DEFLECTOMETER FOR MEASURING CONCRETE PAVEMENT DEFLECTIONS UNDER MOVING LOADS

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SYNOPSIS

The deflectometer was designed to measure concrete pavement deflections at any desired point under moving loads The instrument that has been developed consists essentially of a ratio arm of 25 to 1 obtained by means of a train of gears and of a Kymograph drum on which deflections, speed-switch indicators and a time-graph are recorded simultaneously. Deflections of a slab at the point to be measured may be determined for any position of the moving axle load by calculating distances from the average speed of the moving load Timing is controlled by a standard tuning fork of 100 vibrations per second With an optimum speed of the kymograph drum, it is possible to determine the time within plus or minus 0 001 sec. Preliminary tests by static displacements show that it is possible to measure displacements of the magnification arm within plus or minus 0 001 in Actual displacements are measured with an "88" Ames dial and magnified displacements on the kymograph chart are measured with a pair of microcalipers

APPARATUS

The apparatus is operated electrically by two six-volt storage batteries and a bank of three six-volt dry cell lantern batteries connected in series One storage battery is used to operate the Kymograph drum, a solenoid and two speed-switches; and the other is used for the master tuning fork The bank of dry cells connected in series is used to furnish power for coils on the automatic "lock and release" type of relay.

Detailed drawings of the apparatus were not made because many standard items would not be supplied by manufacturers and it was necessary to use whatever materials could be found A description of each essential working part is given.

Air-electric switches are used to operate the lock and release coils on the automatic relay. These switches were designed by Mr. Roy Johnson of the Missouri Highway Commission Safety Bureau in connection with speed tests. This patented switch consists essentially of a rubber diaphragm attached to an air cell connected to a rubber hose that is stretched across the wheel lane of the pavement When the hose is compressed, the diaphragm causes two contact points to make a circuit in the particular connected coil on the automatic relay. Two air-electric switches are used with the apparatus. One switch closes the automatic relay and keeps it locked without a sustaining current in the coil, and the second switch releases the automatic relay. The second air-electric switch is shown in Figure 1 in a typical layout It is nearly opposite the front wheels of the parked automobile

The automatic relay (Fig. 2), is used to control the current going through the solenoid that controls the position of the Kymograph drum. When the relay is locked, six-volt current is passed through the Ford starting switch solenoid and upon releasing this relay, no current is passing through the solenoid. Condensers are placed across each coil of the automatic relay to prevent excessive burning of the contact points in the air-electric switches.

The Ford solenoid is attached to a 3 to 1 lever arm that makes a contact with the Kymograph drum frame. Since the axis of the Kymograph drum frame is offset from the axis of the Kymograph drum, any movement of the frame will shift the revolving drum. By this means the revolving Kymograph drum can be placed in a recording or non-recording position While the current is passing through the solenoid, the revolving Kymograph drum is lifted into recording position At the break of the current through the solenoid, the drum drops into a non-recording position and prevents superimposition of recordings. One superimposition is permissible since such graphs have been made and calculated without difficulty. If more than one superimposition is made, the time graph becomes vague.

The Kymograph drum (Figs. 3 and 4) is rotated by a small D. C. motor that was formerly used on a defroster fan on an automobile. A heater switch of the automobile type is connected in series with the motor and variable speeds of the drum are obtained in

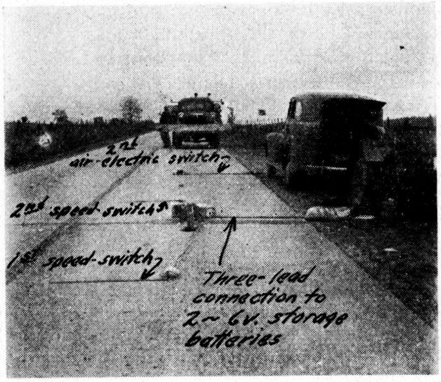

Figure 1. Showing Layout of Deflectometer on a Test Slab

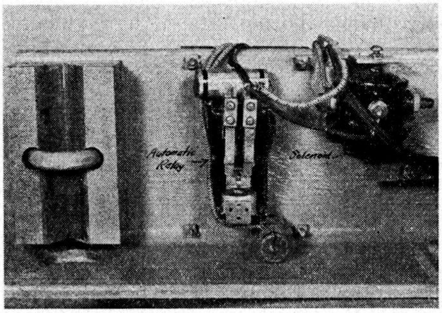

Figure 2. Showing Arrangement of Automatic Relay "Lock-Release Type," and Solenoid

this manner. The Kymograph drum does not have to rotate at any definite speed nor does its angular velocity have to be constant during recording because all calculations and plotting of distances are made from the time graph. A fairly uniform velocity of the drum is desirable in that it provides a rapid check upon calculations of distances. Kymograph paper, supplied by the Central Scientific Company, is placed on the drum and the small overlap is cemented with rubber cement. The Kymograph paper is blackened with a long open flame of a kerosene lamp.

Deflections of a slab under moving loads are scribed by a stylus attached to a hori-

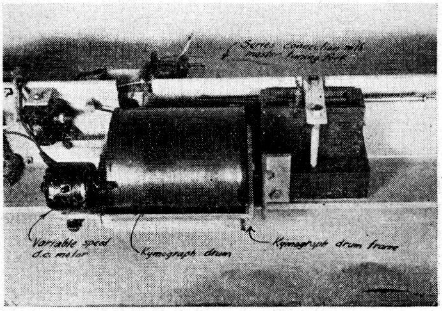

Figure 3. Showing View of Kymograph Drum and Train of Gear Mechanism

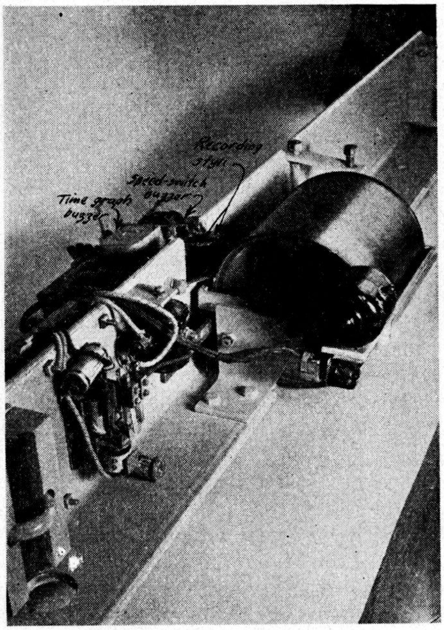

Figure 4. Showing Arrangement of Electrical Equipment and Timing Buzzers

zontal rack and the 25 to 1 gear train mechanism shown in Figures 5 and 6. In this mechanism small brass gears of 100 and 48 teeth, pinion wire of 10 teeth and $\frac{1}{8}$ inch steel racks, all of 48 pitch were used. The compression spring at the bottom of the vertical rack is used to overcome the inertia of the gears and to seat the vertical rack against a brass bearing clock on the slab. In order to

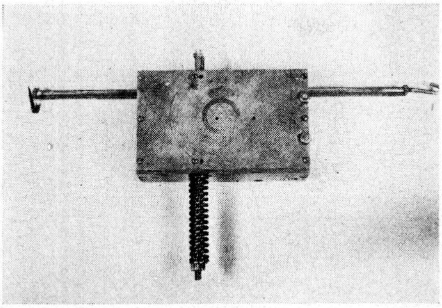

Figure 5. Showing Train of Gear Mechanism. A 25 to 1 Gear Ratio Magnifies Vertical Displacements on Horizontal Kymograph Drum.

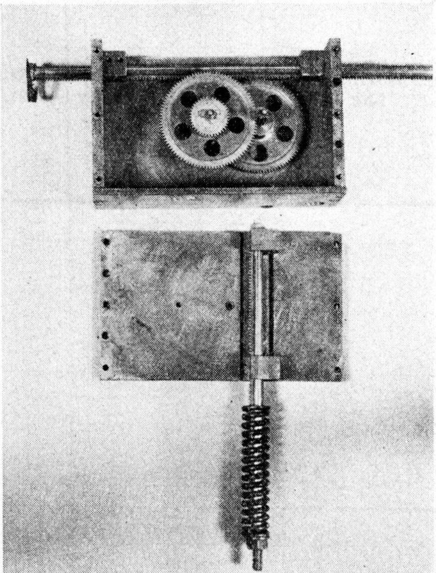

Figure 6. Showing Working Parts of 25 to 1 Ratio of Gear Train Mechanism

overcome teeth play in the gear and rack mechanism, a tension spring is placed on the horizontal rack on the opposite end from the stylus and fastened to a hook on the V-block as noted in Figure 7. The recording stylus on the horizontal rack is adjusted so that it will trace a fine line on the smoked paper when the drum is in a recording position.

A second stylus scribes a line that indicates the speed and position of the moving load. The scribed line is shown immediately below the time graph in Figures 8 and 9. The stylus is actuated by a reconstructed door bell buzzer connected in series-parallel to brass strip-switches on the slab. This door bell buzzer is shown in Figure 4 without cover plate. The brass strip-switches, referred to as speed switches, were made by attaching two brass window weather strips on a strip of inlaid linoleum (burlap back) with a ⅛-in. rubber

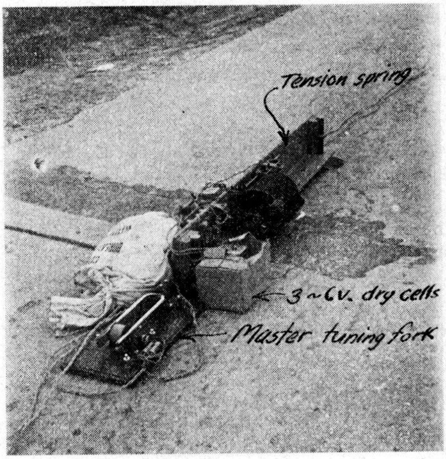

Figure 7. Showing Deflectometer at Place of Measurement

tubing separator. The rubber tubing acts as a spring for the top weather strip and separates the two overlapping strips until pressure is exerted on the top strip. The switches are approximately 3 ft. long and are fastened to the pavement by means of lead screw adapters. They are spaced 18 ft. apart in a wheel lane on the pavement. The speed switches are shown in Figure 1. As each switch is compressed a current of 6 volts is sent through the door bell buzzer which causes the stylus to scribe a line away from its normal position. By means of these offsets, the speed of the moving load and its position at any instant on the chart may be calculated.

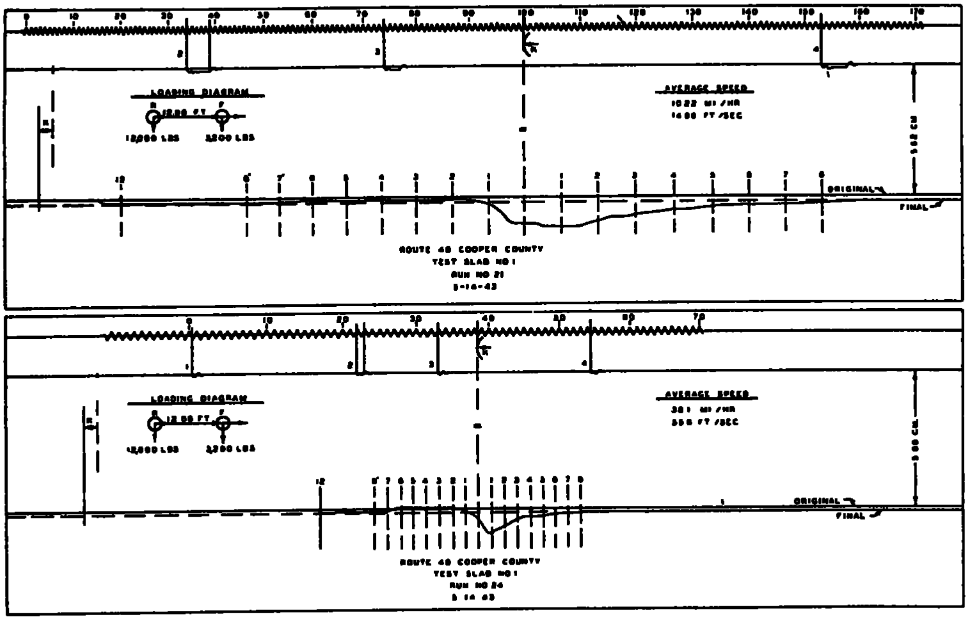

Figure 8. Chart Records of Slab Deflection under Moving Loads at Near End of Long Slab. The same axle load of 12,000 lb. was used in each test. The original chart record has white lines on dark background.

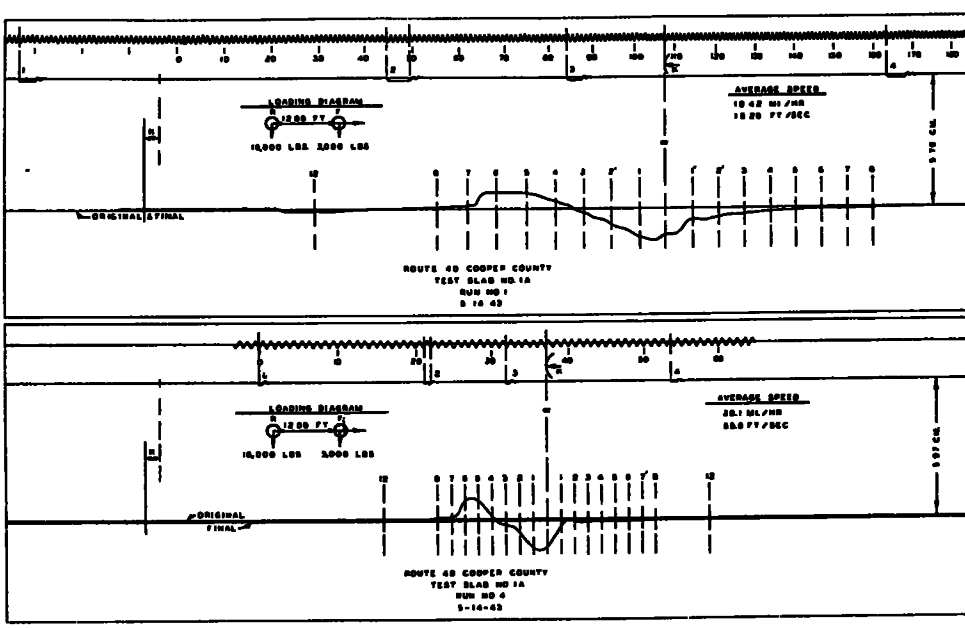

Figure 9. Chart Records of Slab Deflections under Moving Loads at Far End of Short Slab. The same axle load of 16,000 lb. was used in each test. Note rocking effect of short slab.

A time graph, the uppermost line shown in graphs of Figure 8 and 9, is obtained by means of an electrically maintained tuning fork the coil of which is connected in series with a reconstructed door bell buzzer. The master tuning fork has a frequency of 100 cycles per second. The stylus attached to the buzzer keeps the same time as the master tuning fork. Its position is shown in Figure 4 The electrically maintained tuning fork, shown in Figure 7, is operated by a 6-volt current from a storage battery. Condensers are placed across the "make and break" points of the tuning fork to prevent excessive burning of the points. In Figure 3 it should be particularly noted that the series circuit is connected through the vertical rack of the gear mechanism and at any time the vertical rack contact is broken with the brass plate on the slab, which is also in the series circuit, the break will be recorded on the time graph By this means, it is known if sufficient compression of the spring is present to overcome the inertia of the gear mechanism. If a break in the circuit occurs, more compression must be applied to the spring.

Coarse adjustment of the time and speed styli is made by rotation of the wooden platform to which both door bell buzzers are attached Finer and final adjustments of each stylus are made by adjusting screws on the base of each buzzer.

A panel switch board is mounted on the rear of the steel angle frame from which all circuits originate. A three-lead connection is attached to the panel board which receives current from the two storage batteries placed on the shoulder adjacent to the pavement The lead wire is shown in Figure 1. 18-volt current is also attached to panel board as shown in Figure 7.

PROCEDURE OF MAKING DEFLECTION TESTS

Before measurements of slab deflections are made, two 6-in cores are drilled through the concrete slabs equi-distant from a crack or joint and along the center line of a lane. A 3-in. pipe casing, 3½ ft long, is placed centrally in each hole just below the surface of the pavement and the outside of the casing is back-filled with dirt and well tamped The space between the casing and the wall of the concrete hole is filled with a fine bituminous mixture and thoroughly tamped to prevent exuding of mudjack slurry. Centrally in each casing a 1½-in rod, 7 ft. long, is driven into the subgrade to such a depth that approximately six inches of the rod are above the surface of the slab. The rods are given horizontal support by screwing short couplings on the casings Each short coupling has three horizontal adjusting bolts. The bolts are adjusted until a snug fit is obtained to prevent any horizontal movement of the rods while at the same time any vertical movement of the casing due to subgrade reaction will not be transmitted to the rod. This procedure eliminates any subgrade effect on the rods to a depth of slightly over 3 ft. Sufficient clearance is available between the rods and casings to permit shifting of the deflectometer to either side of a crack or joint for measurements without complete dismantling of the set-up.

Brass plates (each 1 in. by 1 in. by ⅛ in.) are embedded in plaster of paris slurry at either side of a joint or crack that is to be measured The brass plates serve a dual purpose They furnish a smooth bearing surface for the vertical rack on the train of gears mechanism and also a contact surface to complete the electrical circuit through the coil on the master tuning fork. As mentioned before under the description of the time graph stylus, a break in this circuit will be made whenever the rate of deflection is greater than the spring value on the vertical rack of the train of gears and will be indicated on the time graph To date the rate of slab deflections have not been found greater than the force of the spring that is necessary to overcome the inertia of the train of gears and racks. If current in the time graph circuit is broken, more compression of the spring is supplied. In this respect the apparatus has some limitations in that it will not measure "snap action" of downward displacements of slabs, but it is believed that these cases are rather rare

The assembled deflectometer is fastened to the 1½-in. rods by means of U-bolts against V-blocks Figure 7 shows the position of the deflectometer on the rods Vertical adjustments are made by sliding the deflectometer on the rods until the deflection stylus is about mid-way on the Kymograph chart, after which the nuts on the U-bolts are tightly drawn. Horizontal bolts in the short couplings on the casings are drawn up until no horizontal play at the deflectometer is noted. Overall heights are checked and compared to truck axle clearances to make sure that the moving truck has sufficient clearance to pass over the deflectometer set-up

Air-electric switches, which operate the automatic relay are fastened to the pavement at the center line and shoulder with nails. The first air-electric switch is placed about 20 ft. before the point to be measured and the second air-electric switch about 50 ft. after. These switches are readily moved and their optimum position for a good Kymograph chart depends upon length of slab, wheel base of truck and speed of truck. The brass-strip speed switches are anchored to the pavement with screw adapters 18 ft. apart and approximately equi-distant from the place of measurement A typical pavement set-up is shown in Fig 1. In this picture the first air-electric switch is not shown. The master tuning fork is set in place and all electrical connections are made. The bank of three lantern dry cells is connected to the panel board socket and the three-lead rubber-covered cable is connected between the two storage batteries at the edge of the pavement and the multiple plug on the panel board. A check is made on all electrical connections and all switches are operated manually to see that they are in proper adjustment

The horizontal rack of the train of gear mechanism that carries the recording stylus is shifted about its vertical axis until it is parallel to the axis of the Kymograph drum. This is done to get a true projection on the drum. All of the styli are adjusted so that only fine lines are scribed on the smoked paper when the drum is in a recording position

The Kymograph drum and frame mechanism is removed from the deflectometer and attached to a special holder in a closed automobile Regular Kymograph paper is attached to the drum by cementing a small portion of the paper to the drum and the small overlap of the paper with rubber cement The paper is blackened with a high flame of a kerosene lamp in a closed car The paper is very difficult to coat with lampblack in the presence of air currents. After coating the paper, the Kymograph mechanism is placed on the deflectometer, and the drum is revolved at the rate of approximately one revolution per second by means of the small variable speed D. C. motor. The automatic relay is operated manually to cause the drum to lift into recording position Three lines are scribbed by the three recording styli. The line scribed by the deflection stylus is used as a base line for measurement of deflections. The recording drum is then released into its non-recording position and the master tuning fork is set to vibrating. The truck driver is signaled to advance at a predetermined speed (approximate, according to the accuracy of the speedometer) and all recording thereafter is done automatically.

After the deflections of the moving load have been recorded, the current on the master tuning fork is broken, the revolving drum is again moved into recording position and the final position of the slab is recorded. The revolving drum is then stopped and the position of the speed-switch stylus is referenced to the position of the deflection stylus. The projected distance between these two positions is known as a "K" correction on all charts, and it remains constant for any given set-up. This distance must be known in order to bring the speed-switch stylus into alignment in the same vertical plane on the Kymograph paper as the deflection stylus and it is used in all projections of horizontal displacements as will be explained later The distance on the slab between the vertical rack on the gear mechanism and the first speed-switch is measured and recorded. This distance is necessary to determine in part the position of the axle load on the chart when the axle load is directly over the place of measurement.

The Kymograph drum and frame mechanism is removed again from the deflectometer and attached to the special holder in the automobile. The Kymograph paper is cut and taken off of the drum It is tacked on a thin board which fits into a special cabinet After enough recordings have been made, they are coated by dipping in a bath of clear colorless industrial lacquer. Under normal temperature conditions they are dry to touch in about twenty minutes

Under favorable working conditions, deflection tests can be made every 15 min. with the same load at different speeds Time for changing axle loads and weighing varies with the amount of load Original loading of concrete right-of-way markers takes approximately one and one half hours while subsequent load changes and weighings are done in 30-min. All axle loads are weighed in the field with Black and Decker Loadometers. The time required to set up the deflectometer, after 3-in. casings are in place, is approximately one hour

METHOD OF CALCULATION

To determine the average speed of the moving load, the first and second speed-switch "make and break" points registered by the tires of the axle load on the speed line are projected through the time graph An arbitrary starting point is chosen on the time graph and every tenth cycle is marked, after which, they are marked in tens to form a time scale Counting the hundredths of a second and estimating to the nearest thousandth of a second between the "make" registers of the speed switches, the time is determined that it takes the moving axle load to go 18 ft. From this, the average speed of the axle load is calculated.

To determine the position of the axle load on the chart when it coincides with the place of measurement, several steps involving corrections are necessary Hereafter this position will be called "Alpha" It is assumed that the center of the axle load occurs midway of the "make and break" contacts of the first speed switch These contacts are projected through the time scale, and the time, in which the speed-switch is compressed, is determined One half of this time is added to the time to determine in part the "Alpha" position.

To determine another part of the "Alpha" position, the distance between the first speed-switch and the point of deflection measurement on the slab is computed in terms of time by dividing this distance by the average speed in feet per second This gives the number of seconds in advance of the "make" point of the axle load on the first speed-switch To this time must be added the above speed-switch correction At this stage, the total time necessary to bring the center of the axle load in coincidence with the place of measurement is known. This total time is added to the time at the "make" point of first speed-switch, rear axle register, on the time scale, after which, any position of the axle load ahead or back of this coincidental position can be computed in terms of the time scale. To each axle position computed, the "K" correction must be made. The correction of the present deflectometer is always toward the left on the chart It can not be measured in terms of time on the time graph if the Kymograph drum velocity was not uniform during the recording but it must be done graphically. If the velocity of the drum was uniform during recording, the correction may be made in terms of time. Uniformity of drum velocity is determined with a pair of compass dividers and this occurs when the tens spacings on the time graph are equidistant.

The usual procedure is to determine the time when the positions of the axle loads are in 1-ft. intervals ahead and back from the point of coincidence After the "K" corrections are applied, these positions are scribed on the chart.

All of these steps in determining a deflection at any position can be seen in Figure 8. The direction of the moving axle load is always to the right The deflections are in their true position, that is, deflections above the original scribed line are plus and those below are minus

Each slab deflection measured at any interval represents the slab deflection of the point measured, when the load is at that particular interval For example, if the deflection is measured at an interval 3 ft. back of "Alpha", the deflection is the amount at "Alpha" when the axle load is 3 ft back of "Alpha" All deflections are measured from the original scribed line with a pair of microcalipers Work and accuracy of measurements are greatly facilitated by placing the Kymograph charts on a frosted pane with a light source below the pane.

TYPES OF LOADING TESTS CONDUCTED

Moving test loads with total axle loads of 12,000 and 16,000 lb at speeds of 10, 20, 30 and 40 m p h have been made at the near and far sides of slabs adjacent to a crack before and after mudjacking Static load tests have also been made with the deflectometer. All of these deflections were taken at the center line of the traffic lane

Additional tests have also been made of slabs at joints adjacent to the center line of a pavement that spalled badly along the longitudinal joint. For these tests total axle loads from 14,000 to 22,000 lb., in 2000-lb increments at speeds from 10, to 50 m p h., in 10 m.p.h. increments were used

All of these tests have not yet been computed Visual inspection of the Kymograph charts show many interesting features on slab deflections, such as load-speed effect, mudjack pumping effect, transload characteristics of joints, curling effect due to temperature changes, rocking of short slabs and possibly subgrade compression in case of longer slabs.

SOME TYPICAL PAVEMENT DEFLECTIONS UNDER MOVING LOADS

Four reproduced Kymograph charts, that were made in field tests, are shown in Figures 8 and 9 Due to sensitiveness of the photographic negative for black and white, the prints give a high contrast. The original Kymograph charts do not have this contrast and in fact it is not necessary to thoroughly blacken the paper to get a good recording.

In Figure 8 slab deflections of the same slab are shown at speeds of 10.22 and 38.05 m p h with a total rear axle load of 12,000 lb The influence of the front axle load of 3200 lb can be noted at approximately 12 ft. left of the point of coincidence which is indicated by the letter "Alpha." It should be noted that the final position of the slab is not the same as the original position and that the difference is less at the higher speed. It is generally true that at faster speeds the final position approaches the original position and in many cases they coincide. The graphs shown in Figure 8 were taken at the near end of a long slab.

In Figure 9 Kymograph charts are shown that were taken at the far end of a short slab. It will be noted that rocking of the slab took place in this case while very little to no rocking took place in the long slab in Figure 8. The total rear axle load traveling over this short slab was 16,000 lb. and the front axle load was 3,000 lb. It should be noted that the front axle load in this case had no influence on the slab deflections at the higher speed and also that the original and final positions of the slab are identical at both speeds

CONCLUSION

The deflectometer has given satisfactory results in measuring pavement deflections under moving loads. Two or more of these machines could be used on the same slab to measure deflections at various points since it would be an easy matter to orient the charts with each other. Some improvements in the apparatus are foreseen and changes will be made to suit particular conditions whenever the critical materials are available.