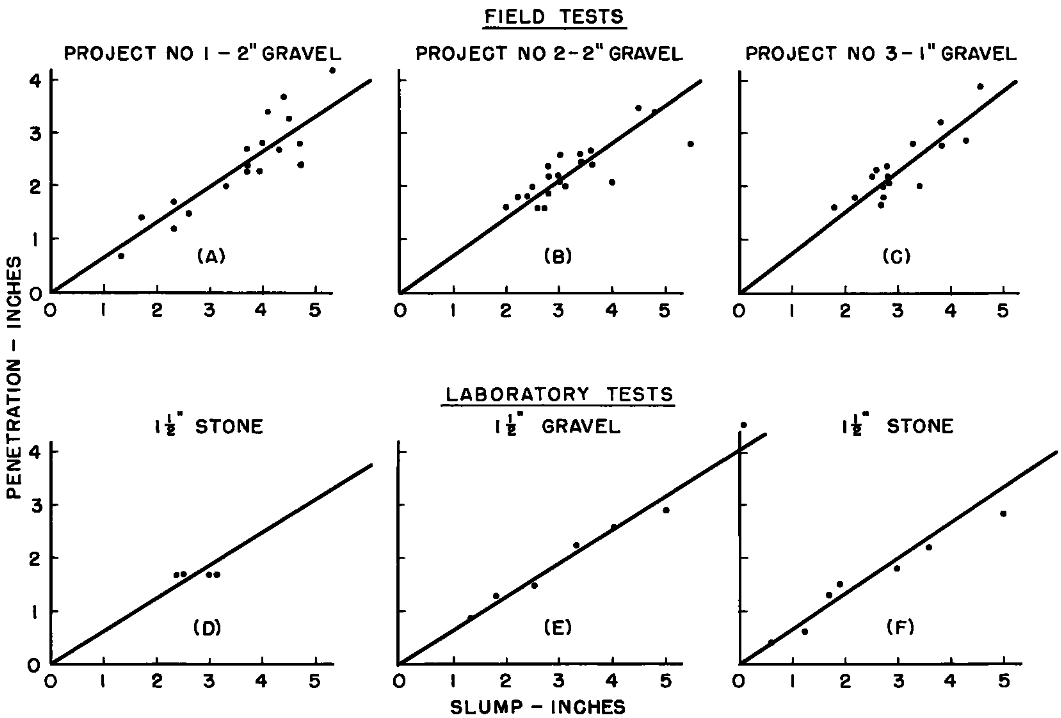

Figure 4. Correlation of Kelly ball penetration test and slump test.

imum size coarse aggregate as that on the first project. The aggregates were from a different source and the concrete was mixed in a ready-mix truck. The test data taken over a 7-day period are tabulated in Table 2 and are shown graphically in Figure 4 (B). For this job the average penetration was 2.3 and the average slump was 3.2 inches. The ratio of penetration to slump was 1 to 1.4.

The concrete in the third project was similar to that in the second project, but the maximum size of coarse aggregate was 1 inch instead of 2 inches. The test data were taken over a 6-day period and are tabulated in Table 3 and are illustrated in Figure 4 (C). The average penetration and average slump for this job were 2.3 and 3.0 inches respectively. The penetration-slump ratio was 1 to 1.3.

The data in Tables 1, 2, and 3, and Figure 4 (field tests) show a reasonable correlation between Kelly ball penetration and slump readings for a range in slump of 1 to 5½ inches. The average Kelly ball reading multiplied by 1.4 would provide a fair estimate of the corresponding slump for the range indicated, and materials used. These limited data indicate that for a maximum size of coarse aggregate of 1 inch this ratio might be reduced to 1.3.

Laboratory Tests

Slump tests and Kelly ball penetration

TABLE 2

CORRELATION OF KELLY BALL PENETRATION TEST AND SLUMP TEST FOR CONSISTENCY OF CONCRETE

Field Tests — Project No. 2

Kelly ball penetration		Slump
Individual	Average	
Inches	Inches	Inches
1 6	1 6	2 7
2 1	2 1	4.0
2 0-1.8	1 9	2 8
2 2-2 0	2 1	3.0
3.1-2 0	2 6	3.0
1.7-2 2	2 0	3 1
2 3-1.3	1 8	2.5
2.1-2 8	2.4	2.8
2.8-2.5	2 6	3 4
1.6-1 7	1.6	2.6
2.2-2.2	2 2	2.8
3.6-3.4	3.5	4 5
1.6-1.6	1.6	2.0
2.0-1.6	1.8	2.2
2.2-2 2	2 2	3.0
2 4-2.6	2 5	3.4
2.6-2.1	2 4	3 6
2.8-2 9	2.8	5.5
3.5-3 3	3 4	4.8
1.6-2.1	1.8	2 4
2 5-2.9	2.7	3.6
Average [a]	2.3	3.2

Course aggregate - Gravel, 2-inch maximum size.
Cement content = 6½ sacks per cubic yard.
Air content = 5 percent.

[a]Ratio of penetration to slump = 1 to 1.4.

readings were also made on concrete mixed in the laboratory and placed in steel forms for the fabrication of slabs for structural tests containing approximately 33 cubic feet of concrete. The water content was the same for all batches.

The concrete was non-air-entrained and contained 6 sacks of cement per cubic yard with crushed stone coarse aggregate of 1¼-inch maximum size. The results of these tests are shown in Table 4 and in Figure 4 (D). This figure does not have much significance due to the limited number of tests. For these tests the average slump was 1.6 times the Kelly ball reading.

Laboratory tests were made on concrete mixes using both gravel and crushed stone coarse aggregates of 1¼-inch maximum size and having variable slumps. The concrete was non-air-entrained and contained 6 sacks of cement per cubic yard. The water content was varied to produce slumps ranging from 1 to 6 inches. The results of these tests are tabulated in Table 5 and are shown graphically in Figure 4 (E) for the gravel concrete and Figure 4 (F) for the crushed stone concrete. The ratio of the average Kelly ball penetration to slump was 1 to 1.6 for crushed stone and 1 to 1.5 for gravel. These tests show approximately the same relation between the slump and Kelly ball readings as were shown for the field tests where similar materials were used.

The results of field and laboratory tests discussed in this article are in reasonably good agreement with those obtained by other investigators. In an extensive series of tests conducted by the Concrete Division, Waterways Experiment Station of the U.S. Army Corps of Engineers at Jackson, Mississippi, the average ratio of slump to penetration of 1.8 was reported as compared

TABLE 3

CORRELATION OF KELLY BALL PENETRATION TEST AND SLUMP TEST FOR CONSISTENCY OF CONCRETE

Field Tests — Project No 3

Kelly ball penetration: Individual	Kelly ball penetration: Average	Slump
Inches	Inches	Inches
3.4-3.0	3.2	3.8
2.3-2.5	2.4	2.8
2.4-2.2	2.3	2.6
2.3-2.2	2.2	2.5
3.0-2.6	2.8	3.8
2.0-1.7	1.8	2.7
1.6	1.6	1.8
2.8-2.9-3.1	2.9	4.3
1.9-2.4-1.8	2.0	2.7
1.8-1.9-1.8	1.8	2.2
2.1-2.2-2.0	2.1	2.8
3.8-4.0	3.9	4.6
1.6-1.5	1.6	1.8
2.1-2.4	2.2	2.8
2.8-2.8	2.8	3.3
1.8-1.6	1.7	2.7
2.0-1.9-2.2	2.0	3.4
Average[a]	2.3	3.0

Coarse aggregate - Gravel, 1-inch maximum size.
Cement content - 6¼ sacks per cubic yard.
Air content, 5 percent.

[a] Ratio of penetration to slump = 1 to 1.3.

TABLE 4

CORRELATION OF KELLY BALL PENETRATION TEST AND SLUMP TEST FOR CONSISTENCY OF CONCRETE

Laboratory Tests - Fixed Water Content

	Kelly ball penetration	Slump
	Inches	Inches
	1.7	-
	2 2	-
	1.7	2.5
	2 0	-
	1.7	2.4
	1.7	-
	1 4	-
	1.5	-
	1.7	3.1
	1 5	-
	1.7	3.0
Average[a]	1.7	2.8

Coarse aggregate - Crushed Stone, 1¼-inch maximum size.
Cement content = 6 sacks per cubic yard.
Non-air-entrained concrete.

[a] Ratio of penetration to slump = 1 to 1.6

TABLE 5

CORRELATION OF KELLY BALL PENETRATION TEST AND SLUMP TEST FOR CONSISTENCY OF CONCRETE

Laboratory Tests — Varying Water Content

	Mix 1 - Stone C.A.		Mix 2 - Gravel C.A.	
	Kelly ball penetration	Slump	Kelly ball penetration	Slump
	Inches	Inches	Inches	Inches
	0.4	0.6	0.9	1.3
	0.6	1 2	1.3	1.8
	1.3	1 7	1.5	2.5
	1 5	1.9	2.3	3 3
	1 8	3.0	2 6	4.0
	2.2	3 6	2.9	5.0
	2.8	5.0	3.8	5.6
			4 5	6.5
Average[a]	1.5	2 4	2.5	3.8

Each value for slump is average of two tests and each value for Kelly ball is average of six tests.
Maximum size coarse aggregate 1¼ inches.
Cement content = 6 sacks per cubic yard.
Non-air-entrained concrete.

[a] Ratio of penetration to slump for gravel = 1 to 1.6.
Ratio of penetration to slump for stone = 1 to 1.5.

to 1.5 and 1.6 obtained in this study. Walker and Bloem[2] in an unpublished report give the average ratio of slump to penetration of 1.66 for over 250 tests.

Advantages of the Kelly Ball Test

On any particular project using specific materials, a limited number of tests will correlate the Kelly ball readings with the corresponding slump tests sufficiently to permit using the Kelly ball for the control of the consistency of the concrete when a slump range has been specified.

The following comments are made on the Kelly ball test as a replacement for the slump test for measuring the consistency and uniformity of concrete in the field:

1. The concrete may be tested in place, therefore the selection or preparation of a sample is eliminated.
2. Three or more Kelly ball tests can be made at a selected location in less time and with less effort than is required for one slump test. Due to the speed with which

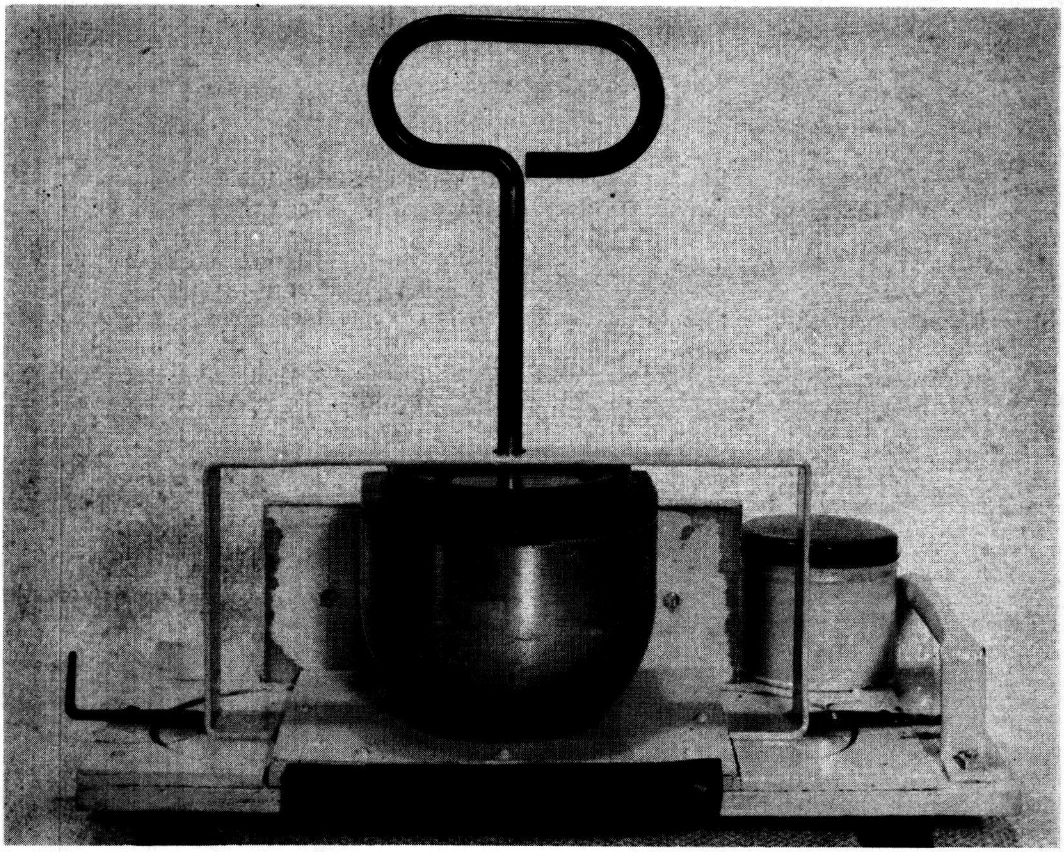

Figure 5. Field carrying kit for Kelly ball apparatus.

the test can be made, the operator can work where the concrete is being discharged from the mixer without delaying paving or finishing operations.

3. Making the consistency test easier and faster, should encourage more frequent testing and should be helpful in the control of the uniformity of the concrete.
4. The apparatus can be maintained in usable condition between tests by merely wiping with an oily rag.

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[2] Director of Engineering and Assistant Director of Engineering, respectively, National Sand and Gravel Association and National Ready Mixed Concrete Association.

5. The slump test is not practical for use in testing concrete with a maximum size of coarse aggregate over 2 inches. The Kelly ball penetration test may be used on concrete containing larger aggregate if a sufficient volume is available to provide adequate depth.

Field Kit

For ease in transporting, the ball with wood float and a base plate can be readily assembled into a compact field kit as shown in Figure 5. The wooden float is used to level the concrete at the area to be tested. A tin "rag can" provides a place to keep oily cloth or waste to wipe the ball clean after each test. The ball should not be placed too near the side forms or the edge of a pile of concrete in order to meet this requirement, the operator must often place one foot into wet concrete to set the ball in place. The carrying base plate is designed as a foot board to support the weight of the operator on the plastic concrete.

The apparatus may built in any machine shop. However, it has been adopted as a tentative standard by the American Society for Testing Materials and may be offered for sale by the leading instrument companies.

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Sawed Joints In Concrete Pavements: Progress and Problems

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● SINCE the earliest days of concrete paving, joints have been formed in the plastic concrete by various means. Recently there has developed a new practice of cutting joints in the hardened concrete by means of special sawing equipment of various makes utilizing diamond or silicon carbide blades or discs. The cut is made only part way through the slab, creating a weakened plane which subsequently cracks through the full depth of the slab.

Purpose of Sawing Joints

The purpose of experimenting with sawed joints was to find a type of joint that would be smoother riding and less subject to spalling than the customary formed joints. Considerable difficulty had been experienced in many states in obtaining consistently good results with formed joints. The various processes employed to create a weakened plane, such as inserting and removing a steel bar and the hand tooling of the joints, apparently disturbed the plastic concrete in a way that weakened it and caused subsequent spalling. Also the finishing process often resulted in elevating the concrete slightly, creating bumps at the joints. The quality of a formed joint depends largely upon the skill of the workman making the joint. In contrast the sawed joint appears to have overcome these shortcomings even when the work is done by novices.

Spread of Experimentation over the States

In the past five years the practice of sawing joints has spread rapidly over the country until at least 28 states have tried it and with minor exceptions have found the new practice to their liking. Sawed joints have been tried with apparent success upon a variety of pavement designs both reinforced and plain with slab lengths from 15 to 100 feet, both with and without load transfer devices of various designs. Kansas was the first state to make widespread use of sawed joints and was the first state to develop standard specifications. Relatively few other states have had sufficiently varied sawing experience to warrant the drafting of standard specifications.

Construction Problems

While sawed joints appeared to eliminate the spalling and roughness often associated with formed joints they created new construction problems. It became apparent in the early sawed-joint projects that random transverse cracks were likely to occur unless so-called "control" joints or relief joints were either formed at intervals of 60 to 100 feet or sawed at an early age. Kansas initially elected to use formed control joints at 80 to 100 feet thereby eliminating the problem of early sawing. With their wet earth curing, to reduce shrinkage, and their 20-foot reinforced slab design, Kansas experienced no cracking between the formed control joints up to 30 days. Other states sawed intermediate joints at various times and little or no uncontrolled cracking was encountered.

Sawing Control Joints. There was a tendency for other states to follow the lead of Kansas and to form control joints in the plastic concrete rather than saw them. However, some believed that if sawed joints were superior to formed joints it would be beneficial to have all joints sawed, provided the sawing of control joints was feasible. Minnesota's experience showed that it was feasible to saw control joints and that the best procedure to assure an adequate margin of safety between the time of sawing and the time of cracking was to saw at an early enough age of the concrete to produce a slight amount of spalling and water erosion of the joint edges. Under certain favorable conditions such as (1) uniform temperature, (2) aggregates having a low coefficient of thermal expansion, and (3) curing methods having high insulating properties, the sawing of control joints may be deferred until the concrete has hardened sufficiently to prevent spalling and water erosion.

Experience in Virginia, Minnesota, Wisconsin, California and Colorado on projects utilizing sawed-control joints indicates that concrete placed in the first part of the day or up until 12 or 1 o'clock has a tendency to crack much sooner than that placed in the afternoon. The morning concrete usually cracks the first night after placing while the afternoon concrete generally cracks the second night. Consequently it appears advisable to saw the control joints for morning concrete the same afternoon or night unless weather conditions retard the setting of the concrete to such a degree as to make sawing unfavorable. The time required for the concrete to become hard enough to saw without excessive tearing has varied from 4 hours to over 24 hours. The most common way of determining when the concrete has hardened sufficiently to saw without excessive tearing is to make a very short cut with the saw and observe the condition of the joint edges. Other means are being sought to determine the earliest time when the concrete is hard enough to saw. Experience has shown that it is impractical to define the time for sawing as a specific number of hours elapsed after placing the concrete, due primarily to the influence of weather. Hot dry weather accelerates and cool damp weather retards the hardening of the concrete.

Some uncontrolled cracking has been experienced in a number of states where control joints were sawed rather than formed; but, in practically all cases when the cracks had a tendency to occur prior to sawing the control joints the trouble was corrected by sawing at an earlier age. There was one exception to this general observation: Control joints were being sawed in the early morning within the 24-hour specification limit for concrete placed the previous day and the slab was cracking through while the saw was only part was across the pavement, producing a random crack from the blade to the opposite edge of the slab. This trouble was remedied by delaying the sawing for several hours during which time the sun raised the slab temperature and reduced the tensile stresses to the point where sawing could be accomplished without danger of premature rupture. It is probable that earlier sawing in this instance, before shrinkage and contraction stresses approached the rupture point, would also have solved the difficulty. In similar situations where cracking is occurring during the sawing operation and temperatures are not expected to rise it might be expedient to reduce the depth of saw cut.

Regarding the preceding discussion of control joints it should be pointed out that the sawing was done with diamond blades which wear out much faster in cutting the green concrete than when cutting the intermediate joints in the older concrete. Consequently this system of sawing control joints in the green concrete and sawing the intermediate joints in the older concrete was preferable to consecutive sawing of all the transverse joints in the green concrete not only because of the better quality of the joint edges but also for economic reasons. It is reported that due to the sand particles working loose from the green concrete blade life in sawing control joints is reduced to approximately one-half that in sawing intermediate joints.

Consecutive Joint Sawing. In the past two years increased use has been made of reinforced silicon carbide discs, in lieu of diamond blades, for sawing concrete made with the relatively softer aggregates such as limestone and slag. It is reported that these abrasive discs permit earlier sawing of the green concrete than diamond blades and unlike diamond blades have a longer life in sawing green concrete than for sawing older pavement. Consequently the practice with silicon carbide discs has generally been to saw all joints early and consecutively.

Cost of Sawing. From an economical standpoint there appears to be a zone of aggregate hardness where the cost of sawing is approximately equal for diamond and silicon carbide discs. For relatively softer aggregates the silicon carbide is more economical and for harder aggregates the diamond is better. In some instances silicon carbide discs were used for sawing the control joints and diamond blades were used to saw the intermediate joints.

The cost of sawing joints varies over a wide range depending upon a number of variables, such as the type of aggregate, age or hardness of concrete mortar at the time of sawing, depth of cut, type of equipment and skill of operators. Reported prices per linear foot range from a low of $0.03 to a high of $0.83 and average about $0.35 per linear foot. The largest single item of expense connected with sawed joints is the blade cost, which for a 12- by ⅛-inch diamond blade averages about $150.00. Reports on various experimental projects indicate that the blade life ranges from about 400 to 6,000 linear feet and averages approximately 1,500 linear feet.

The cost of silicon carbide discs ranges from $5 to $18 per disc which is 10 percent or less of the cost of diamond blades.

Some attempt has been made to correlate blade life with aggregate hardness as measured by the percentage loss in the Los Angeles Rattler test, however the relation is inconsistent in some instances. Two states have reported that the presence of a small percentage of flint in the coarse aggregate caused silicon carbide discs to break. Apparently when a disc strikes a piece of the hard flint rock it is deflected from a straight cut and an excessive bending movement causes the disc to shatter.

A comparison between the cost of forming and the cost of sawing joints is difficult due to the wide range in sawing costs. On several projects where aggregates were relatively hard the cost of sawing was reported as approximately double that for forming joints. On numerous other projects costs for sawing and forming were estimated to be equal. Certain benefits resulting from the sawing practice are difficult to evaluate such as elimination of mixer shutdowns to allow the joint forming operations to catch up, and reduction of time between placing the concrete and applying the curing compound.

Sawing Longitudinal Joint. Some states have experimented with the sawing of the longitudinal joint as well as transverse joints. From their experience it has been found that the time interval before sawing is not critical and the cost of sawing longitudinal joints is comparable with that for sawing intermediate transverse contraction joints.

Single-Lane Construction. Most of the pavements where sawed joints have been tried were placed full width or two lanes constructed at the same time and the preceding observations apply to that type of construction only. Where a single lane is placed and the adjacent lane is constructed later a serious construction problem is presented in placing and forming joints in the second lane. If the temperature drops after the second lane has been placed, the hardened concrete in the first lane contracts and joints in it that have cracked through, open up. This movement is transferred to the green concrete slab by way of the tie bars and edge friction thereby adding external stresses to the internal stresses caused by hardening, shrinkage and temperature contraction. California experimented with this type of construction and found that at times the initial lane transmitted enough stress to the second lane to result in an uncontrolled crack before the concrete had set hard enough in the latter to permit sawing. Subsequently other states had similar experiences and some solved the problem by using formed joints in the second lane opposite every open joint in the first lane. Others due to favorable local conditions such as relatively soft aggregates and moderate temperature fluctuations have successfully eliminated uncontrolled cracking in this type of construction by very early sawing. The use of insulation applied to the surface of both lanes has not yet been reported by any state but from theoretical considerations would seem to be worth trying.

Design Problems

Joint Depth. The sawed-joint technique has not necessarily created a new problem concerning the depth of cut since the depth of a formed joint adequate to control the location of cracking will also be adequate depth for a sawed joint. There is one important difference. The cost of forming joints does not vary appreciably with the depth. Consequently it has been customary to allow a generous safety factor in specifications for depth of formed joints. On the other hand the cost of sawing varies pronouncedly with the depth. It is reported that a 2-inch cut costs over twice as much as a 1-inch cut. Several states have varied the depth of cut from 1 to 2 inches on 8- and 9-inch slabs. Due to varying local conditions the 1-inch cut was found to be adequate in some states and inadequate in others. In all instances it was reported that 1½-inch depth of cut was satisfactory for both transverse and longitudinal joints. Colorado reports that with 1-inch cuts in 8-inch slabs all the joints cracked through, but cracks of various lengths developed about 1 to 2 inches alongside of and roughly parallel to the saw cut. These cracks were from a few inches to several feet in length and would start and end at the saw cut. It is their belief that these cracks formed around the larger aggregate particles lying close to the surface. The maximum size of aggregate was 2 inches in this case. It is believed that aggregate size is a factor in determining the minimum depth of cut.

Joint Spacing. The question as to the optimum spacing of joints has been with us since the earliest days of concrete paving and the advent of sawed joints has little effect upon the problem except as related to joint width and sealing.

Width of Cut and Sealing. While sawed joints may be cut the same width as formed joints they generally are narrower being about ⅛-inch when diamond blades are used and ¼-inch with silicon carbide discs. Wider joints may be obtained by making a second cut parallel to the first and usually shallower. The intervening concrete may be broken out with hand tools. Obviously this would materially increase the cost of jointing.

Until special equipment was made available it was difficult to introduce seal material into the narrow ⅛-inch diamond blade cuts. After elimination of this difficulty there still remained the question as to whether or not ⅛-inch provided a reservoir for sufficient seal material to withstand the stretch to which it is subjected when the joints open in cold weather. One one project having 50-foot slabs joints which were originally cut ⅛ inch were measured to be ⅜ inch at near freezing temperature. This indicates a stretch of 200 percent for the seal material which is considerably above the 50 percent stretch commonly specified for seals. Opinions vary regarding the importance of obtaining a perfect seal against moisture and foreign matter possibly due to varying local conditions. Several states are experimenting with unsealed sawed joints; however available data are insufficient to warrant the drawing of conclusions. The gathering of data regarding joint openings has been greatly simplified with the advent of sawed joints. The smooth vertical faces of the saw cut make it relatively easy to measure joint widths by means of calipers or thickness gages without the necessity for casting reference plugs in the concrete as was formerly required.

Curing. The curing method used is probably of greater importance for sawed-joint construction than for formed-joint construction. The effectiveness of the curing method with regard to water retention and insulating value affects the shrinkage stresses in the pavement and is related to the time of sawing and joint spacing. Various types of cures have been used in conjunction with sawed joints and apparently successful application of sawed-joint construction is not dependent upon the use of any one type of cure as was formerly believed by some highway engineers.

Equipment

A variety of sawing equipment is available from a number of manufacturers. There are manually pushed saws with single blades and self-propelled saws having one or several blades in tandem. The relative merits of the different types have not yet been evaluated. A separate water tank is usually required to provide ample water for cooling the blade and washing the saw kerf from the joint.

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