FACTORS IN ASPHALT PAVING MIX DESIGN WHICH AFFECT VIBRATORY COMPACTION

BY

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FACTORS IN ASPHALT PAVING MIX DESIGN

WHICH AFFECT VIBRATORY COMPACTION

SYNOPSIS

A brief review of the historical development of paving mix design in relation to developments in compaction equipment and procedures. Particular emphasis is given to vibratory asphalt compaction, a recent development in the U.S.A. since 1969. The empirical nature of paving design procedures is then discussed in terms of the compaction problems which can develop and how these problems are treated with a vibratory roller.

M. Geller
Stanhope, N J.

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The determination of asphalt paving mixtures developed from trial and error into established empirical practices in which experience and intuition played a large part in the selection of the ingredients and their relative proportions. In the early 1900's patents were issued to Warren Bros. and a product called "Bitulithic" was produced under the patent. Another pavement design was developed in 1910 called Warrenite and these even eventually combined into "Warrenite-Bitulithic" in about 1920. These mixtures were relatively open graded compared to current specifications but gave very good performance during their service life.

During the highway expansion of the 1920's and 1930's, many states and the Federal Government became involved in developing specifications for bituminous mixtures which included every facet of the product from material selection, grading, proportioning, mixing, drying, laydown, rolling, etc. Technical organizations such as the Asphalt Institute, Association of Asphalt Paving Technologists and the Highway Research Board were formed and sought to correlate, coordinate and organize the information which was being published.

During World War II, the Corps of Engineers developed the "Marshall" method for asphalt pavement design which was widely accepted by many, but not all states. Preceding and coincidential with this development was the design procedure developed in California known as the Hveem Method.

In the great majority of instances, these methods produce equally satisfactory end results but in a proportion of cases, the results of one design could be less satisfactory than the other during compaction. The Hveem method was noted for harsher mixtures at lower AC contents than the Marshall method.

The design of asphalt mixtures to this day remains an empirical method. The danger in following any empirical method is that the fundamental laws of behavior, which are approximated by empirical methods are only partly understood and only partly considered in discussing variations to the method. Over a period of time, customs and opinions harden into rules, the origins for which become increasingly more obscure; such rules become difficult to change.

A long view perspective of the asphalt paving industry indicates that it really has not changed very much from the days of its origin. Equipment design has developed modern machinery and more efficient methods by which the product quality can be more closely controlled and produced in larger quantities and transported and laid down at higher rates. We have increased our basic understanding of the many basic phenomena which take place in combining aggregate and AC together in various proportions but major breakthroughs in the future will depend on our abilities to incorporate this additional knowledge into a design procedure that knowingly details the input in terms of aggregate and bitumen parameters and can precisely and accurately anticipate the output in terms of pavement performance for any particular periods of time, and what is more, can precisely predict pavement performance for the future under a variety of different traffic loadings. At present, we are not at that stage of development.

Reviewing compaction's role in developing suitable asphaltic concrete pavements, we find that steel wheel rollers were used from the first applications of sheet asphalt up to the present time. The equipment function has not changed in 100 years, although the design has kept pace with new technology.

In the 1950's, pneumatic tired rollers were promoted and gradually adopted by many states as part of the rolling train. Several sizes of pneumatic rollers were developed. The larger versions had devices for varying the inflation pressure of the tires so as to influence the contact area and contact pressure exerted. The pneumatic tired rollers were seldom applied as a break down roller or finish roller, but more often as an intermediate roller. Asphalt pickup by rubber tires is a serious obstacle to their use on high temperature mixtures. From this application developed the 3 roller concept publicized by the Asphalt Institute and others as the most common practice for compacting asphalt mixtures.

The pneumatic tired roller was not an economical solution for reducing compaction costs. On the contrary, it called for another operator and roller without any increase in compactive productivity. Its justification was in quality improvement, essentially in the area of sealing the surface texture, healing hair cracks and reducing permeability.

Pneumatic rollers which appear to be most effective are the heavier (expensive) sizes with large tires and variable inflation. Inflation pressures should be in the range of 90 psi and up, if the more difficult density requirements are to be reached.

More recently, a number of state highway tests have concluded the pneumatic rollers were not consistantly making the sort of contribution for which they had been promoted and accepted. Again variations in mix behavior and variations in the methods employed for rolling can account for much of this.

A tremendous forward step has been taken with the nuclear gauge when used for the rapid measurement of compaction results during the rolling process. A nuclear density gauge offers two principal benefits.

a. Permits relative measurements of two or more methods or techniques as to economy (fewer passes, speed) and as to density.

b. Enables rapid correlation between actual results and specified results for purposes of quality control.

During the past five years, vibratory rollers have been promoted for asphalt compaction. Within this time period, there have been several phases of vibratory roller design of varying degrees of effectiveness. The latest development in vibratory roller design, namely the double drum vibrating roller, does offer an economic benefit by being able to achieve a suitable compaction and surface finish with fewer passes and consequently fewer rollers. Within this five year period, vibratory rollers have experienced both good and bad field results. There are several reasons for this among them being:

- Improper vibratory roller design and/or application
- Improper testing and evaluation
- Human inertia and resistance to rapid acceptance of a new technique which though promising economies also entailed additional risks.

The initial promotional phase in applying vibratory rollers to asphalt involved rollers with essentially vibratory soil characteristics. Frequency ranges of 1400 to 1700 vpm and nominal single amplitudes of about 1.5 mm were found unsuitable for binder and surface courses although they did achieve some benefits on base. These rollers had a single drum propelled by a drive axle and rubber tires.

The second promotional phase in applying vibratory rollers to asphalt involved single drum rollers with specific vibratory characteristics intended for bituminous mixtures, namely higher frequencies in the range of 2000 vpm to 2500 vpm, lower nominal amplitudes at about .8 mm maximum and the ability to vary both amplitude and frequency. Some of these rollers are also fitted with steel traction wheels in order to overcome the pickup problem inherent to rubber tires. These rollers usually require a backup finisher to roll out edge marks.

The third and latest promotional phase for applying vibratory rollers to asphalt involved using the same vibratory characteristics as developed in the second phase, namely high frequency and lower multiple amplitudes but also the combination of tandem steel drums rather than one steel drum and a rubber tired propel axle. This last category offers a more economical design in that both drums compact and both drums propel.

Such rollers are applied to satisfy specifications for density, impermeability and surface finish, being the sole roller required as long as the roller can maintain pace with the paver.

In this context, it is necessary to reduce the number of passes to the minimum required; to establish an optimum working speed and to develop the proper operating pattern dependent on the workability of the mix during the compaction process. This approach finds the nuclear gauge to be invaluable for minimizing the time required to establish these parameters for a given mix.

Nevertheless, neither vibratory rollers nor static rollers are panaceas. They do not have cureall capabilities and there are still circumstances to be met in the field which present considerable difficulties in compaction for any type of roller. This is not necessarily due to the roller's limitations but often to the way in which the mixture was developed through design, selection of materials and plant process.

The principal purpose of compaction is to impart stability and permanency to the mix so that it will carry the intended traffic load economically. Since the volume of aggregate is approximately 80 to 90% of the mixture, compaction accomplishes this by primarily manipulating the solid particles into a closer contact with one another thereby developing greater frictional resistance to displacement. Therefore, any compaction method which can achieve this manipulation more rapidly than another method will tend to be more economical.

The compacted pavement offers a resistance to deformation which is a function of several resistances: [1]

1. Frictional resistance
2. Initial resistance
3. Viscous resistance of the mix.

However, these resistances are also present to a much lesser degree in the mixture at lay down and they progressively increase during the compaction process and therefore they define the workability of the mix.

These resistances are functions of the material behavior properties of the ingredients of the mix, essentially the aggregate, the bitumen and the filler.

Mixtures which are normally workable can support the roller without excessive lateral displacement and are compactable within a temperature zone of 275°- - 160°F.The bitumen- filler volume relationship, if properly designed, provides workability without cracking or checking.

In such mixtures, the roller is primarily overcoming the frictional resistances. The initial resistance (cohesion) and the viscous resistance are not too significant at this point.

The shape of the particles, the concentration of coarse aggregate and the gradation influence the amount of frictional resistance to displacement. The degree of confinement by the boundary conditions such as shoulders, curbs, underlying lifts, etc. also influence frictional resistance and the relation of coarse aggregate concentration to lift thickness also plays a part in developing frictional resistance to displacement.

As the particles are placed in closer and closer contact and the number of contact points increase, they also develop an interlocking resistance which increases as the mixture consolidates.

In this phase of the discussion, we have in effect compacted a well graded crushed stone base. In terms of its ability to carry a stationary load (bearing capacity), it is the practical equivalent of a bituminous mixture as long as moisture is not allowed to influence the packing behavior developed by the compaction equipment.

As a point of interest, the use of vibration to compact crushed material is so well accepted at this date that it requires no discussion other than to point out that such a technique should achieve similar benefits on bituminous mixtures if properly applied.

A bituminous mixture requires the addition of bitumen to this gradation in a quantity which after mixing, coats the particles with a film of bitumen. This film of bitumen will vary in thickness depending on the quantity added for the purpose of coating the surface areas of the aggregate. Upon cooling, this film of bitumen exerts a cohesive or binding effect on the aggregate and prevents its displacement under a moving wheel load, and again it should be mentioned that for static loads, it does not add too much to the bearing capacity of the mixture and could in fact reduce it over a long period of time, particularly in areas subject to stationary loadings of relatively long duration.

However, air and moisture are enemies to the ability of the bitumen coated aggregate to maintain a consistent resistance to displacement. We want to prevent them from exerting this influence, so we add some more asphalt to the mixture so that after compaction there is a residue of bitumen which will fill up a part of the void space which will be left in the aggregate, and we also want to knit the surface as tightly as possible (sometimes) to prevent moisture from entering. I say sometimes because there is also a capillary action of moisture from below traveling upwards which depends on the underlying material. It is possible to cause considerable damage in such a situation by not allowing the pavement surface to breathe and relieve itself of this capillary pressure.

Holding this consideration in obeyance, we have a selection of mixtures of various sizes of aggregate chosen for dense gradation; an amount of bitumen intended to coat the surface of the material with a predetermined film thickness; and a little excess bitumen mastic to fill a part of the remaining voids in order to prevent detrimental effects of water stripping and atmospheric oxidation or hardening of the bitumen. However, it is essential that the mix shortly after laydown has sufficient capacity to support the roller without excessive lateral deformation. This capacity to support the roller is primarily a function of the frictional resistance of the particles, the concentration of coarse aggregate and the lift thickness.

At this point we can examine some of the compaction problems which may occur through the use of empirical design methods even though the laboratory requirements are satisfactory in indicating suitable pavement performance after construction.

There are several ways by which the semi-empirical methods of design in use today can combine to establish a rolling requirement which is simply impractical to satisfy. Any projection about the future of improvements in compaction must account for these situations and must also presume that eventually the flaws or limitations in the design approach will also be improved.

Briefly there are two design techniques which differ somewhat in determining the amount of asphalt to be added to the mix.

Marshall	a --	Determines the volume of asphalt based on filling a portion of the voids which are remaining in the compacted specimen, but the volume of void space cannot be calculated until the asphalt content has been added, so it is a trial and error examination.
Hveem	b--	Volume of asphalt based on covering the surface area and

maintaining a certain percentage of air voids in the compacted mixture usually a minimum of 4%.

Both methods suffer from the limitations of laboratory methods which do not precisely duplicate conditions in field. For example -

1. The degree of confinement in a mold is not the equivalent degree of confinement which may exist during field compaction.

2. The height of the mold specimen in relation to the coarse aggregate concentration which is approximately 2.5" may not be comparable to field conditions where the actual compacted lift thickness is 1½" or 4".

3. The compaction of any material is essentially one of changing the volumetric relation of the ingredients by effectively packing the particles into the least amount of space. Pavement design procedures for practical reasons use weight rather than volume and bridge across to volume concepts with specific gravity factors. However, specific gravity does not allow for the variances in packing characteristics. When compaction is a problem, it is a problem of volumetric relations not density. Very often the corrective measures for the volumetric relation are obscured by the emphasis on density, particularly on the part of field personnel who must deal with density because there are no valid field techniques to treat the problem as fundamentally one of volumetric efficiency.

There are a number of other problems which can create compaction problems. such as the resiliency or stiffness of the underlying material, base and subbase, insufficient drying, etc.

Compaction problems can be broken down into two major categories:

- Harsh Mixtures
- Tender Mixtures
  - relatively temperature dependent
  - relatively nontemperature dependent

In dealing with Harsh Mixtures and presuming we are compacting at customary mat temperatures, the primary resistance to be overcome is frictional. Vibratory rollers are most efficient in this respect and have clearly demonstrated an ability to achieve satisfactory compaction at high productivity rates and have demonstrated ability to perform the finishing function as well, since they (the tandem vibrators) have sufficient static pli to roll out marks. The advantage is that the vibratory achieves the compaction in less time and the mix is still hot enough to permit finish rolling and removal of edge marks.

It is the vibratory action plus weight which when applied, agitates the particles and facilitates the development of more contact points during vibration, thereby achieving higher volumetric efficiencies which are measured in terms of increased density.

In dealing with Tender Mixtures, that are relatively temperature dependent, we are primarily concerned with binder and finish mixtures where the maximum aggregate is 3/4" or less. When such gradations are plotted on Bureau of Public Roads Gradation chart,[2,3] some of them exhibit a pronounced hump in the medium to fine fraction when measured against the maximum density line. Such mixutres are often tender at conventional rolling temperatures. The concentration of sand in relation to bitumen exhibits a low frictional resistance, too low to carry the roller without excessive lateral displacement.

In such cases, it is necessary to allow the mixture to cool off and thereby develop an increase in viscous resistance to assist in supporting the roller weight. At this point, a working zone some distance behind the paver is established and the roller is then operated at the proper amplitude to achieve satisfactory density. It should be understood that a tandem vibratory roller can be operated with both drums vibrating, only one drum vibrating or both drums static. When vibrating, the operator has a choice of amplitudes. The Dynapac practice is to avoid varying frequency and to run at the highest frequency rating of the roller. This is done to prevent an excessive gap between roller impacts in order to protect the finish. The distance between impacts being a function of frequency and roller speed. When density requirements are in the range of 95% relative or theoretical, such mixtures are no more of a problem to a vibratory roller than they are to the conventional train of static rollers, providing the one vibratory roller is allowed to find the most suitable zone of operation. Rule of thumb practices such as "Roll in close to the paver" often do not apply to mixtures with this behavior.

Tender Mixtures which are relatively nontemperature dependent are in the class of binder to finish gradation particularly when the density is 98% of 75 blow Marshall. A prime example being the 3/4" minus FAA Binder Mixture.[4]

These types of mixtures can be rolled to 95, 96 or 97% density and seem to resist all efforts and techniques to reach the final 98%.

We have met FAA gradations which follow the maximum density line according to the PBR [2,3]chart and they present no problem. We have met FAA humpbacked mixtures which follow the finer gradation and we have also achieved 98% but not without considerable experimentation in the rolling pattern. Nevertheless, there have been a few mixtures on which we were unable to achieve 98% and neither could the static rollers.

Our interpretation of the mix behavior is based on this hypothesis:

> Such mixtures have a low void content when compaction is completed, usually in the range of 3%. They also have a film of bitumen coating each particle and as the number of contact points increase during compaction, a certain amount of this bitumen becomes displaced and must join that amount of bitumen intended to fill the void space in the mineral aggregate. If the

pore sizes are too small to prevent the flow from taking place, the voids remain partially filled and the bitumen remains in suspension confined within the coarser aggregate skeleton. In effect, the roller no longer seems to be compacting aggregate but rather is attempting to compact a confined fluid which has a very high resistance. In our experience we have tried all different sorts of rolling patterns at temperatures as low as 140° F and the result remains limited to about 96% or 97%.

When this condition is really severe, continued passes of the roller only seem to aggrevate the fluid behavior of the mat surface and this can occur over a wide temperature zone. When the viscous resistance finally makes the mix stiff enough to eliminate the behavior, further efforts to achieve that last measure of compaction often result in hair line cracks or cracks in the aggregate. This increases the voids and drops the density.

Such a condition is difficult to determine in the field. It is difficult to predict from looking at the mix and the diagnosis is usually made reluctantly after all other possibilities are exhausted. Very often, it is only a fractional change in the bitumen or in the filler bitumen volumetric relation that is necessary to overcome the problem and permit vibratory rolling to achieve 98% compaction.

One final word on finish courses, such courses are fine graded and usually thin lifts of 1½" or less. The relationship of the lift thickness to the interface of the underlying mat often imparts a high frictional resistance. However, if vibrated in high amplitude, the pressure wave rebounds from the interface and can upset the compaction effect. Our procedure in such instances is to use the low amplitude mode and determine a roller pattern based on either single or double drum vibrating passes and finishing off static.

It is primarily on finished courses that the need for specific roller operator skills and technique are most obviously required.

- roll at high frequency to reduce impact spacing.

- do not overroll in vibration and avoid overrolling static, since it is uneconomical and can reduce density.

- do not vibrate in place and always reverse in echelon across the mat

- select the right vibrating technique and stick to it as long as the underlying conditions do not change.

In conclusion, properly designed tandem vibratory rollers have demonstrated an ability to achieve economies in compaction within the concept of one roller for one paver as long as the roller can achieve its functions and still keep up with the overall forward speed of the paver. The use of a nuclear gauge is quite effective in determining in a relative sense the most efficient roller pattern. It is also useful in a cross check on core densities.

Vibratory rollers do require a certain level of skill and understanding in operation but this level is within the range of skill and understanding of the average roller operator allowing for some degree of training.

Vibratory rollers are not panacea, they are limited by the empirical nature of accepted mix design procedure, as are all types of rollers. In our opinion, further advances in compaction will depend on design practices which can accurately predict workability during the roller process but until that capability is achieved, tandem vibratory rolling properly employed has been demonstrated to be the most economical method for achieving rapid and effective compaction now in use.

MG/ld/mc
103074

References:

1 "Plasticity as a Factor in the Design of Dense Bituminous Road Carpets", L.W. Nijboer, Royal Dutch Shell Group, Elsevier Publishing Amsterdam 1948.

2 "A New Graphical Chart for Evaluating Gradation" - J.F. Goode and L. A. Lufsey, Assoc. Asphalt Paving Technologists, Vol. 31, New Orleans, 1962.

3 "Voids, Permeability, Film Thickness vs. Asphalt Hardening" - J. F. Goode and L. A. Lufsey, Assoc. Asphalt Paving Technologists, Vol. 34, Philadelphia, 1965.

4 "Standard Specifications for Construction of Airports", Federal Aviation Administration, Washington, D.C. 1968, Para. 401-3.2 Table 1

DYNAPAC®

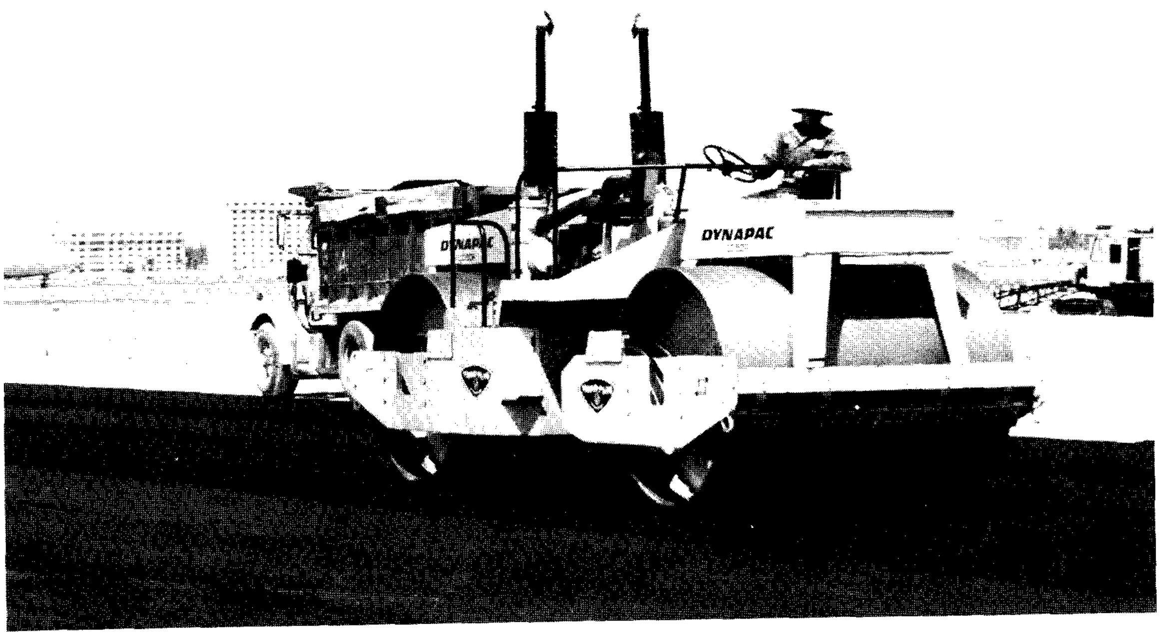
VIBRATORY COMPACTORS

ON THE JOB

THE CC-50A AT MIAMI INTERNATIONAL AIRPORT

At Miami International Airport, General Asphalt Paving Co. successfully tested and then utilized a Vibro-Plus Dynapac CC-50A tandem vibratory self-propelled roller as the only compaction roller on a runway strengthening project. The lay down rates handled by the one roller ranged at 450 tons per hour and peaked at 800 tons per hour. Density was achieved in two round trip passes vibrating in low amplitude at 2400 vpm and one static round trip pass. All passes ran at 5-1/2 to 6 mph rolling speed. Density requirements were consistently met at 99% of Marshall 75 blow lab density without any difficulty on lift thicknesses as high as 12" and as low as 2-1/2".

Surface smoothness was satisfactory. Approximately 150,000 tons of asphalt concrete were handled by the CC-50A on this project. One of the most interesting facets of this particular job was the ability of the CC-50A roller to achieve these results at rolling temperatures which averaged at 180° F with rolling commencing at mat temperatures not above 230° F and finishing at temperatures not below 150° F.



In the Fall of 1972, the General Asphalt Co. Inc. tested the CC-50A under contract 3-10b for the Dade County Port Authority. This contract consisted of strengthening various on-off ramps, aprons, and taxiways amounting to 68,000 tons of asphalt concrete and it is still underway. The testing of the CC-50A and other pieces of compaction equipment was in prelude to contract 4-1 awarded to the joint venture of General Asphalt and Brewer. This contract included 162,000 tons of asphalt concrete and involved strengthening two runways 9R and 9L, one taxiway and several approach and holding aprons.

The first day of testing the CC-50A on job 3-10b showed nuclear tests not above 96% of 75 blow Marshall Density but the cores showed 99%.

The second day of testing revealed that the problem was not going to be density but rather one of displacement, waviness and hairline cracks.

In efforts to solve this problem numerous rolling patterns were tried including static rollers which also included a 40 ton traffic roller as well as single axle rubber tire propel vibratory rollers. Chief Engineer DeMoya found that by allowing the mat to cool, the CC-50A was able to achieve density and the waviness and hairline cracks disappeared. Conventional static equipment could not achieve acceptable density at lower mat temperatures and had problems of displacement and hairline cracks at high densities. Operating the 40 ton behind the paver was not a solution because it left the mat in a rutted condition.

The result was acceptance of the CC-50A as the roller to be used on the larger contract 4-1.

Contract 4-1 had a tight completion date — all work had to be done in about 90 days and before January 1, 1973. To accomplish this, the paving contractors set up six producing plants and developed a logistical system that could average 4500 tons per 10 hour day in lay down and on occasion delivered 7,000 and 8,000 tons per 10 hour day.

The FAA compaction specification called for 98% of Marshall Density ASTM D-1559 at mixing temperature of 270° — 325° F and a minimum rolling temperature of 250° F.

The contractors used two Cedar Rapids BSF-3R pavers in echelon wedging from the centerline out to the edge. The first lift was to set a crossfall of 1-1/2% instead of 1/2% and ranged from 4" — 5" at the center to about 2-1/2" at the edge of the runway. The second lift was 4". One runway was 100' wide and the other 150' in width.

The contractors found that the runways were in rough shape in some spots and in fact they had to wedge as much as 9" and in one instant 12" in order to bring the cross slope to grade. All bituminous concrete was laid over the existing asphalt concrete runway.

The six suppliers of plant mix were:

AGGREGATE SOURCE	PLANT
Sterling Crushed Stone Maule Industries	1. General Asphalt
Florida Rock & Sand	2. U.S. Asphalt Co. Inc.
Broward, Eureka & Kozzo Lehigh	3. Brewer Co.
Seminole Rock Prod.	4. Pan American
Southeastern	5. O'Keefe Paving
Maule Industries	6. Asphalt Material & Paving Co.

MIX DESIGN DATA

Aggregate Physical Characteristics		Min.	Max.	Average
1. Specific Gravity @ Optimum AC Content	—	2.152	2.245	2.189
2. Unit Weight	pcf	134.3	140.1	136.8
3. Specific Gravity of the Aggregate	—	2.38	2.49	2.419
4. Absorption AC lbs. per 100 lbs. of dry aggregate	—	1.50	1.70	1.60
5. Specific Gravity of Asphalt Cement	—	1.02	1.02	1.02
6. % AC of Total Weight at Optimum Content	%	7.1	7.8	7.364

GRADATION SPECIFICATION

Sieve Size	% Passing Specification Limits	% Passing Job Specifications	Tolerance
3/4	95 — 100	100	± 2%
1/2	82 — 100	95	± 5%
3/8	73 — 90	85	± 5%
# 4	55 — 70	60	± 5%
10	40 — 55	45	± 5%
20	27 — 43	38	± 5%
40	19 — 35	31	± 4%
80	8 — 20	14	± 4%
200	2 — 5	3.5	+ 1.5%
		Bitumen	+ 0.25%

All materials classified as Absorptive with water absorption over 2.5% by weight of dry aggregate.

ASPHALT SPECIFICATION

Asphalt Cement Texaco AC-6, 60-70 penetration, with silicone added (or equal) to Florida State material specification # 10542-B.

MARSHALL DESIGN VALUES

	Specification Limits	Min. Max.	Avg. Tolerance
Stability	2200 — 3200	2200 — 2915	2630 ± 10.0%
Flow	9 — 14	10.3 — 13.2	11.4 ± 2.0%
Voids Mineral Aggregates	14 — 18	15.4 — 16.6	16.0 ± 1.0%
Voids Filled	75 — 85	76.8 — 80.0	78.6
% Voids	2.5 — 4.5	3.0 — 3.8	3.44 ± 0.8%

LAYDOWN EQUIPMENT

2 — Cedar Rapids BSF-3R Pavers — Operating independently or in echelon — 14' paving width.

COMPACTION

From testing on the previous contract, Chief Engineer DeMoya had determined that the mix, though possessing a good stability, tended to behave as a tender mix when laid down in 4" lifts and higher at temperatures 280° F.

After some experimentation on Project 4-1, the following procedure for the CC-50A was established:

1. Allow the mat to cool off to a temperature not above 230° F.
2. Pretest with a static pass to see if any mat displacement or hairline cracks occur.
3. If not, commence rolling with two round trips (A-B; B-A) in vibration at 2400 vpm and low amplitude (18,000 lbs. centrifugal force per drum).
4. Step 3 began at an average mat temperature of 180° — 190° F and finished off above 150° F.
5. Working travel speed for static and vibratory passes 5-1/2 to 6 mph.

Densities achieve with this pattern were consistently 99% of Marshall and in the thicker wedges, densities of 100% were not uncommon. It is of interest to note that this same rolling pattern was used on single lift thickness of 2-1/2" to 9" on Contract 4-1.

It is of further interest to note that at these lower rolling temperatures lateral displacement was very minimal and that surface waves were eliminated.

This rolling pattern took place as much as 3500' behind the paver depending on the rate of cooling according to the lift thickness involved.

(Note: In Contract 3-10b, a wedge of 12" lift thickness was allowed to cool 6 hours before rolling commenced, and it is of further interest to note that this was the only way in which the contractor was able to achieve a satisfactory end result).

Dade County Port Authority Consultants, Howard Needles Tammen & Bergendoff observed the roller performance and cross checked laboratory cores with nuclear field measurements on Contract 3-10b. As a result Contract 4-1 was written to permit vibratory rolling at temperatures above 150° F instead of 250° F and density was set at 99% ± 1%.

It is of further interest to note that prior to the successful roller pattern worked out by DeMoya and as a result of previous tests with conventional equipment, serious thought was being given to reducing the density spec to 97% ± 1% of Marshall.

Presently nuclear field testing is carried out to insure that achieve densities *do not exceed 100%.*

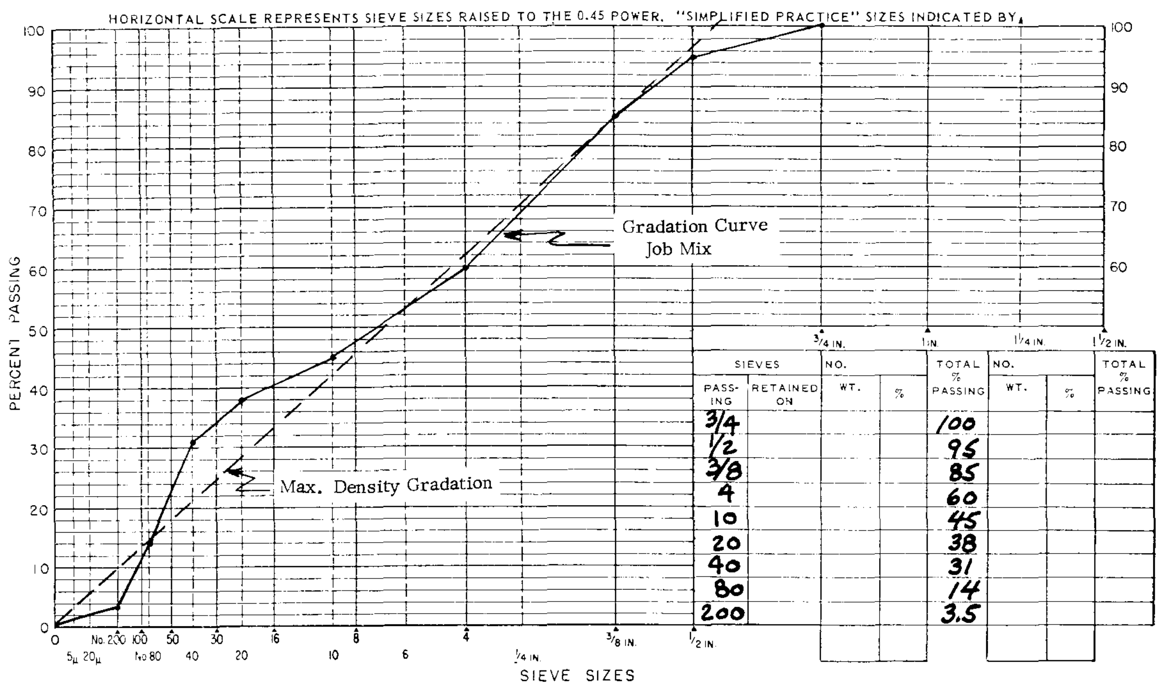
FIELD TESTING

Testing for this contract was by Wingerter Laboratories of Miami, Florida. Field tests consisted of a Troxler Gauge and core sampling. Correlation between nuclear tests and core samples were within less than ± 1%.

Toward the end of contract several laboratory samples were compacted at 100 blow Marshall on both sides of the sample. Results were a density increase of less than .5lb/cft and the roller achieved this without any change in procedure.

The CC-50A rolled over 150,000 tons of this mix on Contract 4-1. The owners received a job within their specifications and the contractor was pleased because he achieved this end result without any strain on his compaction procedure and at a labor and capital cost input that was substantially below conventional methods.

GRADATION CHART



SIEVES PASSING	SIEVES RETAINED ON	NO. WT.	%	TOTAL % PASSING	NO. WT.	%	TOTAL % PASSING
3/4				100			
1/2				95			
3/8				85			
4				60			
10				45			
20				38			
40				31			
80				14			
200				3.5			

STATE Florida PROJECT NO.

TYPE, SOURCE, PRODUCER OF AGG. Sterling Crushed Stone, Maule Industries, Florida Rock & Sand, Broward Eureka & Kuzzo, Seminole Rock, Southeastern

TYPE CONST; LOCATION ON PROJECT Miami Int'l Airport - Contract 4-1 - General Asphalt Paving HNTB Consultants - Oct. - Dec. 1972

SAMPLED FROM | SAMPLED BY | DATE | QUANT. REPRESENTED | SIEVED BY | DATE | SIEVE METHOD ☐ WET ☐ DRY | REMARKS See Job Report - SA-010-0173

Miami International Airport
October/December 1972
CC-50A — S/N 149

Owner: Dade County Port Authority
Consultant Engineer: Howard Needles Tammen & Bergendoff
Contractor: Joint Venture
General Paving — Brewer Co.
George DeMoya, Chief Engineer

For Presentation to HRB Committee A2-F02
January 23, 1973
Washington, D.C.

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NO. ______ DATE ______
BY: ______

JOB SITE ______
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PAVING CONTRACTOR ______
Name · Main Address · Main Phone

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[ ] Binder
[ ] Finish

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[ ] CTB
[ ] ATB

Superintendent	Paving Foreman	Roller Oper.	Inspector	Resident Engr.	Distr. Engr.
CONTRACTOR			STATE / COUNTY		

OBTAIN THIS DATA FROM ASPHALT PLANT OR INSPECTION

JOB MIX GRADATION % PASSING

	STONE SIZES								COARSE SAND		MEDIUM SAND		FINE SAND			FILLER	
	2-1/2"	1-1/2"	1"	3/4"	5/8"	1/2"	3/8"	1/4"	#4	#8	#16	#30	#50	#80	#100	#200	
%																	%

If a different size sieve is used – note the size under the % Passing

SPECIFY APPROPRIATE GRADE OF ASPHALT BY CHECK ✓

Pacific Coast		or	Penetration Grade	
AR	1000 [ ]		40 – 50	[ ]
AR	2000 [ ]		60 – 70	[ ]
AR	4000 [ ]		85 – 100	[ ]
AR	8000 [ ]		120 – 150	[ ]
AR	16000 [ ]		200 – 300	[ ]

[ ] Other Specify

Asphalt Cement
Oil Company ______
Refinery ______
Source of Crude ______

VISCOSITY GRADE AASHO M-226-70-1

PENETRATION	VISCOSITY	
77°F	140°F	275°F
100 gr.-5 sec	Poise	Centistokes

MARSHALL VALUES	HVEEM VALUES	OTHER METHODS
Density ______ pcf @ ______ blows	Density ______ pcf	
Stability ______	Stabilometer ______	
Flow ______	Cohesiometer ______ Swell ______	
A-C% ______	CKE-AC ______ %	
Air Voids ______ %VMA ______ %	Air Voids ______ % VMA ______ %	

PAVING METHOD: [ ] Windrow [ ] End Dump Paver Mfg. ______ Model ______

SINGLE PASS PAVING WIDTH [FT.]

SINGLE LIFT THICKNESS: [Inch] LAYDOWN [Inch] COMPACTED

PAVER SPEED [FPM] AVERAGE

PRODUCTIVITY IN TONS PER SHIFT ______ PAVING HOURS PER SHIFT ______ OR [ ] TPH

PAVER CREW [ ] Foreman [ ] Paver Operator #1 [ ] Screed Oper. #2 [ ] Raker #1 [ ] Raker #2 [ ] Raker #3

ROLLER CREW [ ] Breakdown [ ] Intermediate [ ] Finish [ ] Others (how many)

NOTES:

PASSES	Lay-Down	1	2	3	4	5	6	7	8	9	10
Type Roller Pass	xxx										
Type Roller	xxx										
Frequency VPM	xxx										
Amplitude Hi – Lo	xxx										
Mat Temp. F°											
15" Nuclear Count											
60" Nuclear Count											
Std Nuclear Count											
Count Ratio 60" Std											
ROLLER DENSITY pcf											
PASSING DENSITY pcf											
% of Passing											

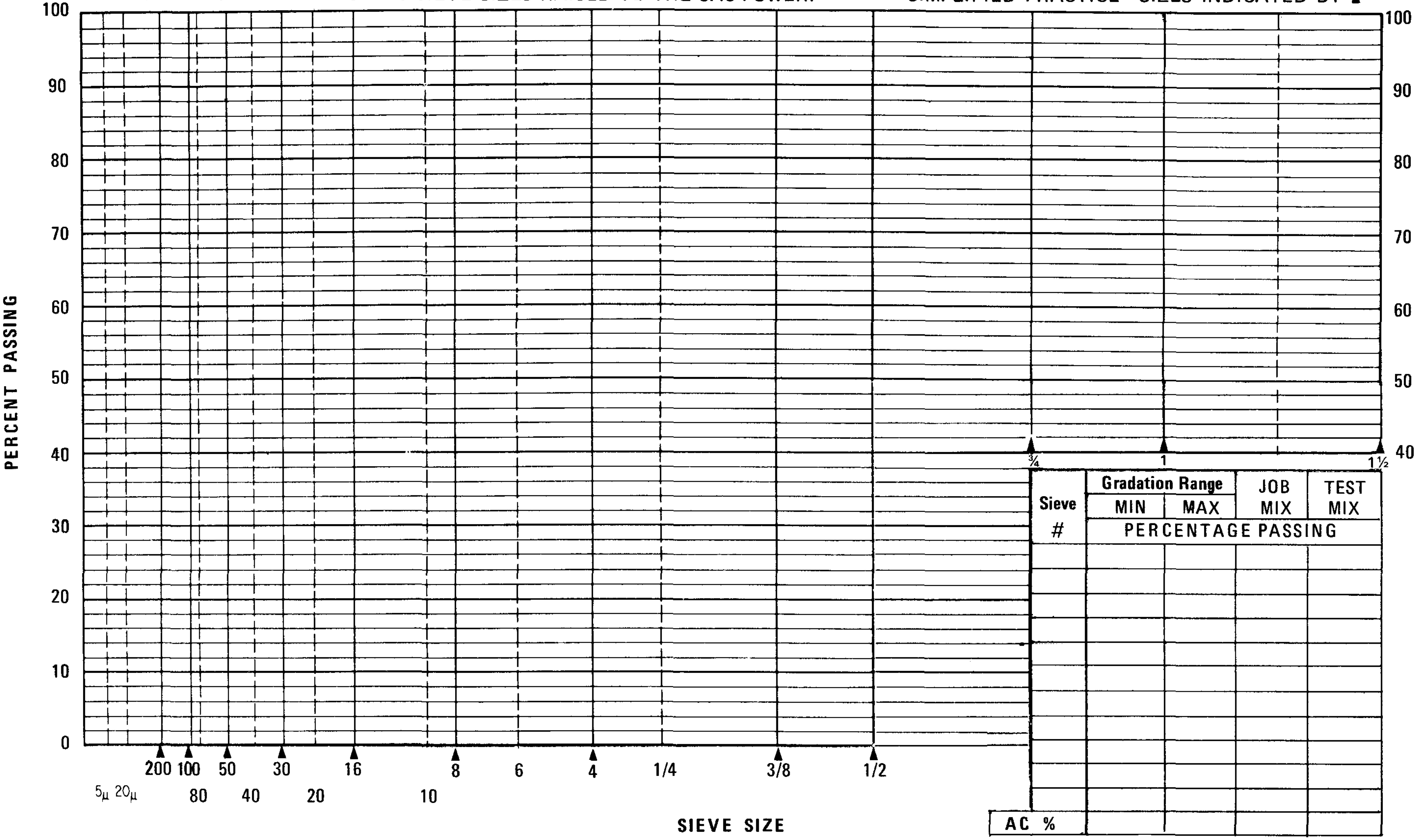
CODE TYPE OF PASS
B – BREAKDOWN
I – INTERMEDIATE
F – FINISH

CODE	TYPE OF ROLLER
3W	3 Wheel Roller
2AT	2 Axle Tandem
3AT	3 Axle Tandem
7R	7 Wheel Pneumatic
9R	9 Wheel Pneumatic
11R	11 Wheel Pneumatic
1V	Single Drum Vibratory
1VS	Single Drum Static
2VV	Double Drum 2 Drums Vibrating
2VS	Front Drum Vibrating Rear Drum Static
2SV	Front Drum Static Rear Drum Vibrating
2SS	Both Drums Static

DYNAPAC®
DYNAPAC MFG INC

GRADATION CHART

HORIZONTAL SCALE REPRESENTS SIEVE SIZES RAISED TO THE 0.45 POWER. "SIMPLIFIED PRACTICE" SIZES INDICATED BY ▲



Sieve #	Gradation Range MIN	Gradation Range MAX	JOB MIX	TEST MIX
	PERCENTAGE PASSING			
AC %				

[ ] LIMESTONE
[ ] GRANITE
[ ] SHALE
[ ] SLAG
[ ] BANK GRAVEL
[ ] RIVER GRAVEL
[ ] ______________

[ ] WASHED SAND
[ ] CRUSHED SAND
[ ] BEACH SAND
[ ] ______________

PRODUCER ______________ (Name) PIT/PLANT ______________ (Location)

State	Route	
Asphalt Grade	Absorption Factor	Mix Density PCF
Min. % of Crushed Aggregate Retained on Sieve	**DYNAPAC** DYNAPAC MFG INC **GRADATION ANALYSIS**	
Sieve #		
% Crushed	Date:	By:

Subject TECHNICAL DATA OF VIBRATORY COMPACTORS

Lars Forssblad, D. Eng.

Ref. No. 8204 Eng. Date 31.10.69

SUMMARY

There are no rules which are generally accepted regarding the technical data which should be given for vibratory compactors in specifications, technical reports, manufacturers´ catalogues, etc. In this report the technical data of vibratory compactors are defined. Their influence on the compaction effect is discussed. The basic technical data for a vibrating roller or a vibrating plate compactor are static weight, frequency and amplitude. The amplitude varies, however, with the elastic and damping properties of the soil and is here defined as the nominal amplitude neglecting the elasticity and damping of the soil.

Eccentric moment, centrifugal force, "dynamic force", "impulse in tons per second" and "equivalent static weight" are other data and expressions which are dealt with in the report.

DISTRIBUTION

This report will have it´s greatest interest for research people, engineers working at Highway Departments and similar organizations and also for consulting engineers and qualified contractors. It should also be used when, for example, "equivalent static weight" of a vibratory compactor is mentioned in connection with tenders, etc.

TECHNICAL DATA OF VIBRATORY COMPACTORS

Lars Forssblad, D. Eng.

There are no generally accepted rules regarding the technical data which should be given for vibratory compactors in specifications, technical reports, manufacturers´catalogues, etc. Static weight, frequency and centrifugal force are the data which most frequently are given. "Dynamic force", "dynamic load", "compaction effort in tons", "impulse in tons per second", "corresponding force" and "equivalent static weight" are other expressions used. These expressions are more or less exactly defined, and are more or less properly correlated to the compaction effect. In the following report the different technical data of vibratory compactors and their influence on the compaction effect are discussed.

The Principle of Vibratory Compaction

A vibrating roller or a vibrating plate compactor produces a rapid succession of impacts on the surface of the ground, Fig. 1. The impact forces develop pressure waves which penetrate into the soil. The pressure waves generate dynamic pressures in the soil, and they also set the particles in a state of motion.

It is important to make a clear difference between the vibrations of the compactor and the data of the pressure waves in the soil. The data of the pressure waves are to a high degree depending on the properties of the soil.

The dynamic impact forces acting on the surface of the ground depend on the weight and vibration data of the compactor as well as on the properties of the soil - mainly its elastic properties. Different types of soils have different elastic properties. For one and the same soil, the elastic properties vary with the degree of compaction. When the density successively increases during the compaction, the modulus of elasticity also increases substantially.

Static Weight

The static weight of vibratory compactors has a great influence on the compaction effect since the kinetic energy, as well as the momentum (mass x velocity) of the vibrating drum or the bottom plate,are directly proportional to the weight, when the frequency and amplitude are kept constant. The linear relationship between weight and compaction effect has been confirmed by compaction tests and practical experience.

Results of compaction tests have indicated that the maximum depth to which a soil can be compacted depends on the total static weight of the vibratory compactor. However, the compaction close to the surface achieved by vibrating rollers is to a great extent also influenced by the static weight per inch of drum width. Tests made with vibrating rollers at the Road Research Laboratory in England indicated a comparatively good correlation between static weight per inch of drum width and compaction effect, but, of course, the vibration data also have an obvious influence on the compaction effect of the machine [1].

The ratio of weight of drum (or bottom plate) to weight of frame is also of importance for the compaction effect. This weight-ratio is, however, often determined by the practical design of the machine. A high frame weight usually has a positive influence on the compaction effect.

Frequency

Frequency and amplitude, defined in Fig. 2, are the basic vibration data. The frequency is determined by the rotational velocity of the eccentric or eccentrics. The frequency is usually comparatively easy to measure or check, i.e. from the r.p.m. of the engine. The frequency of the pressure waves generated in the soil is the same as the frequency of the vibrator.

According to compaction tests and other investigations, an increased frequency results in an increased compaction effect, but only up to a certain frequency range. The schematic curves in Fig. 3 are based on the results of a number of investigations published by different Authors [1], [2], [3], [4], [5].

Fig. 4 shows the relationships between dry density of the compacted soils and frequency according to tests made at the Road Research Laboratory in England [2]. Changes in frequency within the tested range generally had a limited effect on the compaction effect. At frequencies over 2200 – 2400 vibr/min the densities have not increased with increased frequency.

Amplitude and Eccentric Moment

The amplitude of the drum or bottom plate is a function of the eccentric moment, which is defined in Fig. 5. The amplitude depends, however, to a certain extent also on the elasticity and the damping properties of the soil. The amplitude is, consequently, not constant, but will to a certain extent vary with the frequency. For plate compactors another difficulty in defining the amplitude is that the amplitude usually varies along the bottom plate. If the influence of the elasticity and the damping properties of the soil is neglected, the so-called nominal amplitude can be calculated according to the equation:

$$\text{Nominal amplitude} = \frac{\text{eccentric moment}}{\text{weight of drum or bottom plate}}$$

Thus, the nominal amplitude is independent of the frequency and inversely proportional to the weight of the drum or bottom plate. A vibrating roller placed on an elastic bed, for example, large lying rubber-tires will work with the nominal amplitude.

Centrifugal Force

The rotating eccentric initiates a centrifugal force, which is a function of $[\text{frequency}]^2 \times [\text{eccentric moment}]$ as shown in Fig. 5, and consequently approximately also a function of $[\text{frequency}]^2 \times [\text{amplitude}]$. Due to the oscillations of the drum or the bottom plate there will be a small difference between the real centrifugal force and that calculated from Fig. 5. The difference is, however, usually less than 1 %.

The centrifugal force acts inside the drum or bottom plate. Its magnitude is not equal to the dynamic force transmitted to the underlying soil as is sometimes assumed. This would be the case only if the drum or bottom plate were rigidly fixed to the ground.

It can thus be misleading to use the centrifugal force as a measure of compaction effect, especially if the centrifugal force of a vibrator working with a high frequency is compared with the centrifugal force of a vibrator with a low frequency. If the compaction effect were directly proportional to the centrifugal force, the relationship between compaction effect and frequency would follow the dotted curve in Fig. 3. There is, however, no good agreement between this dotted curve and curves based on test results. Thus, the centrifugal force only gives a general indication of the compaction effect. An advantage in using the centrifugal force is, however, that this value can easily be compared with the static weight of the drum (bottom plate) and with the total weight of the compactor. The centrifugal force can thus give a general indication of the vibration intensity and the compaction effect.

Area and Dimensions of the Contact Surface

The area and dimensions of the contact surface with the ground is of importance for the compaction effect and effect-in-depth. With a constant dynamic load per unit area, an increasing contact surface results in a greater effect-in-depth. The contact surface of a vibrating roller with given data is depending on the elasticity of the soil. For a vibrating roller, an increased diameter of the drum gives a larger contact area.

Velocity

The working speed has a greater influence on the compaction effect for a vibrating roller than for a static roller. A higher velocity of a vibrating roller can, however, be compensated by a greater number of passes, and the compaction work is approximately proportional to the time of vibration on a given area.

Dynamic Pressures in the Soil

Up to now it has not been possible to exactly calculate the dynamic pressures generated in the soil under a vibratory compactor. However, the pressures can be measured with pressure cells and results of such measurements are given in Fig. 6. [3].

Approximate Formula to Calculate Compaction Effect

With reference to the foregoing, the following very approximate formula can be given for the compaction effect:

$$\text{Compaction effect} = [\text{a constant}] \times [\text{static weight}] \times [\text{frequency}] \times [\text{amplitude}] \times \frac{[\text{number of passes}]}{[\text{velocity}]}$$

It should be observed, however, that especially the relationship between compaction effect and frequency is approximately linear only within a certain frequency range.

"Dynamic Force (Load)"

In U.S. specifications - i.e. those used by the Corps of Engineers - a minimum "dynamic force" as an expression for centrifugal force is often specified for vibrating rollers. As centrifugal force is not a very exact measure of compaction effect, this definition only gives an approximate value of the efficiency of the roller. If, however, the frequency is also specified within a limited range - i.e. 1500 - 1600 vibr/min - the definition is more exact.

"Impulse in Tons per Second"

The expression "impulse in tons per second" defined as the product of centrifugal force and frequency, is sometimes used as a measure of compaction effect. This expression has the dimensions $[\text{frequency}]^3 \times [\text{amplitude}]$, and is still more misleading than centrifugal force as a measure of compaction effect. It obviously gives an exaggerated value for a vibratory compactor with a high frequency.

"Equivalent Static Weight"

The principle of vibratory soil compaction - the state of motion of the particles combined with dynamic pressure - is quite different from the principle of static compaction. It is clear that this makes it very difficult, and probably impossible, to find technical data which can be used to compare exactly the compaction effect of a vibratory and a static compactor. In spite of this a vibrating roller is sometimes said to have the same compaction effect as a static roller of a certain weight. Such a comparison can only be made if the two rollers are exactly described regarding weight, dimensions, etc. Also the soil conditions have to be exactly specified. With other soil conditions a comparison will give quite other results.

An agreement has been made by the manufacturers of vibratory compactors within the CECE (Committee for European Construction Equipment) not to use comparative weight figures as the above. See the enclosed article by dr G. Garbotz, Appendix 1.

Conclusions

The basic technical data for a vibratory compactor are weight, frequency and amplitude. The amplitude varies with the elastic and damping properties of the soil and is here defined as the nominal amplitude neglecting the elasticity and damping of the soil. The amplitude is basically directly proportional to the eccentric moment which can be exactly defined. It is proposed that the following technical data should be given in specifications, technical reports, manufacturer´catalogues, etc.

Vibrating rollers

Static weight
Static weight per inch of drum width
Drum width
Drum diameter
Frequency
Nominal amplitude
Eccentric moment
Centrifugal force[1)]
Working speed

Vibrating plate compactors

Static weight
Static weight per unit area of bottom plate
Width of bottom plate
Length of bottom plate
Frequency
Nominal amplitude
Eccentric moment
Centrifugal force[1)]
Working speed

1) Can be misleading if compactors with different frequencies are compared.

Literature

1) Johnson, A.W. and Sallberg, J.R. "Factors that Influence Field Compaction of Soils", Highway Research Board, Bull. 272, Washington D.C. 1960.

2) Lewis, W.A., "Full Scale Studies of the Performance of Plant in the Compaction of Soils and Granular Base Materials", The Institution of Mechanical Engineers, Proc. 1966-67, Volume 181, Part 2A, No. 3.

3) Forssblad, L., "Investigations of Soil Compaction by Vibration", Acta Polytechnica Scandinavica, Ci 34, Stockholm 1965.

4) Garbotz, G. and Theiner, J. "Untersuchungen der statischen Walzverdichtungsvorgänge mit Glatt-Walzen und Vergleiche mit Ergebnissen und Versuchen mit dynamischen Verdichtungsgeräten", West-Deutscher Verlag, Köln und Opladen, 1959.

5) Broms, B. and Forssblad, L. "Vibratory Compaction of Cohesionless Soils", Specialty Conference on Soil Dynamics, Seventh International Conference on Soil Mechanics and Foundation Engineering, Mexico City 1969.

Solna, October 31, 1969

LF/ln

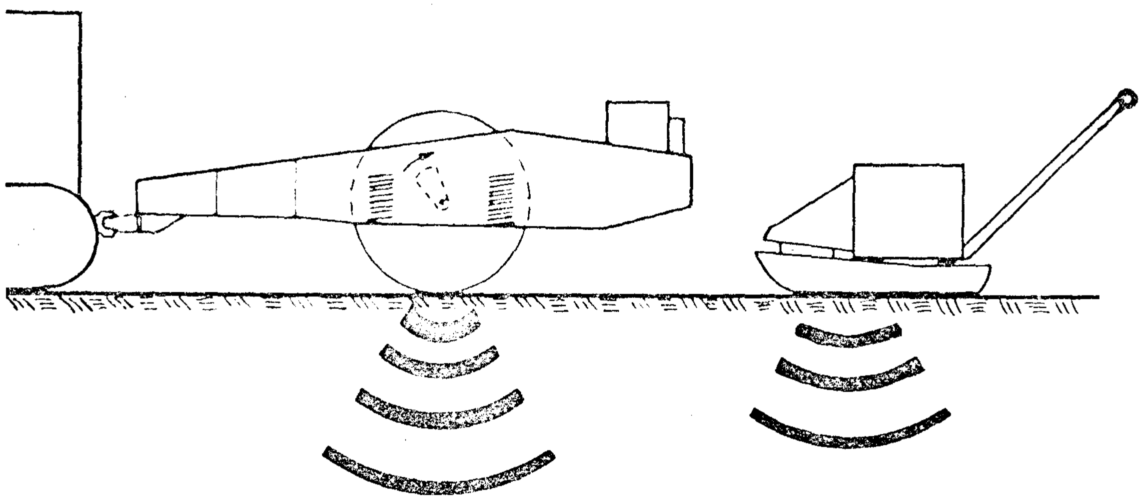
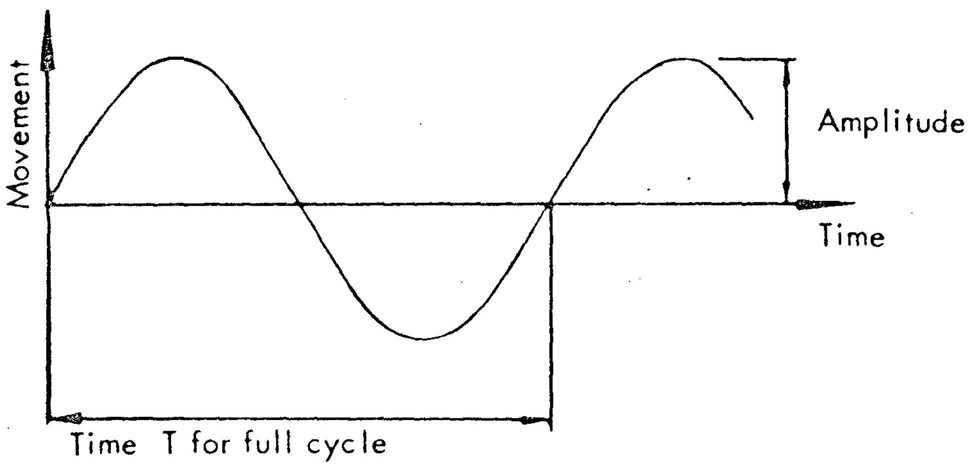


Fig. 1. A vibrating roller or a vibrating plate compactor develops pressure waves going down in the ground.



Frequency (number of cycles per sec. ($^1/T$)) = f cps or Hz

Amplitude (maximum deviation from position at rest) = s cm (in)

Maximum velocity = v_{max} = $2\pi \cdot f \cdot s$ cm/s (in/sec)

Maximum acceleration = a_{max} = $4\pi^2 \cdot f^2 \cdot s$ cm/s²(in/sec²)

Fig. 2. Definition of frequency and amplitude. Velocity and acceleration during a sinusoidal vibratory motion can be calculated according to the equations given above.

> Observe that the amplitude correctly defined is half of the total movement. In some cases the whole "stroke" or movement is <u>incorrectly</u> denominated as amplitude.

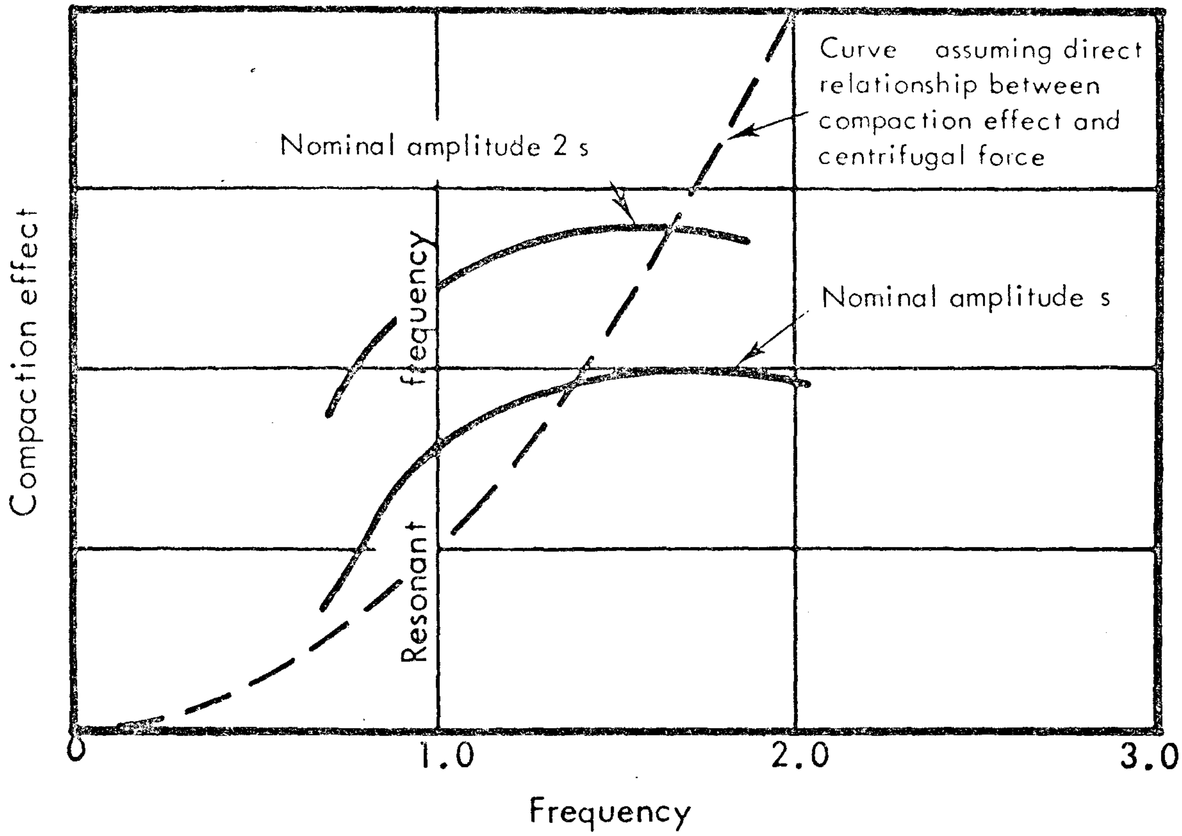
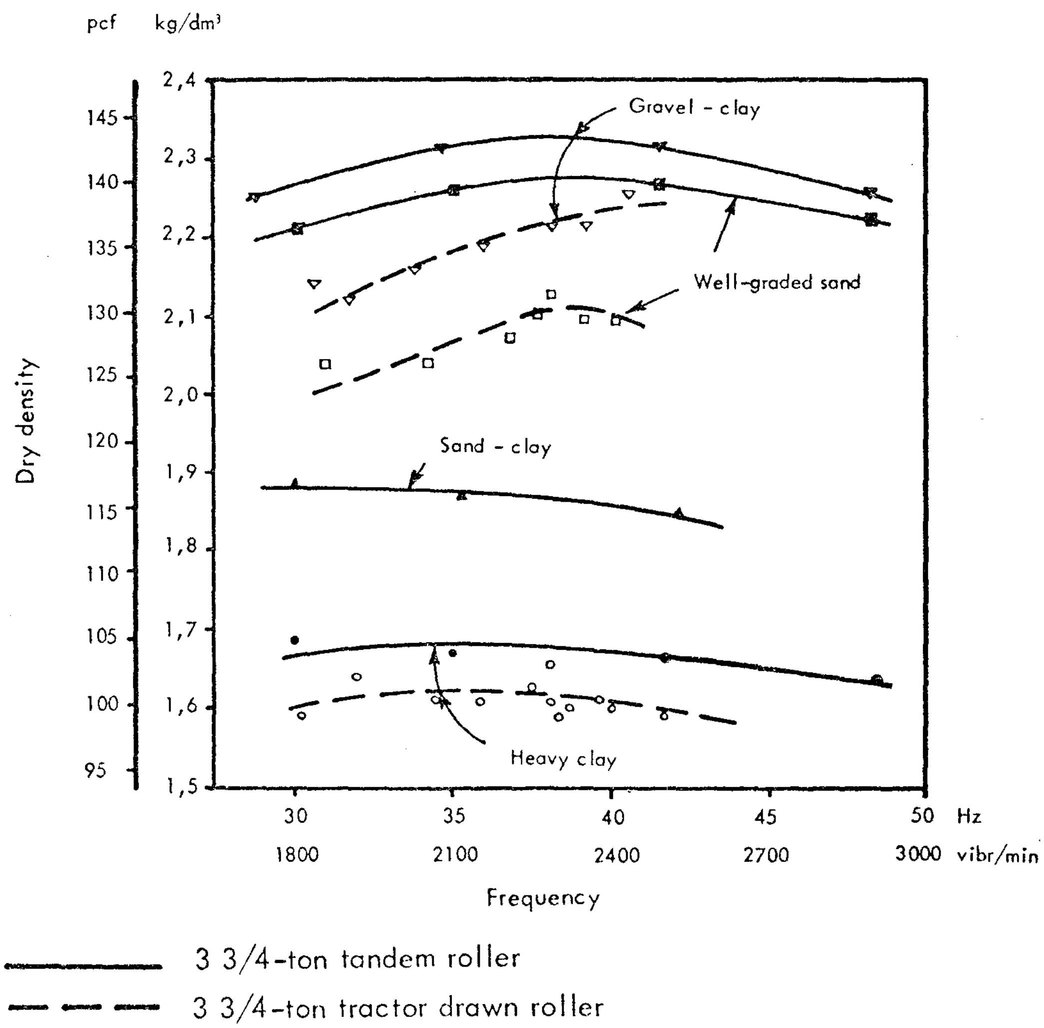
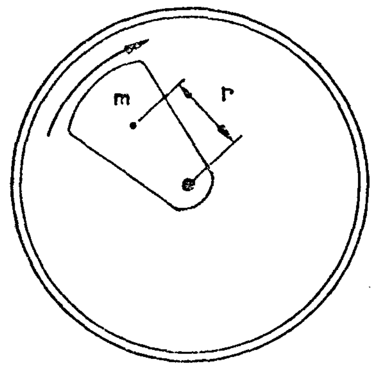


Fig. 3. Relation between compaction effect and frequency shown schematically.





Weight of eccentric = m kg (lb)

Eccentricity = r cm (in)

Eccentric moment = $m \cdot r$ kgcm (lb in)

Centrifugal force = $m \cdot r \cdot 4\pi^2 \cdot f^2 \cdot \frac{1}{g}$ kg (lb)

g = acceleration due to gravity = 981 cm/s^2 = 386 in/sec^2.

Fig. 5. Definition of eccentric moment and centrifugal force

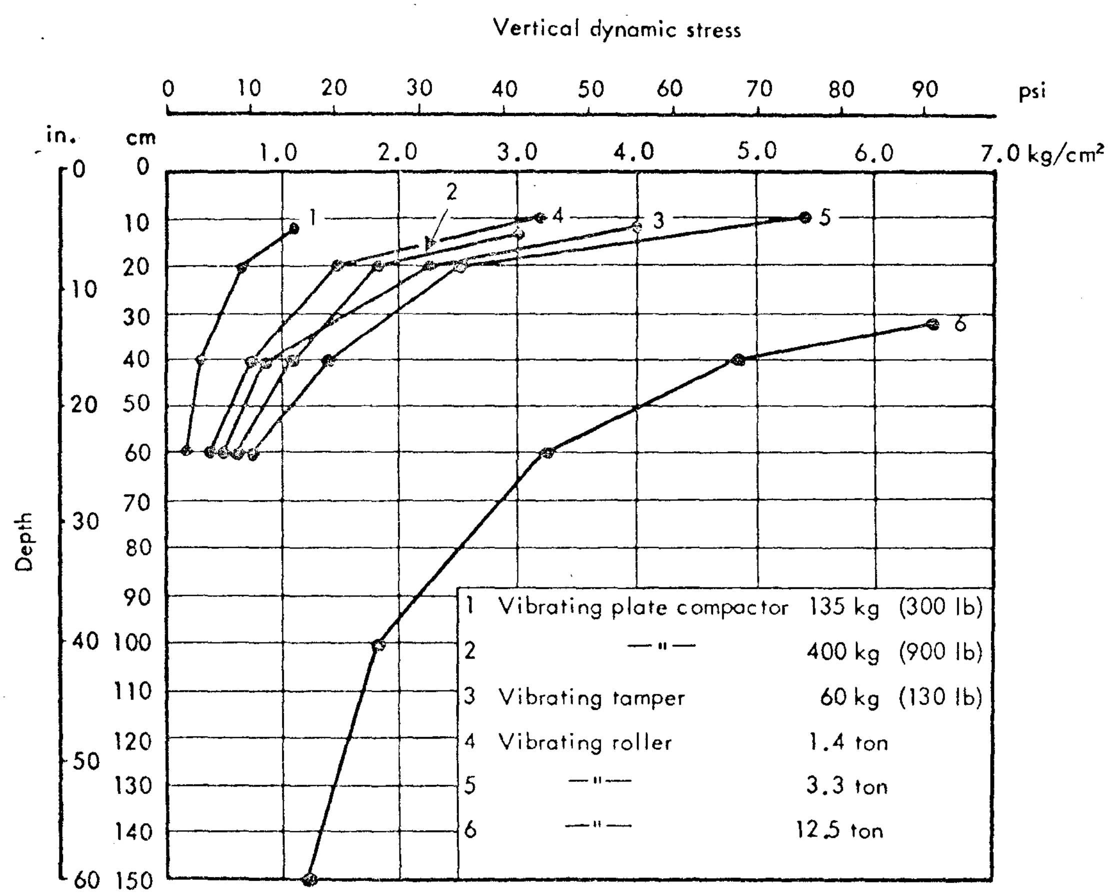


Fig. 6. Vertical dynamic stresses at different depths under vibratory compactors of different types and sizes [3] .

THE IMPACT FORCE . . . (Reprinted from Contract Journal, June 30, 1966)

Compacting Effect And Capacity Of Vibrating Rollers

Appendix 1.

By Prof. Dr. G. Garbotz, Aachen

IN THE COMPETITIVE STRUGGLE between the manufacturers of vibrating rollers one still finds on occasion a statement such as "the vibrating roller as offered has the same capacity or effect as a many times heavier roller with a static action."

Although such claims have repeatedly been declared as nonsensical, it may be opportune to explain once more the conditions arising during soil consolidation by a roller.

It may be best to start with a definition of the terms which are obviously doubtful. The most important term is the impact force. This is connected with the centrifugal force produced by the unbalance only subject to certain qualifications, because the latter depends merely on the unbalanced mass, its eccentricity and the frequency, i.e., on the technical data of the vibrating roller and can be calculated easily.

The impact force K=mb, on the other hand, depends through the term m on the technical data of the roller, i.e., the total mass, and also through the acceleration b on the vibration process of the roller which is excited by the centrifugal force. This process is, however, affected by the damping property of the ground to be compacted. This is the reason why the impact force depends, not only, as shown in Fig.1, very much on the type of ground, but it rises also, as shown in Fig. 2, as the consolidation proceeds.

Not the Case

It is certainly not the case that a greater impact force always results in a better consolidation (see Fig. 3), and a high centrifugal force is not always followed by a higher impact force, for the reason stated above, when the roller rests on the material to be compacted (see Fig. 4). It is therefore absurd to state it in connection with a roller unless the soil concerned and its condition are precisely defined.

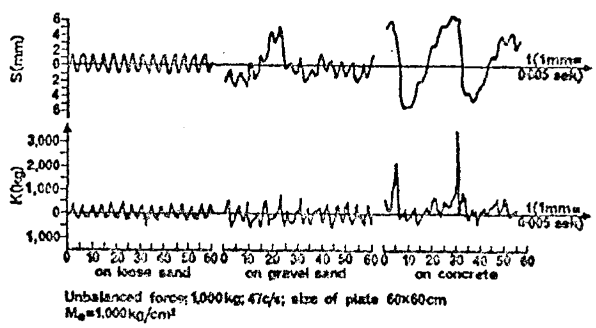
It is just as misguided to speak of the same compacting effect of a statically and of a dynamically acting roller. The compacting effect can be measured by the settlement or by the residual pore volume left by a roller down to the desired depth of consolidation after a certain number of passes. This compacting effect depends, according to what has been said before, to a very large extent to the type of soil and on the compacting appliance (see Fig. 5).

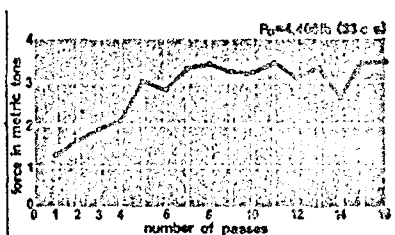
There are types of ground such as well-graded gravels which respond satisfactorily to shaking, and which can be compacted extremely well by dynamic means, i.e., by vibration. On the other hand, there are very cohesive soils for which dynamic consolidation loses in importance compared with the compacting effect of static weight. There is no conceivable case for which we can state or else calculate in advance a definite ratio of the compacting effect between a roller with dynamic and one with static action. It always depends on the type of soil.

For the same reason any comparison of the compacting capacity of statically and dynamically acting rollers is wrong.

(Continued on page 1086)

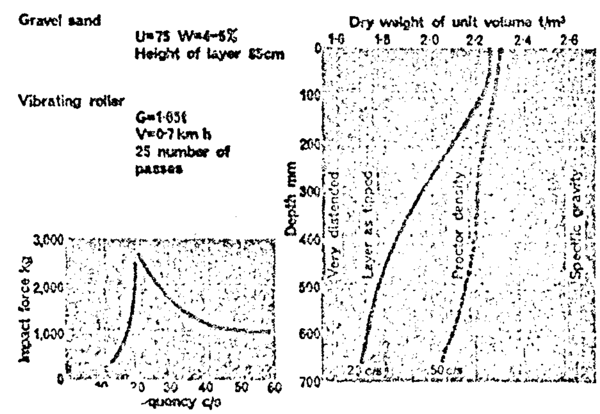
(Fig. 1) Form of jump (S) and impact force (K) on a small-plate vibrator on sand, gravel and concrete

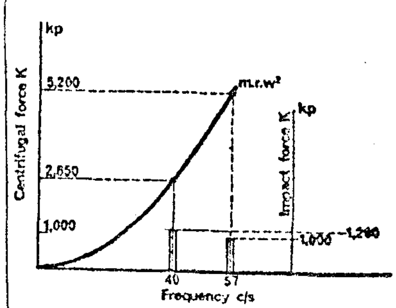




(Fig. 2) Increase of impact force on multi-plate vibrator as consolidation proceeds

(Fig. 3) Impact force (kg) and consolidation of a vibrating roller on gravel at 23 and 50 c/s. The impact force of the roller reaches a maximum of about 2,700 kg at 23 c/s and the consolidation at a depth of, for example, 300 mm corresponds to a dry weight of just under 2.0 t/m³. At 50 c/s the impact force amounts to no more than about 1,000 kg, but the dry weight per volume is 2.2 t/m³





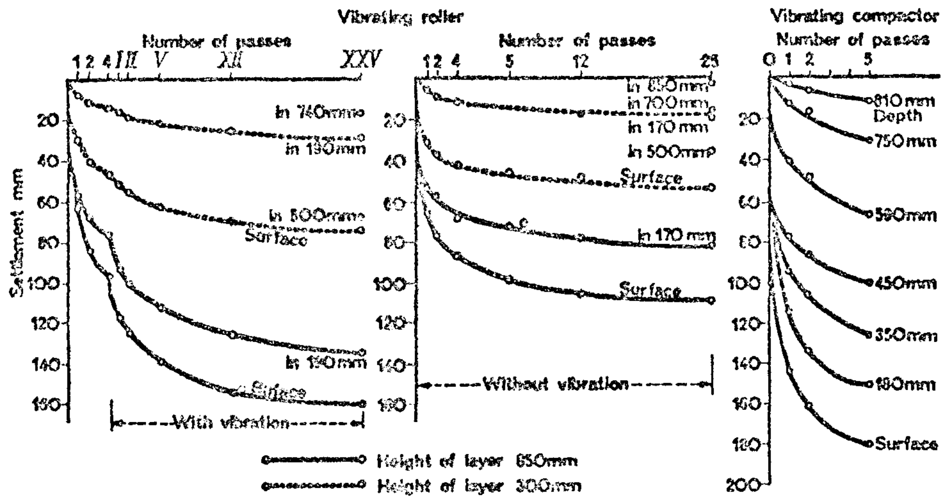
(Fig. 4) Centrifugal and impact forces of a 1.65 t vibrating roller on gravel at 40 and 57 c/s

VIBRATING ROLLERS

(Concluded from page 1083)

The compacting capacity is defined as the capacity in m³/h of uniformly compacted soil which depends on the roller width, the speed, the number of passes and the action in depth. Such a comparison would again, on account of the compacting effect (action in depth), be sensible only for a certain well-*defined* soil, *but never generally* for two certain statically or dynamically acting rollers.

The buyers and users of rollers should, in their own interests, be informed of these facts.



(Fig. 5) Settlements at static (without vib.) and dynamic consolidation of gravel, tipped in layers of 850 and 500 mm height, by a 1.65 t vibrating roller (with and without vibration) at 48 c/s and a 1.6 t large-plate vibrator at 18 c/s