Steel-Tired Rollers

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● THE STEEL-TIRED ROLLER was one of the first types to be used in highway construction and it still plays an important part in the construction of base courses and flexible-type pavements. The correct use and improvements in the design of these rollers to better accomplish a specified purpose is important.

The use of pneumatic-tired, vibratory and other types of rollers is recognized. However, this paper is confined to steel-tired rollers of the static type. There have been many important developments in vibratory rollers, many of which are steel-tired. However, vibratory rollers, even when steel-tired, are not considered in this paper.

Application of the use of steel-tired rollers in this paper is limited mainly to the construction of crushed stone macadam-type base and surface courses and bituminous concrete base and wearing course pavements.

Webster's dictionary defines a tire as "a hoop or band of metal, rubber, air-filled rubber tube, or the like, placed around a wheel of a vehicle to form the tread." Tread is defined as "the part of a wheel, tire or runner which bears on the road, rail, etc., or any of various things or parts on which a person or thing treads, stands or moves." Although this type of roller is commonly called "steel-wheeled," a more accurate term would be to describe it as a "steel-tired" roller.

HISTORY OF THE STEEL-TIRED ROLLER

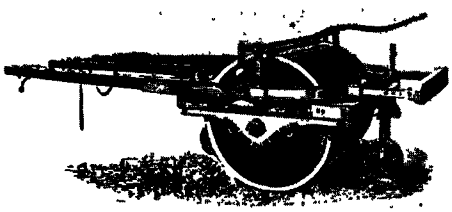
Although it would be appropriate if this paper could be started by stating just who invented the first steam roller, the best that can be said is that this has been a controversial item for many years. Hooley (1), in 1896, stated: "Many claims have been laid as to the first idea of steam rolling, and the author has been many times informed by a man, now deceased, that he first gave the idea for a roller to a noted firm who had hitherto made only traction engines. He used to tell his story somewhat thus: 'Many years ago I was laying water pipes. We could not satisfy the surveyor as to reinstating his roads. One of these ugly great traction engines kept going past our work, so I told the driver one day to just run his hind wheel up my trench. It was a very wet day and down went the trench. I filled it up and had the wheel on again, and so kept on. When the surveyor saw my trench he said he had never seen a better job and set about showing how the whole road could be so made, if a portion could be made with a comparatively narrow wheel; thus you see I started the idea of steam rolling.'"

Whether this really had anything to do with the original rollers, the author, Hooley, did not state. Without doubt the man believed what he was saying, but that does not exclude the fact that others might have had similar ideas.

In a recent publication (2) one equipment manufacturer says: "The earliest known records of intentional pre-compaction date back to the great road construction era during the Roman Empire. Huge cylindrical stone rollers, drawn by slaves, were used to imbed rocks into the earth subbase, in some cases three to five feet below the proposed roadway surface, and to compact successive layers or lifts of smaller stones to the surface level. Many of these roads are still in existence today and some are in use. The Appian Way is an example."

Horse-drawn rollers were in common use during the 19th century and in fact were manufactured both in Europe and in the United States. In 1862 a patent was granted to William Barford for increasing the weight of horse-drawn rollers (Fig. 1) by filling the cylinders with water (3). He was also granted a patent for his turn-table frame, which enabled the horses to turn around without turning the roller. It seems natural to assume that this was the original design of the steel-tired roller used today. The inventor of the original horse-drawn roller is unknown.

In 1865 a roller was designed by Gellerat & Co. of Paris, France. This roller (Fig. 2) was described as follows: "The roller wheels were carried by the bed plate under the boiler. The crank shaft was connected to the two axles by two endless chains,



It was in connection with rollers that in 1862 a patent was granted to William Barford for increasing the weight of horse and hand-drawn rollers by filling the cylinders with water. This method of increasing weight has not been superseded, and is in use to-day on all types and makes of power driven rollers.

Figure 1. Horse-drawn roller with patented water ballast.

both front and hind rollers being driven."

Steering was effected by diminishing or increasing the distance between the ends of the axles by means of two blocks running on a right- and left-hand threaded spindle. When the axles were parallel, the machine of necessity traveled in a straight line.

The disadvantages of this roller were: (a) The smallness of the roller wheels caused the road material to be driven before them; (b) the steering was slow and ineffective; (c) the wide rigid rollers destroyed the crown of the road; and (d) the road was left ridged instead of smooth.

In 1865 Morland & Co., feeling the necessity of designing a road roller rather than using the unsatisfactory method of allowing ordinary traffic to consolidate the fresh-laid road material, designed a covered-in steam roller (Fig. 3). This roller was never a success.

Another unsuccessful attempt was a steam tandem (Fig. 4) designed by John Whittingham and Robert Douglas of Nantwick, England.

It is evident that there were many ideas on the design of rollers, many of which were not practical. It remained for Thomas Aveling to invent and construct the first successful steam road roller.

In a paper entitled "The Economical Use of Road Locomotive, Compared with Horse Labor", read at Sheffield in 1865, Thomas Aveling stated that, "It was an insult to mechanical science to see half-a-dozen horses drag along a steam engine, and the sight of six sailing vessels towing a steamer would certainly not be more ridiculous. ... The work of making the paralytic 'portable engine' self-propelled had at length been affected, and it was now to be seen not only running up hill itself, but pulling a heavy load behind it."

In an 1860 catalog, Aveling's patent "locomotive" is shown as having a fifth wheel mounted on a forecarriage for an independent steersman who, sitting with his back to the smoke box of the boiler, controlled the direction of the machine. In 1861 Letter Patent No. 1295 was granted to Thomas Aveling, which shows that he was the inventor of the steam-jacketed cylinder.

Use of Aveling's steam locomotive as a tractor gained rapid popularity. One of its first uses was for the steam "thrashing" train (Fig. 5) and later for hauling war material (Fig. 6). It was natural that this steam locomotive with some alterations eventually would become a steam roller.

There were several unsuccessful attempts to invent a steam roller prior to 1865. The honor for inventing the first successful steam roller goes to Thomas Aveling. In 1865, after experimenting with his road locomotive engine trying to adapt it to a road roller, he decided to construct a machine expressly for rolling. "The Illustrated London News" of December 15, 1866 recorded the trial of Aveling & Porter's steam road roller (Fig. 7) in Hyde Park as follows:

> The use of steam rollers for the purpose of crushing the stones and smoothing the surface of our macadamized roads has long been advocated as one of the most desired metropolitan improvements.

Figure 2. 1865 roller by Gellerat & Co., Paris, France.

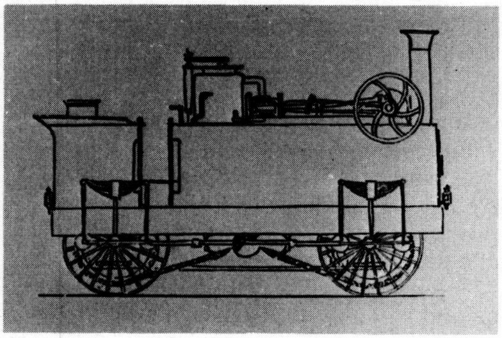


Figure 3. 1865 roller by Morland & Co.

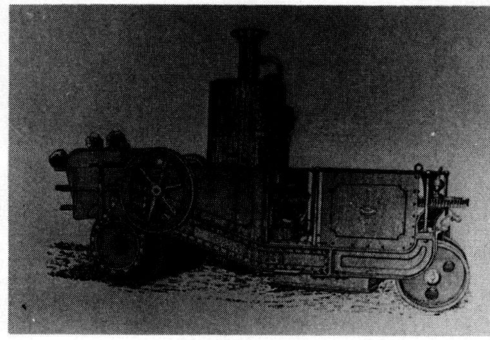


Figure 4. Tandem roller by Whittingham & Douglas.

Though we must, apparently, wait a little longer before we see these effective and economical machines employed in the streets of London, it is satisfactory to observe that the First Commissioner of Her Majesty's Works has resolved to give them a trial in the parks; and one has been doing good service in Hyde Park during the last two or three weeks, to the admiration of numerous spectators. Our illustration is a rear view of this steam roller, which was manufactured by Messrs. Aveling & Porter. The engine is of 12 horse power (nominal), and the rollers are 3 ft broad and 7 ft in diameter, bearing with a weight of 3 tons on each square foot. The weight of the whole is more than 20 tons. We are informed that the parish vestry of Islington

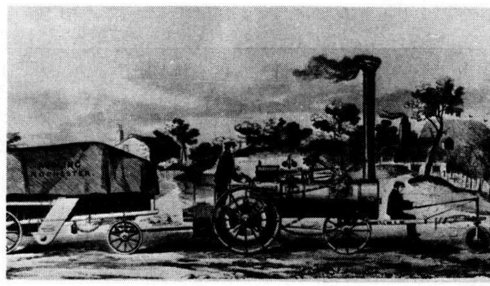


Figure 5. Aveling threshing machine.

Figure 6. Steam sapper.

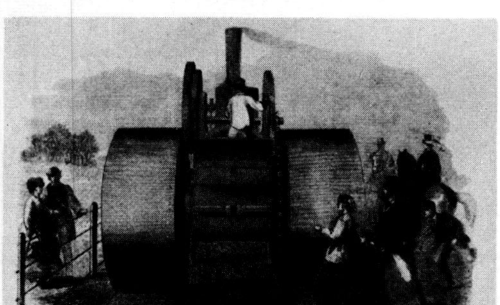


Figure 7. Rear view of first successful steam roller.

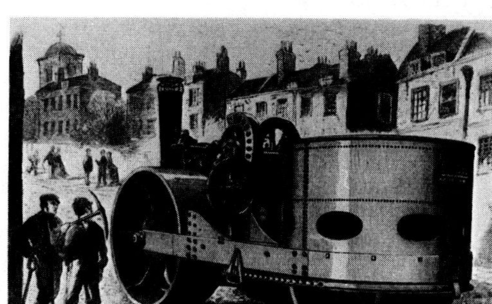


Figure 8. First machine designed throughout as a roller.

has under its consideration a proposal for the use of a steam roller on the roads in that parish.

Convinced of the correctness of the principles employed in the construction of the trial machines and encouraged by the success attending their use, Thomas Aveling proceeded to build the first machine designed throughout as a road roller.

The machine (Fig. 8) weighed about 30 tons and had a single-acting 12-hp engine, the diameter of the cylinder being 11 in. and the length of stroke 14 in. It carried a water tank holding 500 gal and steering was by a ship's handwheel operating a chain to the steering roll through the medium of a worm gear. An indicator was provided to show the position of the steering rolls and, despite its bulk, the machine could be turned around in its own length.

Figure 9. Plaque erected to Thomas Aveling.

The driving rolls were 7 ft in diameter by 2 ft wide and the steering roll, in two sections, was 5 ft in diameter by 5 ft wide. In 1869 two road rollers of similar pattern to the original machine were sent to America—one to Prospect Park, Brooklyn, the other to Central Park, New York. In their report, the commissioners of Central Park stated that in one day's rolling with Aveling & Porter's roller, at a cost of $10, as much work was accomplished as in two days with a 7-ton roller drawn by eight horses at a cost of $20 per day.

In 1951, the Festival Year of Great Britain, the Parish Council of Ruckinge, near Ashfort in Kent, erected roadside plaques (Fig. 9) in the village to commemorate and honor Thomas Aveling as the inventor of the steam road roller.

In 1904 the Company of Barford and Perkins, Ltd. of Peterborough, England, (now incorporated in Aveling-Barford, Ltd.) produced the world's first motor-driven roller (Fig. 10). This was first exhibited at the Royal Show in 1905. Powered by a Simms single-cylinder 8-hp engine, speeds were 1 and 3 mph in either direction. Water ballast-type rolls were fitted. In 1927, another big advancement in the development of the road roller was made when the company built the world's first roller powered by a solid injection high-speed diesel engine. This roller was built in weights from 9 to 15 tons. Due to the performance of this type of roller and its economical working, together with the gasoline-driven motors, the steam roller has gradually disappeared and is seldom seen today. The last of the steam rollers manufactured in the United States was about 1935, although steam rollers were manufactured in Britain between 1930 and 1940, and even after that date in Germany and Japan in limited numbers.

The Buffalo-Springfield Roller Co., formerly the Kelly-Springfield Road Roller Co., published a small pamphlet (4, 5) about 1940 concerning the history of the tandem roller. According to information obtained from this publication, Andrew Lindelof designed and built the first tandem roller (Fig. 11) in the United States. "The frame and rolls were much like present rollers. The power plant consisted of a vertical boiler and a large two-cylinder steam engine, which was geared directly to the driving roll by bevel gears. As the maximum obtained with this gear was about seven to one, it

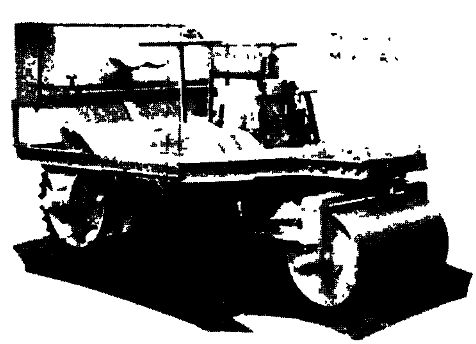


Figure 10. The first motor roller.

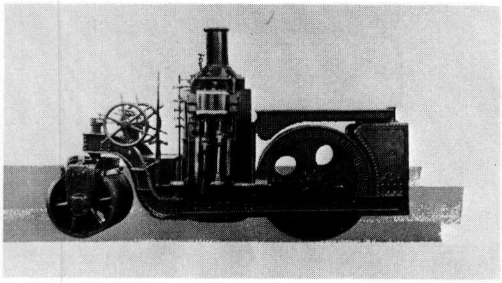


Figure 11. First tandem roller in U.S., by Andrew Lindelof 1878.

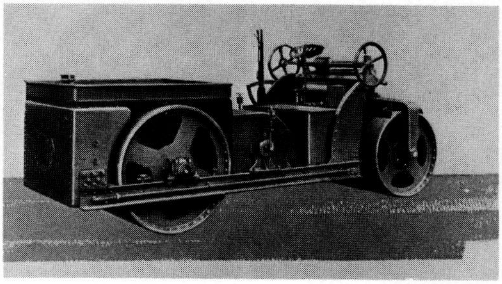


Figure 12. First gasoline-driven tandem in U.S., by Kelly-Springfield.

was possible to run the engine at only 70 to 80 rpm. Large cylinders and heavy pistons had to be used to obtain sufficient power. Mechanically, the roller operated very well, but the slow-speed heavy-duty pistons set up a rocking motion in the machine, which caused undesirable waves in the material rolled."

In 1898 the first Springfield steam tandem was produced. This roller resembled the Lindelof roller. An attempt was made to overcome the defects of the former roller by shortening the piston rods, lowering the engine, and setting the engine in a slanting position. Thus, the rocking motion was reduced but not eliminated. The operator of this roller was placed on the engine side or drive side of the machine because the large boiler occupied the other side of the roller. One of the disadvantages of this design was that with the final drive gears on the operator's side of the machine his vision was seriously obscured when rolling close to obstructions.

In 1902 Kelly-Springfield designed and built a steam tandem roller with a spur gear final drive. This roller represented further attempts to eliminate the objectionable rocking motion of its predecessors. These gears also permitted the engine to be operated at much higher speed than the previous rollers.

In 1908 an important step forward was taken when Kelly-Springfield designed and built the first gasoline-powered tandem in the United States (Fig. 12). The chassis of the steam roller was retained, but a small gasoline engine replaced the steam boiler. This was where the designer failed to note that the difficulties with the vertical-type steam boiler had kept the diameter of the rolls at a minimum and now there was an opportunity to increase the diameter. The spur gear final drive of the former rollers was retained, although sufficient reduction could now be obtained in the reversing gears that were used with the much higher-speed gasoline engines. In 1914 the Buffalo-Springfield Roller Co. designed and built a two-cylinder opposed gasoline tandem roller and in 1922 introduced an improved four-cylinder tandem roller with an improved cooling system. In 1929 Buffalo-Springfield built a six-cylinder roller. This was a much more simplified model than previous ones and marked a real improvement in tandem roller design.

Advent of Inter-Roll

Since 1913 various attempts had been made to produce satisfactory road rollers embodying use of an extra roll or a third axle. The first roller of this type, introduced by Austin-Western in 1934, was known as the "Roll-A-Plane Roller." In 1935 Buffalo-Springfield designed a three-wheel tricycle-type roller with an extra roll or third axle provided with a means of raising and lowering this inter-roll (Fig. 13). The purpose of this was to

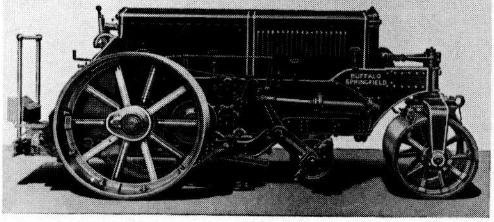


Figure 13. One of the first Buffalo-Springfield inter-roll rollers.

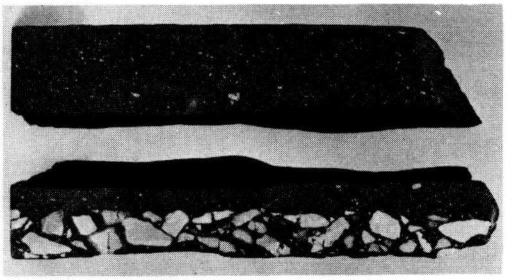


Figure 14. Pavement failure from inter-roll.

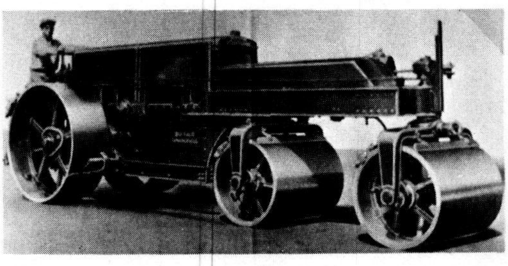


Figure 15. Buffalo-Springfield first three-axle roller with steerable third roll, manufactured in 1935.

put the roller wheels on three separate axles on a straight plane, so that when high spots were encountered there would be a transfer of weight and pressure to the roll in contact with the high spots. This, of course, was an old and well-known principle.

This application, however, had a serious fallacy. The rolling of bituminous mixtures must all be accomplished while the mixture is in a plastic state. The primary function of a roller is to press the material down, and the value of compression is dependent on verticality, which in turn is related to roller diameter. Horizontal pushing of the material is to be avoided and it is obvious that this horizontal pushing is increased as the diameter decreases.

This was where the principle of the inter-roll met with its first opposition. Figure 14 shows the type of failure that occurred when using this small-diameter inter-roll. In accordance with information from Buffalo-Springfield, this failure occurred during the summer of 1936 on an experimental job on Route 20 between Ashtabula and Conneaut, Ohio. As a result of that experiment the use of Roll-A-Planes (or inter-rolls) was not permitted on Ohio State Highway construction.

In 1935 the "three-axle" roller with steerable third roll (Fig. 15) was designed and constructed by Buffalo-Springfield Roller Co.

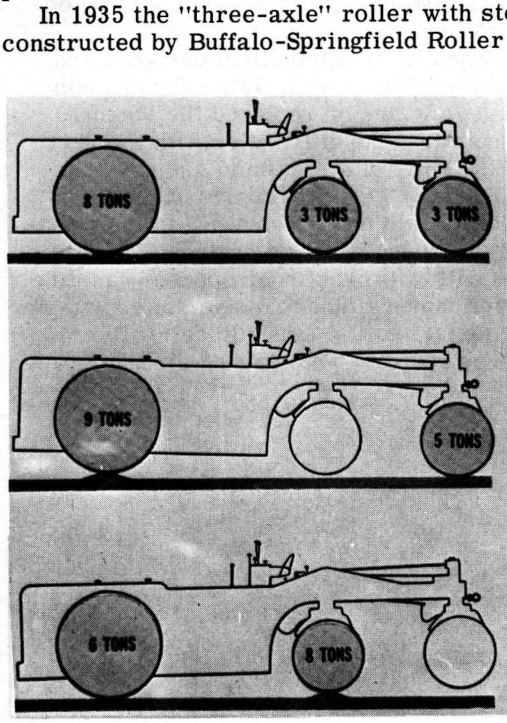


Figure 16. Principle of three-axle tandem roller.

It was commonly believed that one of the faults of the tandem roller was to follow the contour of the road, causing variations in the riding qualities. By now, of course, it is well known that the small-diameter inter-roll was not satisfactory due to the horizontal thrust. The principle of the three axles seemed sound, as the three axles could not follow the contour and automatically concentrated the weight on the high places (Fig. 16). Previous attempts to use this principle failed because the roller could not be steered with two fixed axles and the additional fault of the small-diameter inter-roll causing failures from lamination. Larger-diameter rolls and double synchronized steering of the Buffalo-Springfield design tended to overcome these difficulties. The principle of the three-axle tandem is well shown by Figure 16.

Having now traced the history of the steel-tired roller from the first steam roller to the motor roller, both for the two-axle and three-axle types and the development of the inter-roll, it is evident that roller diameters have been a problem

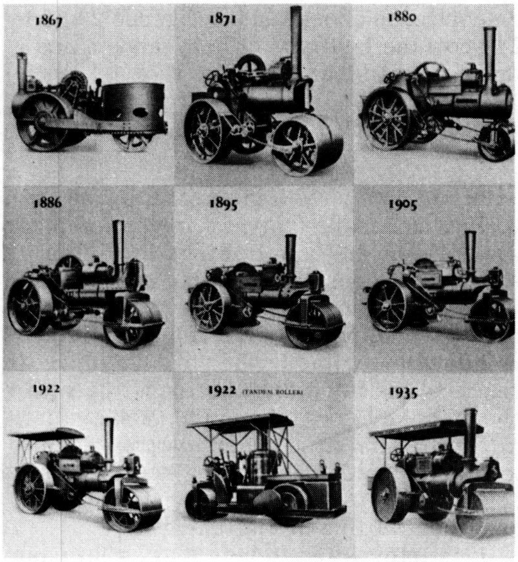


Figure 17. Evolution of steam roller.

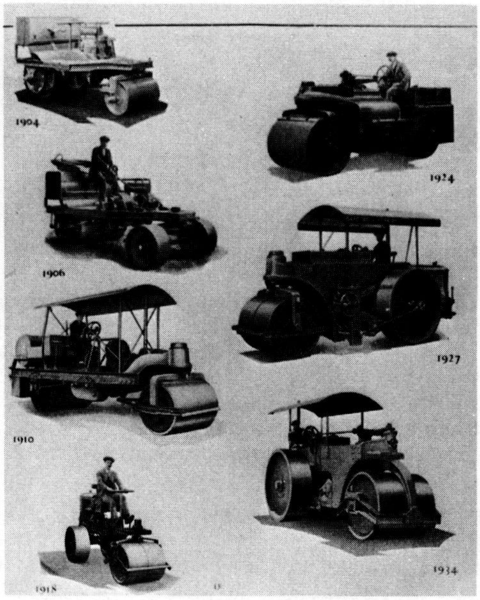


Figure 18. Evolution of motor roller.

not always fully considered. This is shown when the conversion took place from the steam tandem to the motor tandem roller. However, this was forcefully brought to attention with the advent of the inter-roll.

Several companies played an important part in the development of the steel-tired roller in the United States. Included among these are the following:

1. Austin-Western, Construction Equipment Division, Baldwin-Lima-Hamilton Corp., Aurora, Ill.
2. Buffalo-Springfield Roller Co., Springfield, Ohio.
3. The Galion Iron Works & Mfg. Co., Galion, Ohio.
4. Huber-Warco Mfg. Co., Marion, Ohio.

Modern rollers differ considerably from the early models (Figs. 17 and 18). However, the same principles hold true--namely, application of compressive force in pounds per linear inch of roll and maximum practical diameter of rolls. Figures 19, 20, 21, and 22 are some of the recent models both in the United States and Europe.

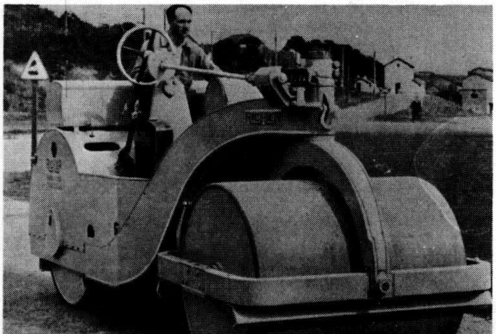


Figure 19. Tandem roller, Paris, France, by Richer.

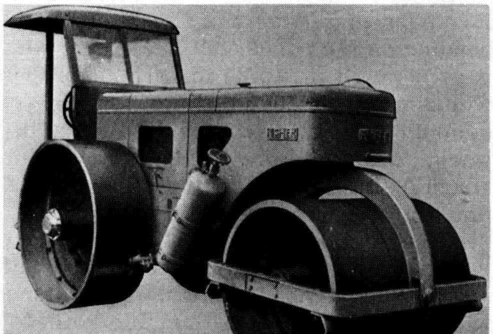


Figure 20. Three-wheel roller, Paris, France, by Richer.

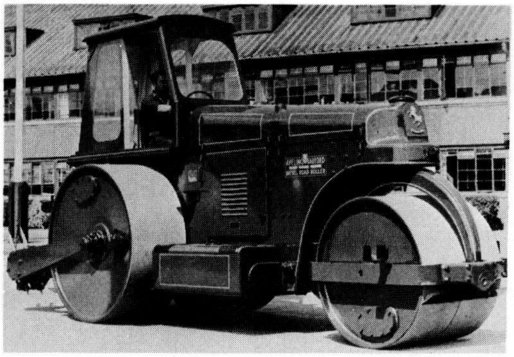


Figure 21. Three-wheel roller, Aveling-Barford, England.

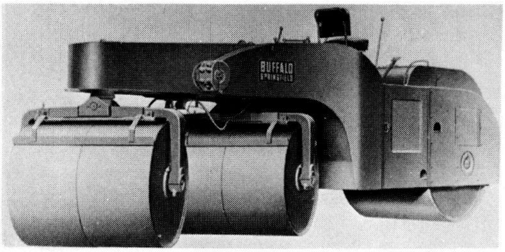


Figure 22. Three-axle tandem by Buffalo-Springfield.

The manufacture of steam rollers was discontinued about 1935. Figures 23 and 24 show the last type of both tandem and three-wheel steam rollers.

CONSTRUCTION OF MACADAM-TYPE PAVEMENTS

A common clause in specifications for rolling macadam-type pavements for many years has been the following: "Rolling should commence at one edge of the roadway and progress toward the center, the roller traveling in a direction parallel with the centerline of the road. After reaching the middle of the road, the roller should pass to the other side, and again work in a similar manner toward the center. This method of rolling keeps the road in shape and prevents either pushing the crown out of line or flattening it."

It is interesting to note that as late as 1914 Blanchard and Drowne (6) stated: "A steam roller is much more effective than a horse roller, since the latter is lighter and hence cannot compact the surface as thoroughly. Moreover, the horses' hooves tend to loosen the surface during compaction, which makes it difficult to secure good results."

For many years the popular type of roller for macadam-type pavements has been the two-axle "tricycle" type . The advantages are the large roller diameter (usually 60 in. or more) and the large compression factor (often in excess of 300 lb per lin in. for a 10-ton roller).

It is common to divide the three-wheel two-axle tricycle type into the two classifications of general purpose and finishing type.

General purpose rollers are normally furnished in a variety of tire widths, depending on the purpose. These tire widths vary from 18 in. to 24 in. The narrower widths give greater compression and are commonly used for compaction of earthwork; rolls for this purpose may be either rough or machined and drilled or not drilled for picks, which are frequently required to add tractive effort, as this type of roller is frequently equipped with scarifiers. They are normally furnished with either spoke or ballastable rolls to obtain variations in compression.

The three-wheel finishing rollers are used for rolling water-bound macadam, surface treatment, and bituminous con-

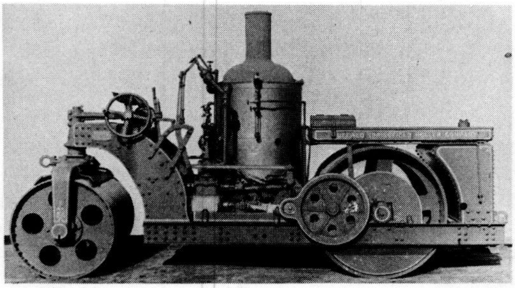


Figure 23. Last type of steam tandem by Buffalo-Springfield.

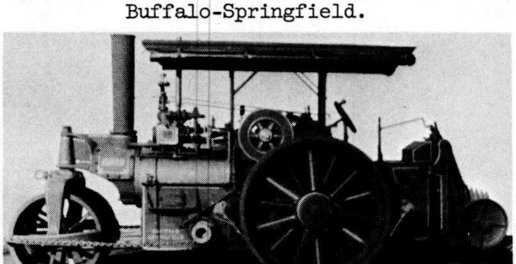


Figure 24. Last type of steam three-wheel by Buffalo-Springfield.

crete. Due to the large roller diameter they are frequently used ahead of the tandem on bituminous concrete. Normally, these rollers are equipped with wide-faced machine-finished tires. This increase in width reduces the compression per linear inch. They are normally furnished with either spoke or ballastable rolls for variations in compression.

In recent years it has become common to use tandem rollers for macadam-type pavements. A common fault has been the small roller diameter and the relatively small compression in pounds per linear inch. Use of the three-axle tandem has done much to overcome this, as a great variation in compression can be obtained, especially when all three wheels are not in the same plane, thereby tending to remove irregularities.

Compaction of the macadam-type base and surface courses make them adequate to resist the vibration, weights and wear of modern highway traffic. Crushed rock has a tendency to "bridge" and cause an excess of air voids or lack of density. A minimum amount of fracture in the construction of macadam-type base courses is not harmful, especially if it is a sand-filled or water-bound type. With a bituminous penetrated type, however, fractures expose uncoated areas. Moreover, it should not be the purpose of a roller to do the work of a stone crusher. The matter of maximum size stone for macadam-type base courses has been covered elsewhere (7).

RECOMMENDATIONS FOR ROLLING MACADAM-TYPE PAVEMENTS

The following recommendations for rolling macadam-type pavements are based on notes from the author's notebook and in many cases are a summary of the opinions of various skilled roller operators the author has been associated with over the past 35 years.

With penetration types the amount of rolling should be confined to only one complete coverage before the bituminous material is applied. There is a tendency to over-roll at this stage, which results in too much compaction and prevents the penetration of the bituminous material. The bituminous material should be applied directly after this first coverage before any other traffic has had an opportunity to go on the unbound stone and cause displacement.

Normally, stone chips are applied after this first penetration before further rolling. A method not as common, but one which is preferred by the author, is "green rolling."

Green rolling has many advantages. There is no wedging apart of the stone by the application of chips, as this is done directly after the penetration of the bituminous material. Hence, it is much easier to obtain greater densities. Placing of stone chips directly after the penetration often displaces the stone, as it is necessary for the stone spreading vehicles to travel over the pavement before compaction, either directly on the applied bituminous material or on the freshly applied chips. Green rolling eliminates this difficulty as the pavement is quite thoroughly compacted before the application of chips. There is some reduction in the amount of key stone or chips used in this method as compared to the normal type of rolling. There is less tendency to fracture stone with green rolling because the bituminous material acts as a lubricant and prevents bridging to a greater extent than when the chips are applied before rolling.

The rolling procedure should start at the edge of the roadway and progress toward the center as previously described. The edge should be retained by the shoulder material and the first pass should lap at least 6 to 12 in. onto this shoulder material. This supports the lowest section of the pavement and prevents or reduces the tendency of the pavement to creep or widen out.

There is some variation in amount of lap by different roller operators. Some maintain that they should lap half the width of the roll, which would naturally require a great many more passes with a two-axle three-wheel tricycle-type roller than with a tandem. Others maintain that a 2-in. lap is sufficient with the three-wheel tricycle type and from one-fourth to one-half the width of the roll with a tandem-type roller. All of the operators complained that it was difficult to steer the three-wheel roller, especially in the initial stages of compaction, due to the small diameter of the guide roll. They described this as a constant trigging action, which can easily be observed when watching rolling procedure. Because of this it is not uncommon for operators to roll with the drive roll ahead, due to its larger diameter.

An important factor in rolling macadam-type pavements is the speed of rolling. A common description is a "slow walking speed," or about 2½ mph. This may be increased some with additional coverages after the initial compaction.

All of the roller operators questioned agree that there should be a definite roller pattern and favor inspection maintaining the enforcement of following a definite pattern. There are exceptions to this rule, as often there are high places to remove that can be smoothed out by "rocking them down" or concentrated rolling on the area to be corrected.

Another factor which has long been recognized by roller operators but which is seldom mentioned otherwise is the time of day when rolling can best be accomplished. Photographers commonly state that the best time to take pictures is from 9:30 AM to 3:30 PM. Actually this same rule of thumb is good for rolling. Temperatures are usually at a maximum for the day at about noon and start falling off quite rapidly after 3:30 PM. In other words, the higher temperatures and greatest uniformity is between 9:30 AM and 3:30 PM. Weather records indicate that on an average during the summer months the maximum temperature occurs about noon to 4:00 PM with a slight peak at about 2:00 PM, the greatest uniformity occurring between 10:00 AM and 4:00 PM during the summer. During the fall months this changes to from about 11:00 AM to 3:00 PM.

Final rolling for this type of pavement may be done the day following construction, but should be completed within two days. This finish rolling should be accomplished in half-mile sections and should all be done between 9:30 AM and 3:30 PM, to be most effective. It is to be noted that this paper does not discuss construction procedure or equipment other than rollers and rolling procedures.

In recent years the three-axle tandem roller has taken an important position in the construction of macadam-type pavements. Great variations in compression pounds per linear inch may be obtained, especially when all three rolls are not in the same plane. The principal difficulty as compared to the three-wheel tricycle type is that the diameter of the roll is smaller and not as much compressive force is exerted. Slippage is also apt to occur, due to the diameter of the rolls and the weight of the roller, which can easily cause damage to the rolls (such as grooving or pitting).

Use of ballast in rolls of both the tandem and tricycle types is unpopular with most operators. The "sloshing" effect causes displacement in the rolling and makes it difficult to manipulate and steer the roller. All operators questioned agreed that it would be more satisfactory to have a spoke-type wheel in which counter or balance weights could be added. This would eliminate the undesirable features of the liquid ballast and could be so designed as to give perfect balance as well as the desired increase in weight.

A common grievance of roller operators is the size of the stone used in the construction, the frequent lack of uniformity, and the flat and elongated particles. Much has been said about this item elsewhere (7). Above all, the material should be uniform and free from segregation.

From all discussions with roller operators and construction men, combined with the author's own experience, it is believed that an ideal type of roller for this type of construction would be a three-wheel tandem roller with a roll diameter of 72 in. or more, ranging from 12 to 20 tons by the use of ballast. This ballast should be in the form of balance weights inserted inside the wheels. With this type of roller the width of the rolls could be increased about 10 percent over the tandem rollers now in use.

BITUMINOUS MACADAM BASE COURSE–MAINE TURNPIKE

Some interesting data concerning rolling with the steel-tired roller were obtained during the construction of the Portland-Augusta section of the Maine Turnpike (8). Because this is of special interest concerning steel-tired rollers, some of the information is also included here.

It became evident during the construction of the bituminous macadam base course on the Maine Turnpike that the penetration of the bituminous material into the macadam pavement was not satisfactory and there also appeared to be a lack of density of the completed macadam base course. A study showed that there was an excess of flat and elongated particles, which caused a lack of uniformity of the macadam base course and also prevented the penetration of the bituminous material.

To evaluate the condition of the macadam base course the plate bearing test was used. The specifications for this work were as follows:

Equipment

The equipment shall consist of two trucks with rear axle load not less than 18 tons and a 12-in. by 12-in. steel I-beam arranged in such a manner as to have a clear span of not less than 16 ft.

The hydraulic jack used to apply the load must have a pressure gage. The 16,000-lb jack shall have a gage equipped for reading to 200-lb intervals. The 60,000-lb jack shall have a pressure gage reading to 1,000-lb intervals.

The bearing plates shall consist of rigid steel plates (may be a series of plates to increase rigidity).

1. Diameter of rigid steel plate = 30 in.
2. Diameter of rigid steel plate = 12 in.

The method of measuring the deflections shall be by means of two dial gages with least count of $\frac{1}{1000}$ in. These gages shall be supported by a beam, the ends of which are supported by a suitable pedestal at a distance of not less than 6 ft from the loading plate and from the nearest truck wheel. The spindles of these dials shall bear against the top surface of the loading plate at two points situated on a diameter and equally distant from the center of the plate.

Preparation of Test Area

The plate bearing test shall be made on the surface in its existing state. A minimum amount of sand shall be used to secure an even bearing and in no case shall the amount of sand used be greater than the amount required to fill the existing depressions in the area being tested (not to exceed $\frac{1}{4}$ in. thick).

Layout

The bearing plate is to be located at least 8 ft from the nearest wheel load and the supports for the gage mountings are to be placed at least 8 ft from the bearing plate and from the nearest wheel load.

Test Procedure

1. Apply load of 5 psi to set bearing plate. Release load and adjust dials to read zero.

2. Apply a load of 5 psi and maintain constant for 2 min and record the dial readings. Follow this procedure using the loads indicated in the following table.

	Load (lb)	
Pressure (psi)	12-in. Dia. Plate	30-in. Dia. Plate
5	575	3,500
10	1,125	7,100
15	1,700	10,600
20	2,250	14,100
30	3,400	21,200
40	4,525	28,300
60	6,950	42,400
80	9,050	56,500

Area of 12-in. dia. plate = 113.1 sq in.
Area of 30-in. dia. plate = 706.9 sq in.

The subgrade modulus, K, was determined for both the bituminous macadam base

TABLE 1

RESULTS OF SUBGRADE MODULUS TESTS, MAINE TURNPIKE

Location	Material	K at 0.05 in. Defl.	Equivalent CBR
1	Bit. macadam base course	544	55
2	" " " "	439	43
3	" " " "	816	100
4	" " " "	529	54
5	Gravel base course	953	100
6	" " "	1,690[a]	100
7	" " "	925	100

[a] Deflection only 0.0355 in.

course and the gravel base course. This modulus is the quotient of the pressure in psi, measured at a deflection of 0.05 in., divided by the deflection in inches of a 30-in. diameter rigid plate. The subgrade modulus is a measure of resistance of the subgrade or base course to deflection induced by traffic or other loads. The results of these tests are given in Table 1.

Similar tests made by applying pressure to a 12-in. diameter plate, which approximates the bearing area of a highway vehicle, showed much greater resistance to displacement.

The results obtained for the K values of the bituminous macadam base course were all smaller than the corresponding values obtained on the gravel base. This was direct evidence that the bituminous macadam base course was more compressible than the gravel base and indicated that the former could be more thoroughly compacted.

Using the CBR values obtained for the bituminous macadam base and applying the Corps of Engineers design table with a wheel load of 10,000 lb, a 3-in. bituminous concrete pavement should be adequate to carry the traffic for a 10,000-lb wheel load. However, there were low CBR values and, as indicated by the results of the load bearing test, it was believed that these values could be increased by further rolling.

The procedure was then as follows: All of the areas showing low CBR values were re-rolled using heavy rollers with full ballast load, giving a working pressure of 505 lb per lin in. for the drive roll and 215 lb per lin in. for the guide roll. Sections were then re-rolled for about four coverages, and load bearing tests were repeated. It was found that the modulus of subgrade reaction was increased from an average of 490 to more than 800 or, in other words, the CBR value was increased from 50 to a value of 100. This revealing study shows conclusively the importance of rolling and that different gradations and particle shapes may require variable amounts of rolling.

This incident in the construction of the macadam base course on the Maine Turnpike further illustrated that it was possible to do a satisfactory job in rolling macadam base courses with a tandem roller provided enough compression in pounds per linear inch could be obtained and the rolls were of large diameter. Table 2 gives comparative data on the various rollers used in the construction of the Maine Turnpike.

It should be noted that the compression in pounds per linear inch, for the fully ballasted machine is nearly equal to that obtained with the large-size three-wheel, two-axle tricycle type.

Satisfactory results can be obtained in the construction of macadam-type pavements with tandem rollers if the roll diameter is in excess of 70 in. and the compression can be varied from 250 to 400 lb per lin in. An added advantage is that with compression reduced to 250 lb per lin in., the roller is adapted to rolling bituminous concrete pavements. With large diameter, metal used in the steel tires can be of sufficient hardness to minimize pitting and scoring such as occur in softer metals, especially with small diameter rolls where more horizontal thrust occurs.

TABLE 2

COMPARATIVE DATA FOR ROLLERS[a] USED ON MAINE TURNPIKE

Model	Type	Over-All Length (ft-in.)	Metal Weight (tons)	Max. Working Weight (tons)	Compression (lb/in.)		Guide Roll		Drive Roll	
					Net Metal Drive Roll Weight	Full Ballast Weight	Dia. (in.)	Width (in.)	Dia. (in.)	Width (in.)
VT-48	2-Wh. tandem	20-7	15	21	330	505	51¼	59	71¾	59
KX25-D[b]	3-Wh. tandem	22-9	13	20	225	383	48	54	60	54
	Beam action	-	-	-	325	467	-	-	-	-
KT-25C2	2-Wh. tandem	16-4	10	15	256	407	48	54	60	54
VM-31-C	Conv. 3-wheel	17-5	10.5	14	368	502	44	44	69	20
VM-32-C	Conv. 3-wheel	17-5	12.5	15.5	422	548	44	44	69	20

[a] All Buffalo-Springfield. [b] Walking beam.

CONSTRUCTION OF BITUMINOUS CONCRETE PAVEMENTS

Rolling procedure of bituminous concrete base and binder courses should not vary much from that of the macadam-type pavements. It is possible that the compression per linear inch should be reduced some from that used on the macadam-type pavements due to the decrease in thickness.

The following is a summary of the opinions of four skilled roller operators, all with more than 25 years of experience in rolling bituminous concrete mixtures:

1. Ballast should not be used in rolls when rolling bituminous concrete.
2. For the knock-down rolling, the use of the three-axle tandem is preferred and from one to two coverages is sufficient provided this is done directly behind the paver.
3. For the final rolling either the two-wheel tandem or three-axle tandem is preferred.
4. All agree that larger roll diameters would be an advantage and would lessen the possibility of damage from over-rolling.
5. All agree that the knock-down rolling should be done directly behind the paver to obtain maximum density, but none could give definite temperatures.
6. All final rolling should be completed before the mixture has reached atmospheric temperature and while still in a plastic state.
7. All agree that the following is a normal good procedure for rolling bituminous concrete surface courses. (This procedure is based on construction of a 22-ft pavement width in two separate passes of the paver.)

Complete one coverage by starting the first pass at the gutter line and roll toward the center or, in the case of a banked curve, start at the low side. Let the pavement set for a short time (less than 20 min) to permit the surface course to bond to the binder. From two to three complete coverages are required for the knock-down rolling. If the pavement is to remain warm by the time the second layer is paved, it is common to leave about 2 in. next to where the longitudinal center joint will be formed. For the finish rolling from three to four complete coverages are required. Pavement temperatures must be watched carefully for the final rolling in order to iron out roller marks but not to cause further indentation. It is considered good practice to have a roller pattern, but it is not considered necessary to follow the same pattern on the final rolling as on the knock-down rolling.

For the second or final paving course or lane, it is recommended making the first pass at the centerline joint, lapping half the width of the roll, or the centerline of the roll on the centerline joint of the pavement. Then, starting at the gutter and rolling toward the centerline, continuing until on the final lap one-third of the roll is on the previous lane and two-thirds on the final lane. From three to four coverages are necessary for the final rolling.

All of those interviewed expressed the importance of rolling while the mix was hot, but also pointed out the necessity of not over-rolling at this stage, causing cracking or displacement. They were of the opinion that rolling at high temperatures could be better accomplished with larger roller diameters and under some circumstances might prefer the three-wheel tricycle-type roller for the initial rolling due to the larger diameter of the drive roll. In this case the roller would be operated with the drive rolls ahead, due to their larger diameter. They all had used water and several had used sand in the ballast wheels; all were opposed to the use of the ballast, stating that it seriously affected the operation of the roller, making it especially difficult to steer.

EXPERIMENT IN COMPACTION AT VARIOUS TEMPERATURES

The effect of compaction by rolling at various temperatures has been studied for some time. An attempt was made to remove cores from the pavement as compacted at a range of different temperatures. This is difficult to do and, frankly, is not practical in the normal construction of a contract paving operation. One very important relationship was found, however, which could be taken advantage of relative to densities. When the pavement is compacted under ideal conditions (including quality and uniformity of the mix, uniform paving conditions, and ideal weather conditions, together with good equipment and operators) the density obtained approximately equals the density obtained by the Marshall method of compaction.

The Marshall method of compaction used was by means of a compaction hammer consisting of a flat circular face 3⅞ in. in diameter, equipped with a 10-lb weight, constructed to obtain a specified 18-in. height of drop. The molds used were the standard Marshall test molds having a 4-in. inside diameter.

The temperature of the prepared mixture was not less than 250F and sufficient mixture was added to the molds to give a compacted height of 2½ in. After the mixture was introduced into the molds, both the mold and the mixture in the mold were brought to to the desired compaction temperature. The specimens were then compacted to the specified 2½ in. by 50 blows on both top and bottom of the sample. Four samples were prepared for each compaction temperature.

With the exception that two from each set, in addition to other tests, were tested by the Hveem stabilometer and Hveem cohesiometer, and two from each set were tested for Marshall stability and flow, the following tests and determinations were made with each sample:

1. Specific gravity.
2. Density, in pounds per square yard per inch of thickness.
3. Percent voids.
4. Asphalt percent of volume.
5. Percent voids filled with asphalt.
6. Marshall stability.
7. Marshall flow.
8. Marshall stability ratio, or $\frac{\text{Marshall stability}}{\text{Marshall flow}}$.
9. Hveem stabilometer values.
10. Hveem cohesiometer values.

With the Marshall method, the stability of the test specimen is the maximum load resistance, in pounds, which the test specimen develops at 140F when tested with the Marshall apparatus. The flow value is the total movement or strain, in units of 1/100 in., occurring in the specimen between zero load and the maximum load resistance for the stability test.

The Hveem stabilometer test as used in this experiment utilized the same type of sample as the Marshall test. The stabilometer is a special triaxial-type testing cell and measures the resistance of the compacted mix to lateral displacement under vertical loading. The Hveem cohesiometer test measures the cohesive or tensile resistance of the compacted mixture. This test is also made at 140F.

All of the samples in this experiment, although compacted at various temperatures, were tested at the specified temperature of 140F.

Tests were made on both wearing course mixtures and binder course mixtures. These mixtures were in accordance with State of Maine specifications and the analysis of both the wearing course and binder mix was in accordance with the following formula:

Square Mesh Sieve	Percent Passing	
	Binder Course	Surface Course
¾ in.	100	
½ in.		100
No. 4	30.5	68.3
No. 10	24.5	44.4
No. 20	20.3	31.6
No. 40	15.1	23.0
No. 80	8.5	13.9
No. 200	3.1	4.7
Asphalt (% of mix)	5.1	6.3

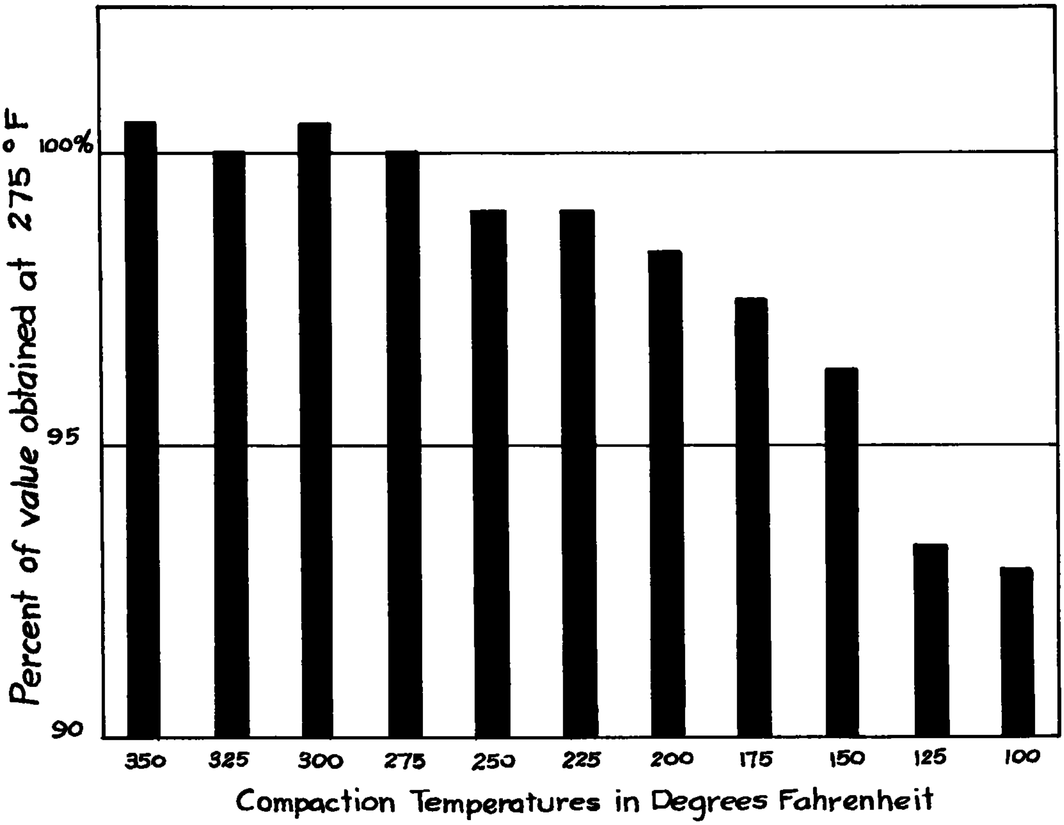


Figure 25. Effect of compaction (Marshall method) at various temperatures on specific gravity of bituminous concrete wearing course.

Several methods were studied for evaluating the data from this experiment and it was felt by the author that if it were assumed that ideal conditions would have been attained if the compaction was at 275F then all other values could be shown in terms of the percent obtained at 275F.

BITUMINOUS CONCRETE COMPACTION STUDY—WEARING COURSE

Specific Gravity

Figure 25 shows the relationship of specific gravity to the compaction temperature. This is based on 100 percent at a compaction temperature of 275F. It should be noted that although there is a reduction almost immediately, rapid loss starts at a temperature of 225F. This indicates that compaction should largely be accomplished before the temperature is below 225F and while the mix is still in a plastic state.

Density

Figure 26 shows the relationship of the density of the mixture in pounds per square yard per inch of thickness when compacted at various temperatures. This is a common method of expressing densities as used by construction men in the field.

Naturally, the same relationship holds true as for the specific gravity and the rapid change occurs after 225F.

Percent Voids

Figure 27 shows the relationship of percent voids to the compaction temperature

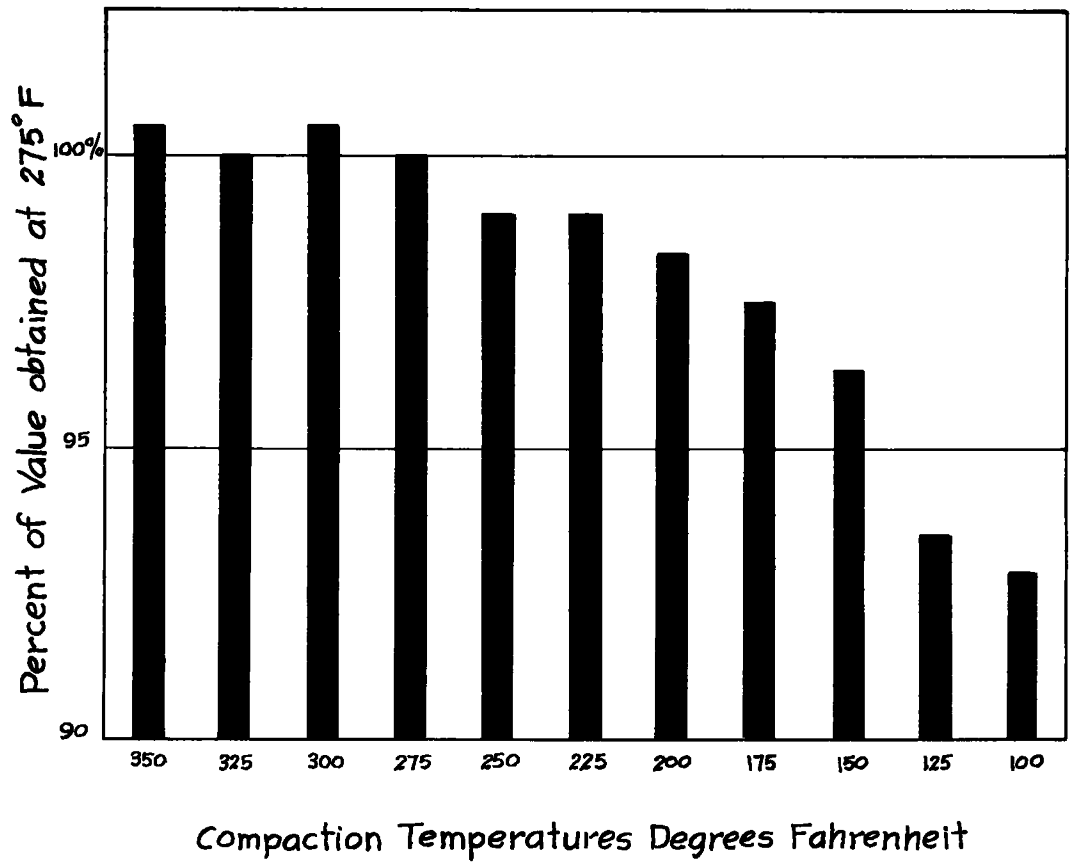


Figure 26. Effect of compaction (Marshall method) at various temperatures on density (pounds per square yard per 1-in. thickness) of bituminous concrete wearing course.

based on 100 percent at a compaction temperature of 275F. This is a striking example of what occurs when the mixture is rolled at too cold a temperature and largely accounts for the difficulties in fall paving in northern climates.

It is noted that there is only a slight reduction of voids at temperatures of 300 and 350F. However, at 200F the voids have doubled and at 150F they have increased four times, whereas at 125F the voids have increased over six times the value obtained at 275F. Certainly this indicates that maximum compaction should be attained at about 250F. This shows that the danger of cold weather construction lies in the ability to accomplish a maximum amount of compaction before the temperature of the mix has reached 225F.

Asphalt Percent by Volume

Figure 28 shows the relationship of asphalt percent of volume resulting from compaction at various temperatures. This is also related to the density and indicates that the critical temperatures are below 225F.

Voids Filled with Asphalt

Figure 29 is similar to Figure 28 for asphalt percent by volume. It is common among field engineers to become familiar with various terms although not directly associating these with other terms which may have the same meaning. For that reason all of the various characteristics are included.

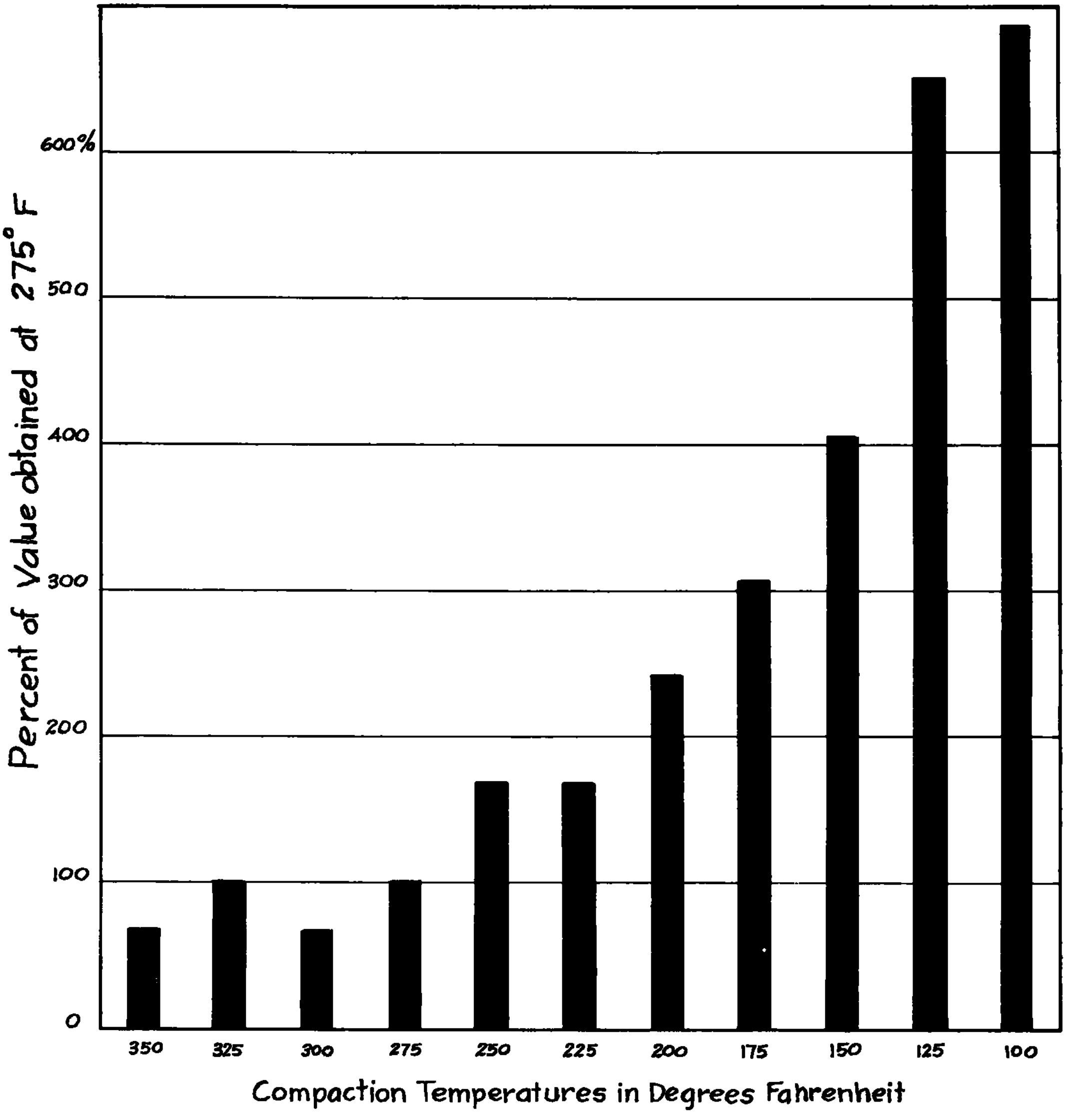


Figure 27. Effect of compaction (Marshall method) at various temperatures on percent voids of bituminous concrete wearing course.

Marshall Stability and Marshall Flow Values

Figure 30 shows the relationship of the stability value for mixtures compacted at various temperatures. These mixtures were all tested at the standard temperature of 140F. The results, as in other cases, are based on a 100 percent value with a compaction temperature of 275F. This indicates that the stability of the mixtures would be increased about 20 percent if the compaction was above 300F. This, in turn, would be related to the viscosity of the asphalt, which was an 85 to 100 penetration grade. The stability falls rapidly below 250F and indicates that maximum compaction should be attained above 250F. It should be noted that at 150F less than 20 percent of the value at 275F was obtained.

Figure 31 shows the relationship of Marshall flow values to the compaction temperature. Values again are expressed in terms of 100 percent at a compaction temperature of 275F. Note also the high flow value obtained at 275F, which is the 100 percent base value. The author is unable to explain the variable results obtained in this test, although the results are not as variable as they may appear when it is considered that the results mainly fall between 75 and 100 percent of the value obtained at 275F. This is further illustrated in Figure 32, which shows the variation of the ratio of Marshall stability for compaction at various temperatures.

Marshall Stability Ratio

Figure 32 shows the stability ratio variation when the mixture is compacted at various temperatures. This irons out to some extent the erratic flow values and indicates a rapid drop after 225F. The author's organization has made a practice of using this ratio for about two years and finds that these values generally tend to give more uniform values than either the stability or flow values.

Hveem Stabilometer

Figure 33 shows the ratio of the Hveem stabilometer values of mixtures compacted at various temperatures but tested at 140F in accordance with the standard Hveem test. This figure indicates that the compaction temperature is not as critical as with Marshall stability values. Increased stabilometer values were obtained at lower temperatures than 275F and the fast drop-off from the 100 percent value starts at about 175F.

Hveem Cohesiometer

Figure 34 shows the relationship of the Hveem cohesiometer values to the compaction temperature. As with the other tests, the compaction temperature was varied al-

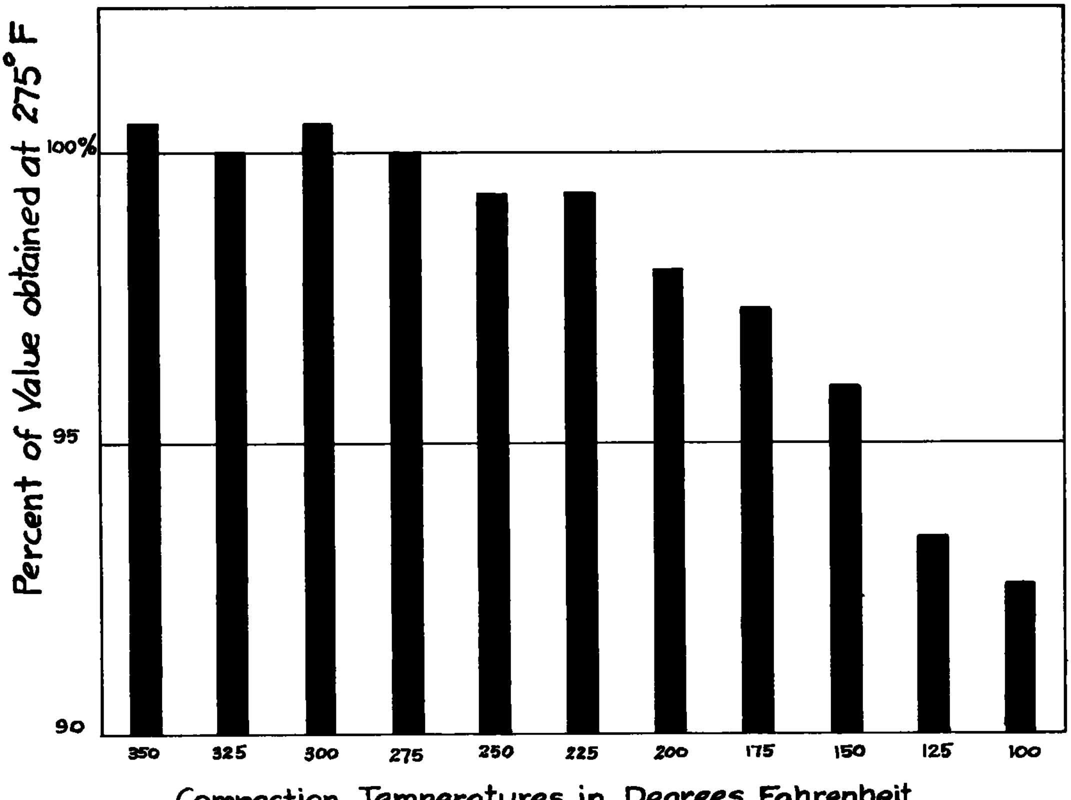


Figure 28. Effect of compaction (Marshall method) at various temperatures on asphalt by percent of volume of bituminous concrete wearing course.

though the test was performed at the standard temperature of 140F in accordance with the standard procedure for the test. As with the Hveem stabilometer values, the drop was not as critical as with the Marshall stability values and this chart indicates that the drop occurs between 150 and 175F.

After conducting this research and analyzing the results it is deemed that the best results can be obtained if the knock-down rolling is accomplished before the temperature of the mixture has dropped below 225F while the material is still in a very plastic state, and final rolling accomplished before the temperature has reached 175F. Rolling after the temperature is below 175F is of little benefit to the density and structural properties and assists mainly in surface sealing.

BITUMINOUS CONCRETE COMPACTION STUDY—BINDER COURSE

As a comparison, similar tests to those used on the wearing course were also tried with a binder mix. The mix is quite similar to a surface mix with ¾-in. maximum size instead of ½-in. as shown for the wearing course and a coarser gradation. All methods were similar to those described for the wearing course mixture.

Specific Gravity

The results of the specific gravity test (Fig. 35) were practically an overlay of the results obtained for the wearing course. That is, the specific gravity of the mixture compacted at 275F taken as 100 percent varies in the same proportion at various compaction temperatures as did the wearing course.

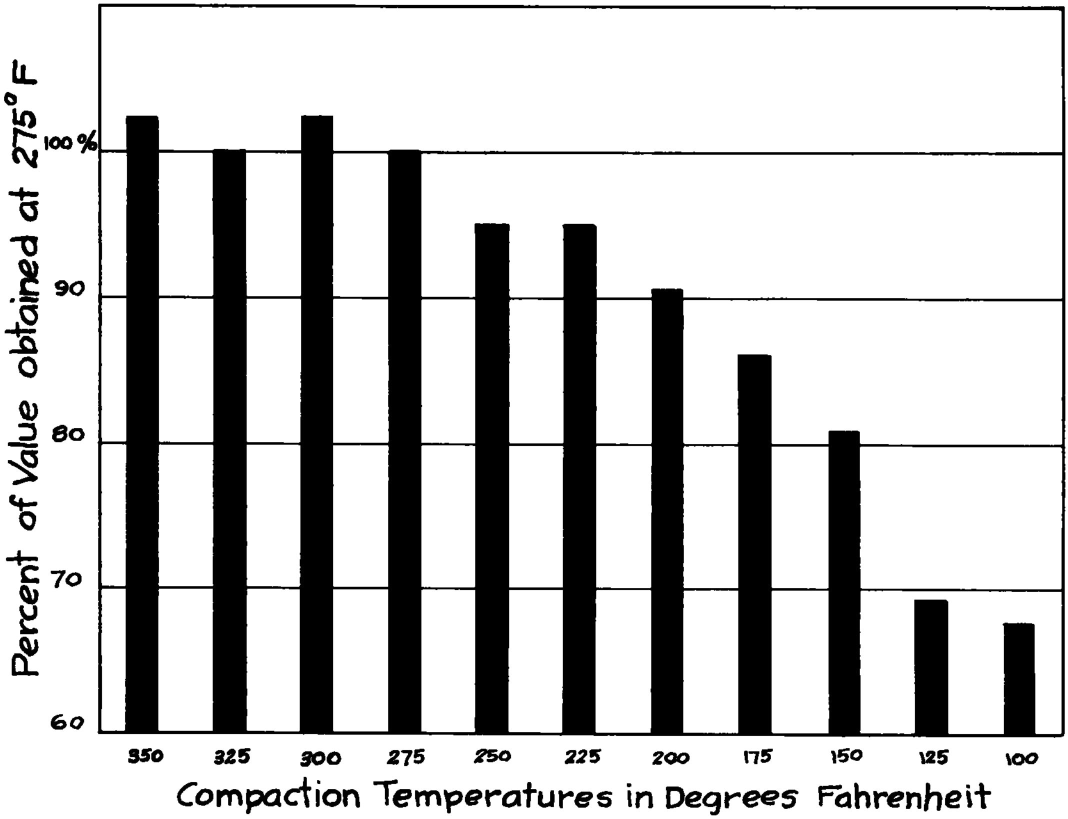


Figure 29. Effect of compaction (Marshall method) at various temperatures on voids filled of bituminous concrete wearing course.

Density

Figure 36 is merely another method of expressing the density or specific gravity and therefore is similar to Figure 35.

Percent of Voids

The results of the voids tests (Fig. 37) were similar to those obtained for the wearing course, showing a rapid increase as compaction temperature decreased.

Asphalt Percent by Volume

The results for the asphalt percentage test (Fig. 38) were also similar to the wearing course, showing that percentagewise the variation is similar when based on a 100 percent value at 275F.

Percent Voids Filled with Asphalt

As with the other related charts, the results (Fig. 39) obtained with the binder

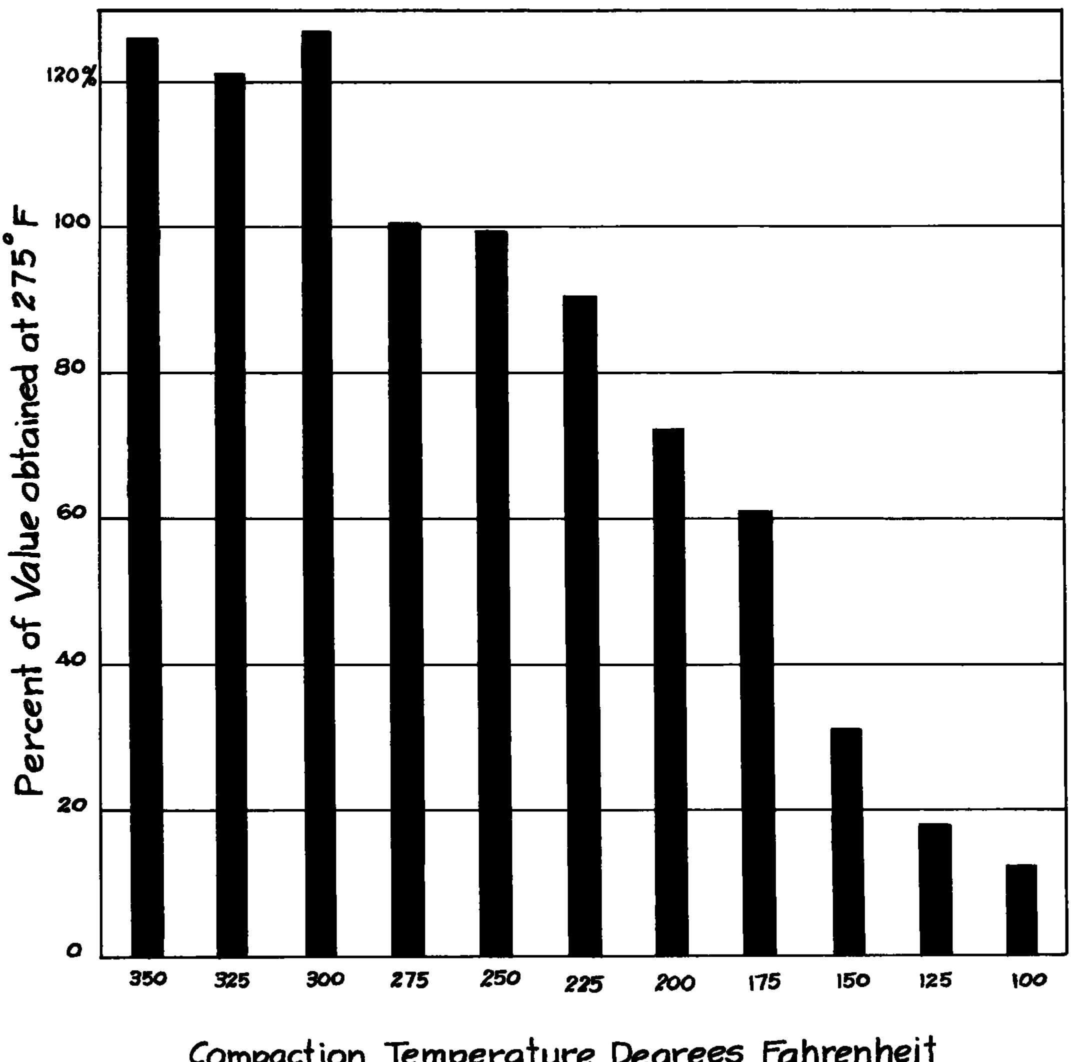


Figure 30. Effect of compaction (Marshall method) at various temperatures on Marshall stability of bituminous concrete wearing course.

course are nearly identical in their ratio of change from the 100 percent value at 275F.

Marshall Stability

This was where there was a noticeable change (Fig. 40) from the results with the fine wearing course mixture. There is nearly a straight line relationship from the compaction temperature of 350F to the compaction temperature of 100F (that is, the drop in stability is nearly directly proportional to the change of compaction temperature).

Marshall Flow Values

The flow values (Fig. 41) showed a great variation from results obtained with the wearing course mixture. Many increased over 100 percent. The values did show a more definite trend or a greater relationship to an increase in proportion to the decrease in compaction temperature.

Marshall Stability Ratio

Although the results obtained with the binder course (Fig. 42) resembled the results obtained with the wearing course mixture, there is a more direct relationship. In fact, the reduction in stability ratio is nearly directly proportional to the compaction tem-

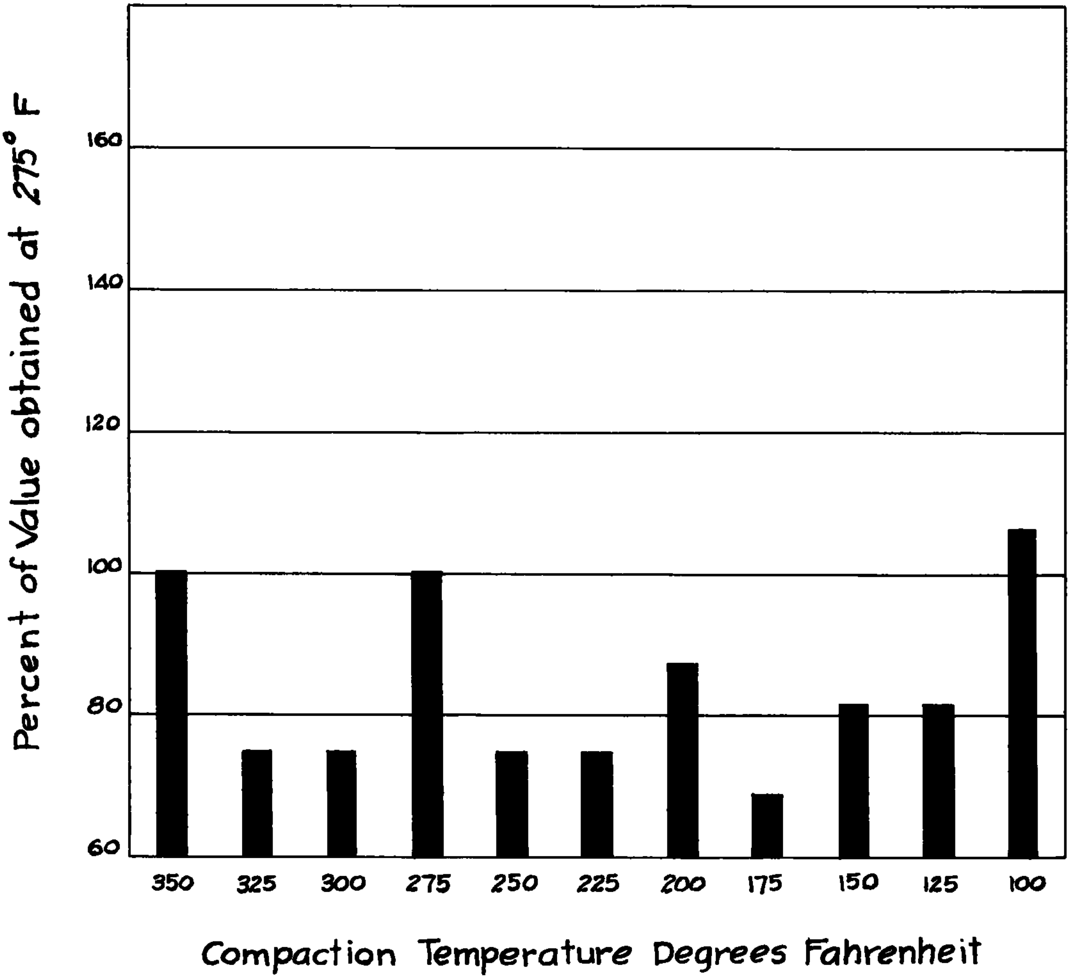


Figure 31. Effect of compaction (Marshall method) at various temperatures on Marshall flow of bituminous concrete wearing course.

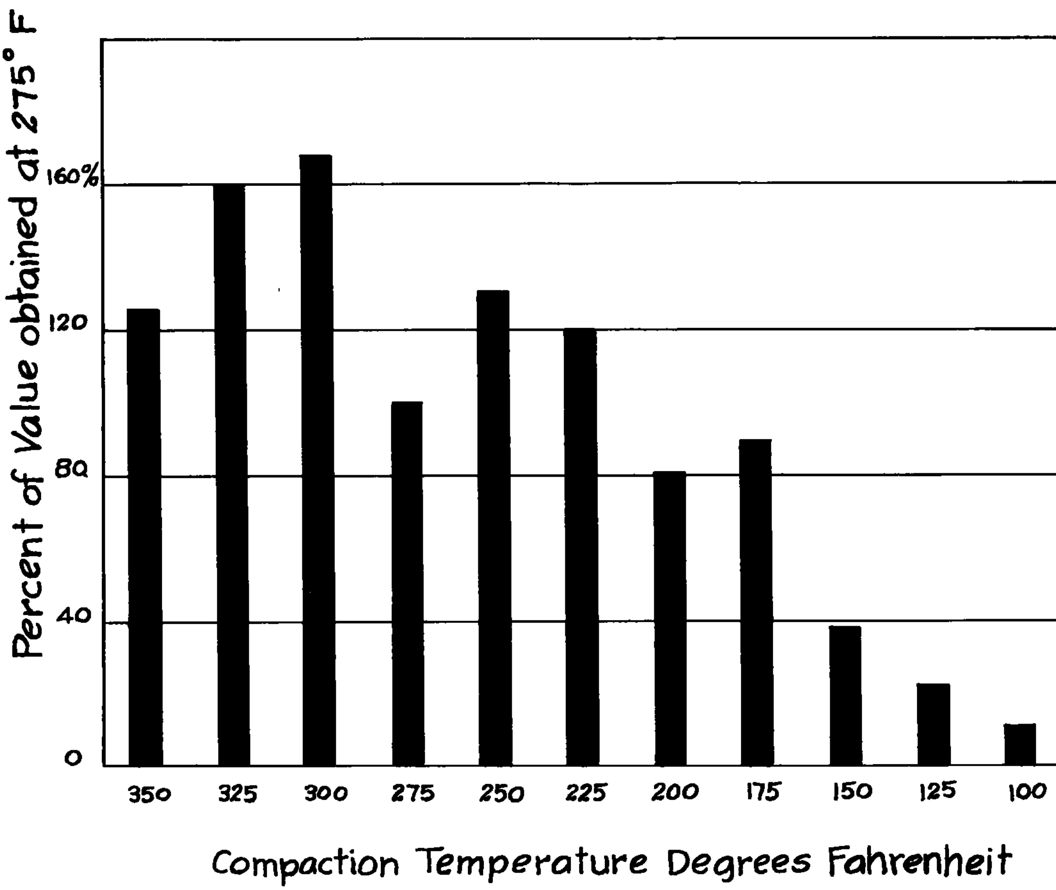


Figure 32. Effect of compaction (Marshall method) at various temperatures on stability ratio (Marshall stability/Marshall flow) of bituminous concrete wearing course.

perature change from 100F to 325F.

Hveem Stabilometer Values

A more direct value was obtained with the Hveem stabilometer (Fig. 43) for the binder or coarse mixture than for the wearing course or fine mixture. The highest value, in proportion to the result at 275F taken as 100 percent, was obtained at 350F; there was a straightline reduction in proportion to the decrease in compaction temperature, whereas this straightline relationship with the wearing course started at a compaction temperature of 250F, or a difference of 100F.

Hveem Cohesiometer Values

A more direct relationship was obtained with the cohesiometer for the binder course (Fig. 44) than with the wearing course. As with the Hveem cohesiometer, the highest value was obtained at a compaction temperature of 350F and there was a straightline drop with reduction in compaction temperatures. At 125F the value was about 50 percent of the value obtained at 275F.

From a study of the results of tests on both binder and surface mix, it is found that relatively the characteristics such as densities, voids, and asphalt characteristics, showed little difference between the wearing course mixture and the binder course mixture.

There was a marked difference in Marshall stability values and flow values, which was brought out more uniformly in the stability-flow ratio. There was more uniformity

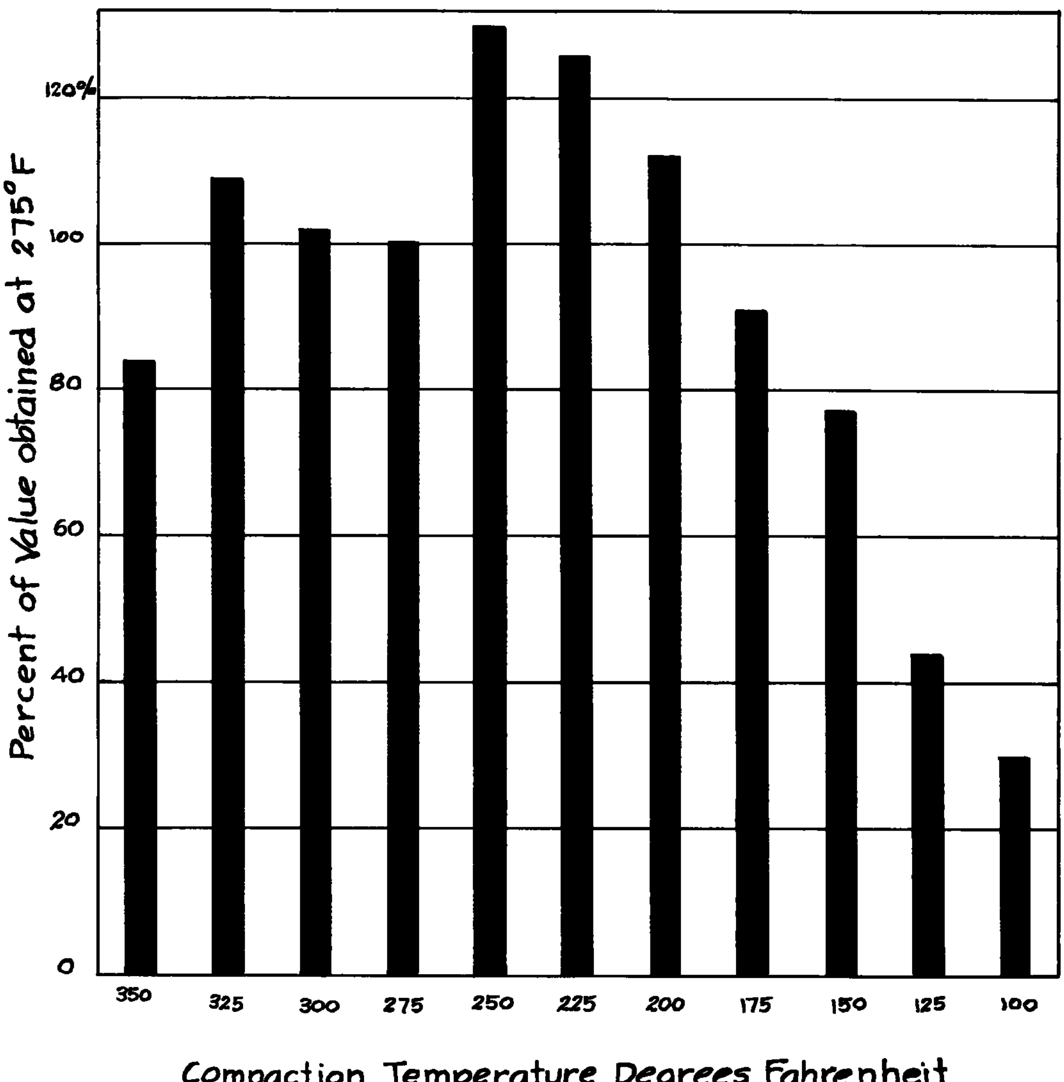


Figure 33. Effect of compaction (Marshall method) at various temperatures on Hveem stabilometer values of bituminous concrete wearing course.

in the results with the coarser or binder mix, although it was expected that more uniformity would be attained with the finer or wearing course mixture.

There was also a marked difference in the results obtained with the Hveem stabilometer and cohesiometer values. It was noticeable that the compaction temperature and stabilometer values, as well as cohesiometer values, varied differently with the with the binder mix than with the fine surface mixture. There was no appreciable increase in the Hveem stabilometer values above 275F for the wearing course, whereas with the binder course the highest value was obtained at the highest compaction temperature. There was an increase in value for the wearing course between 200F and 275F, whereas with the binder course there was a straightline decrease from the highest compaction temperature to the lowest compaction temperature. This same relationship held true for the Hveem cohesiometer values. These changes are believed to have been caused by the high percentage of a larger size aggregate in the binder mix than in the fine wearing course mixture.

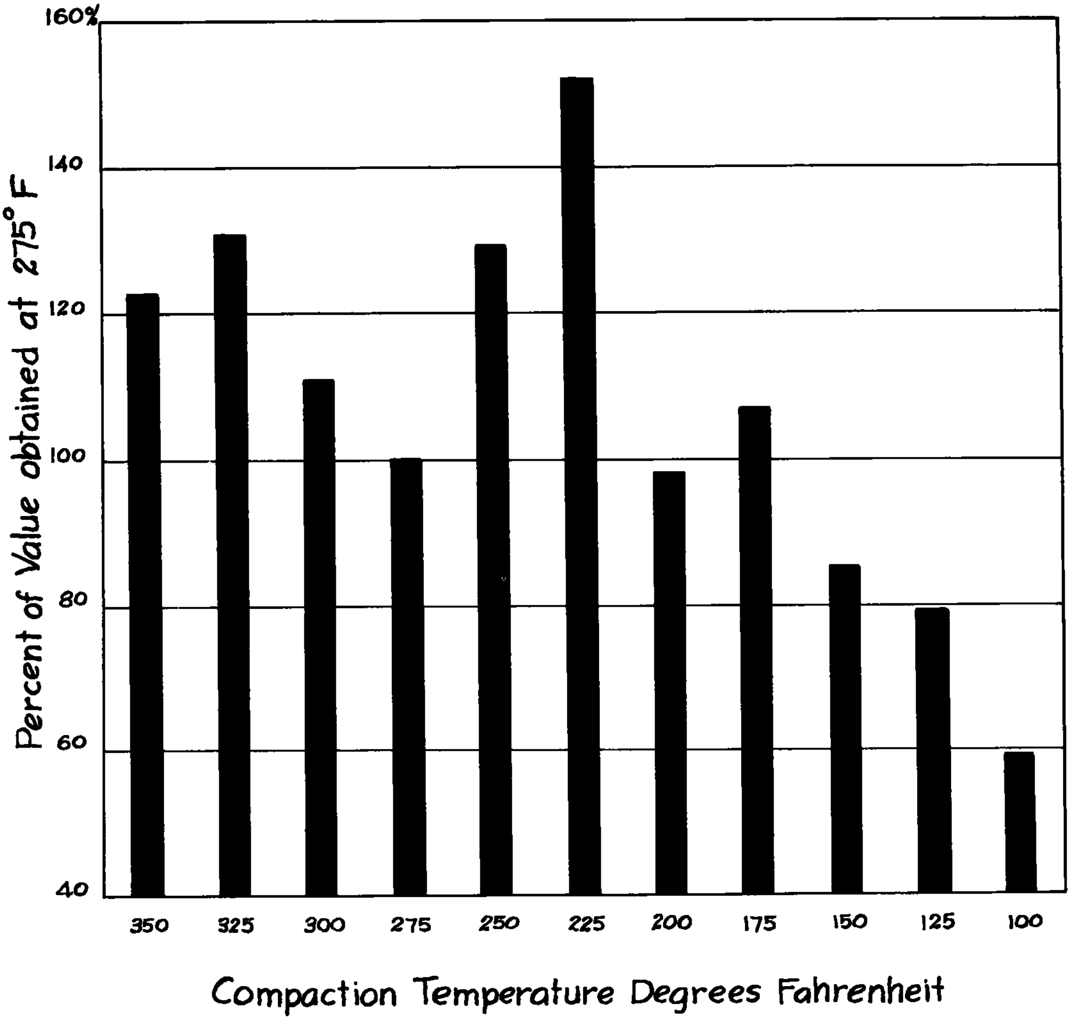


Figure 34. Effect of compaction (Marshall method) at various temperatures on Hveem cohesiometer values of bituminous concrete wearing course.

MATHEMATICS OF ROLLING

Nijboer (9) gives a complete analysis of the mathematics of rolling. He states that the compaction process can be described by:

$$\frac{\frac{P}{lD} C\, r_{cb}}{n_m}\; n\left(\frac{h}{v}\right)^{0.4} = R_f = \begin{matrix} 20 \times 10^{-5} \text{ (kg cm sec) or} \\ 284 \times 10^{-5} \text{ (lb in. sec)} \end{matrix} \qquad (1)$$

in which

P = weight of roller, in kg or lb;
l = length of roller, in cm or in.;
D = diameter of roller, in cm or in.;
n = number of passages;
v = speed of roller, in cm per sec or in. per sec;
h = thickness of carpet, in cm or in.;
C = a constant = 2.5;

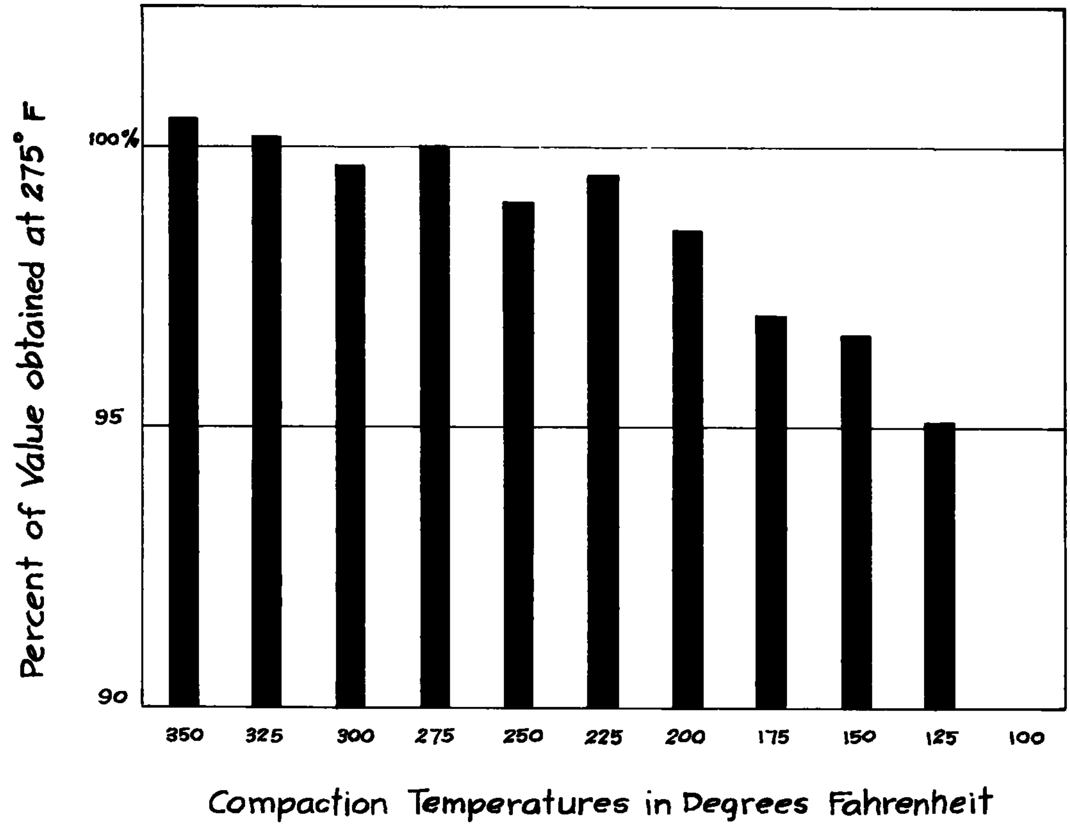


Figure 35. Effect of compaction (Marshall method) at various temperatures on specific gravity of bituminous concrete binder course.

r_{cb} = compound bituminous initial resistance, in kg per sq cm or lb per sq in.;
n_m = viscosity of the mass in poises;
R_f = rolling factor (in kg-cm-sec system = 20 x 10^{-5}, in lb-in.-sec system = 284 x 10^{-5}).

He also gives an example of rolling a sandsheet mixture with an 8-ton roller. From his computations he concludes: "To obtain anything like an acceptable compaction at the limited number of passages of the roller it is clear that a temperature of about 80C (176F), as accounted for in the foregoing, forms the lowest temperature at which rolling is effective. This temperature, however, will hold only for the mixtures and the rollers under consideration, but will be lower when a less stable mixture or a heavier roller is chosen." He goes on to say: "For normal hot-mix work the cooling off of the mixture will take place by a straight line in a log temperature difference-time diagram. So,

$$\frac{T_b - T_o}{T_f - T_o} = \text{time available for rolling"} \qquad (2)$$

Nijboer's formula takes into account the viscosity of the material, which is controlled largely by the mixing temperature (which in turn varies with different grades of asphalt) and the cooling of the mixture during transport from the plant to the project (which follows a law similar to the law that holds for cooling of the mixture after spreading). Relative to the mixing temperature and rolling temperatures Nijboer (9) gave an example of Venezuelan and Mexican bitumen of 50/60 penetration lying some-where in the neighborhood of 160C (320F), whereas for a similar California bitumen 130C (266F) gives the same viscosity.

Attempts have been made to analyze this problem in a practical manner in the field for many years. This has been described in detail in the section dealing with bituminous mixtures. It is interesting to note that this method of comparison by laboratory compaction at various temperatures closely approaches the mathematical analysis of Nijboer.

Drawbar Pull

That the drawbar pull is related to the roll diameter is a well-established fact. Nevertheless, considerable research should be done along this line: The only information of such experiments was one performed by the Buffalo-Springfield Roller Co. on its proving grounds at Springfield, Ohio.

In this experiment a 46-in. diameter roll weighing 3,280 lb was used in conjunction with a hydraulic dynamometer to determine the following coefficients for various materials:

Material	Coeff.
Bituminous concrete (compacted)	0.27
Oiled clay (compacted)	0.46
Sandy clay, loose surface	0.30
Untreated macadam	0.27

Using these coefficients the drawbar pull was computed theoretically for 53-, 60-,

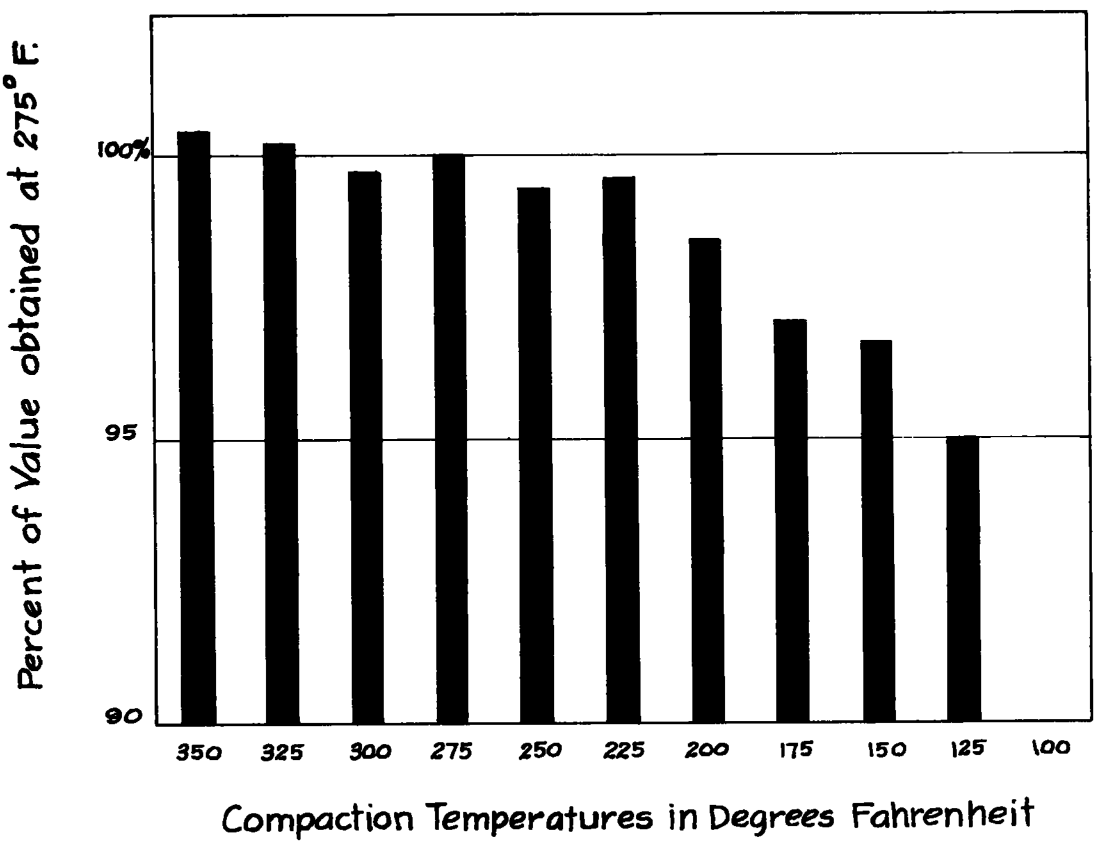


Figure 36. Effect of compaction (Marshall method) at various temperatures on pounds per square yard per 1-in. thickness of bituminous concrete binder course.

and 72-in. diameters. A mathematical analysis of computing the drawbar pull is as follows:

The coefficient of rolling friction is

$$f_r = P/W \qquad (3)$$

in which W is the load and P is the frictional resistance (10).

From Figures 45 and 46,

$$P = \frac{WG}{R - H} \qquad (4)$$

Combining Eqs. 3 and 4 gives

$$f_r = \frac{G}{R - H} \qquad (5)$$

But

$$\tan \theta - \frac{G}{R - H} \qquad (6)$$

and

$$\tan \theta' = \frac{P}{W} \qquad (7)$$

Therefore,

$$\tan \theta = \tan \theta' \qquad (8a)$$

$$\theta = \theta' \qquad (8b)$$

Angle θ subtends the arc of rolling contact, S, and a graphical solution for the value of S can be made using the coefficient of rolling friction and a certain roll diameter.

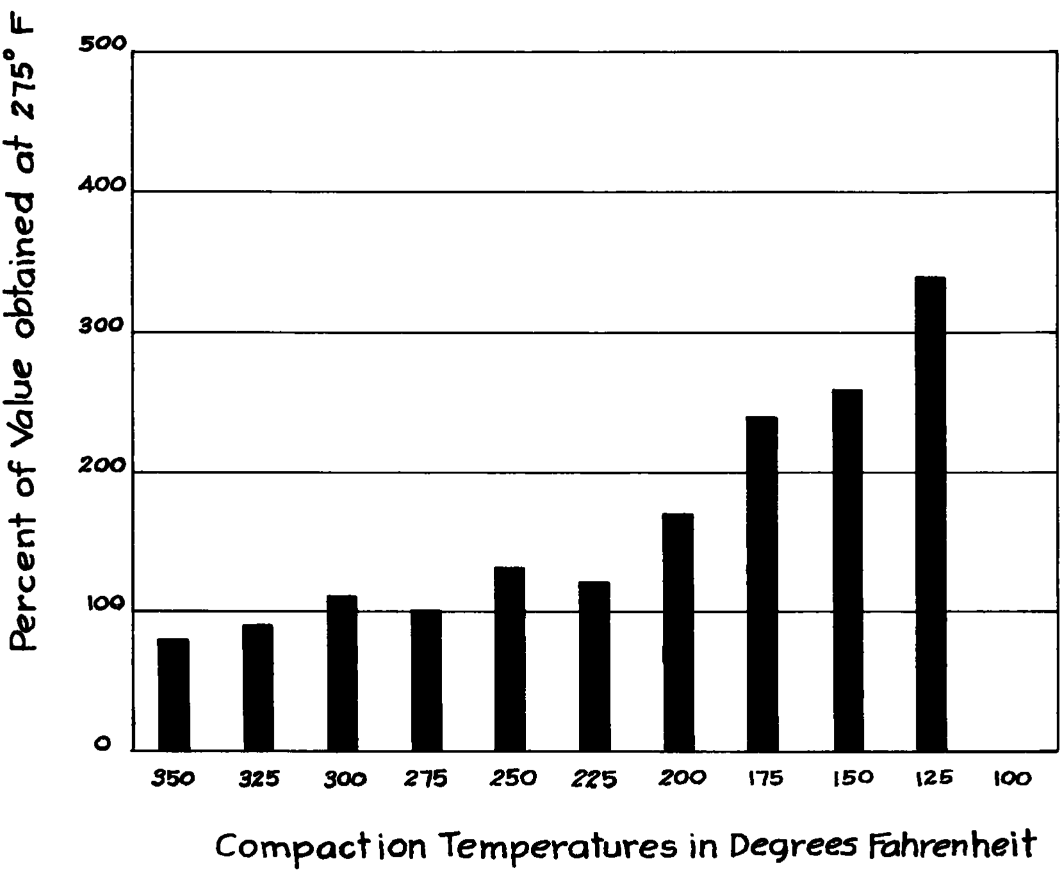


Figure 37. Effect of compaction (Marshall method) at various temperatures on percent voids of bituminous concrete binder course.

By geometry,

$$H = G \tan \theta/2 \quad (9)$$

or

$$H = G \frac{\sin \theta}{(1+\cos \theta)} \quad (10)$$

Combining Eqs. 3 and 10,

$$f_r = \frac{G}{R-G \frac{(\sin \theta)}{(1 \cos \theta)}} \quad (11a)$$

or

$$G = \frac{f_r R}{1+f_r \frac{(\sin \theta)}{(1 \cos \theta)}} \quad (11b)$$

Arc length S can be found by

$$S = \frac{\pi R \theta}{180 \text{ deg}} \quad (12)$$

The results of the previously mentioned Buffalo-Springfield experiment are as follows:

Coeff.	Drawbar Pull (lb)[a]			
	Actual Test	Theoretical		
	46-In. Dia.	53-In. Dia.	60-In. Dia.	72-In. Dia.
0.27	890	764	683	560
0.30	985	846	745	620
0.46	1,570	1,290	1,130	945

[a] See Figure 47 for graphical comparison.

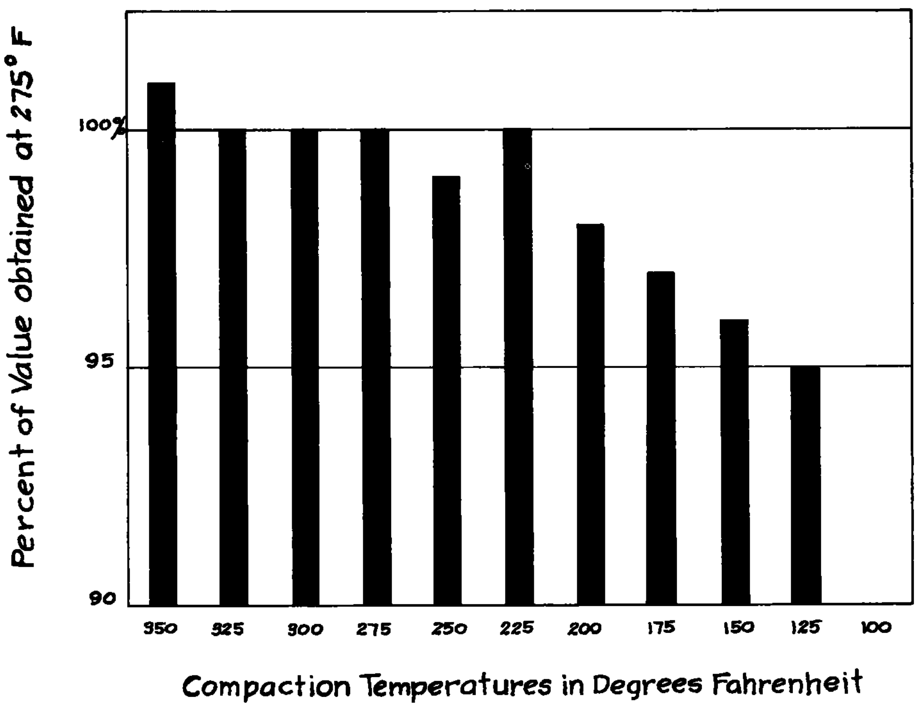


Figure 38. Effect of compaction (Marshall method) at various temperatures on asphalt by percent of volume of bituminous concrete binder course.

Capacity of Rollers

The item of roller capacity in square yards per hour is subject to great variation, depending on many things such as mixture, type of equipment, operators, and other factors.

The comparison made here is mainly relative and does not necessarily reflect any particular practice. It is included to show how the rate varies with the lap of the rolling pattern and the diameter of the rolls. The following conditions were analyzed:

Case 1

Length 300 ft, stagger 50 ft, lap 6 in.

Case 2

Length 300 ft, stagger 50 ft, lap ⅓ of roll width.

Case 3

Length 300 ft, stagger 50 ft, lap ½ of roll width.

In all three cases roll widths of 60 and 54 in. were used. The capacity for two complete coverages, using a roller speed of 2½ mph, is as follows:

Roll Width (in.)	Capacity (sq yd/hr)		
	6-In. Lap	⅓W Lap	½ W Lap
60	3,373	2,619	2,063
54	2,994	2,357	1,833

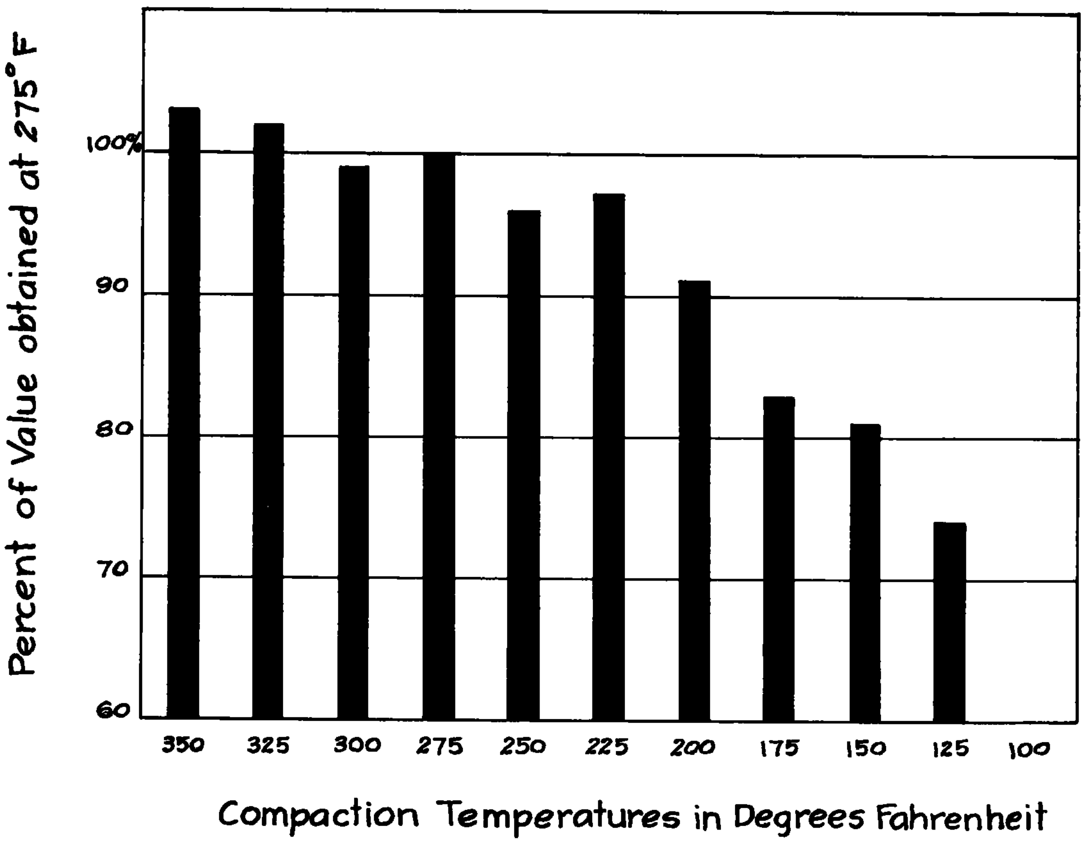


Figure 39. Effect of compaction (Marshall method) at various temperatures on voids filled of bituminous concrete binder course.

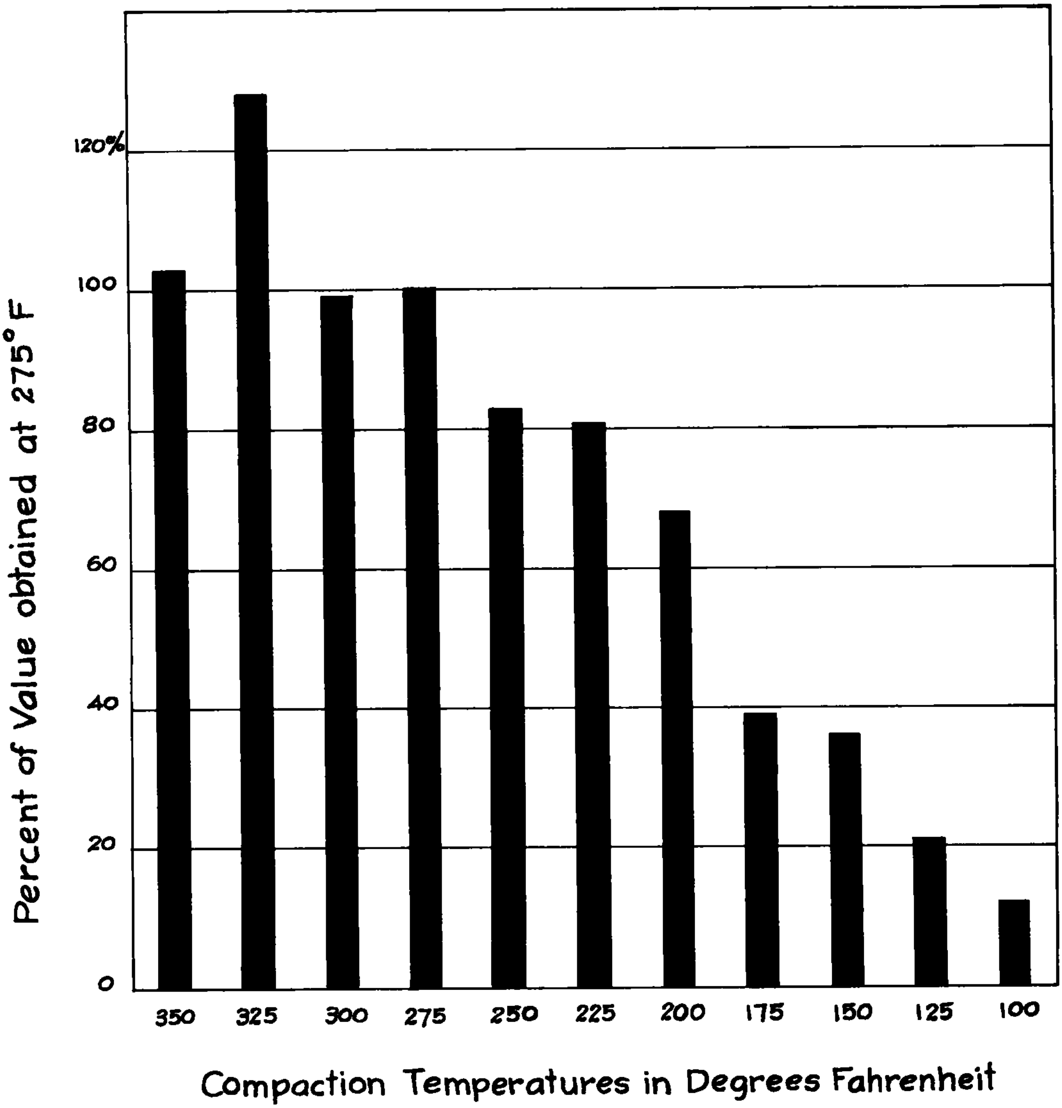


Figure 40. Effect of compaction (Marshall method) at various temperatures on Marshall stability of bituminous concrete binder course.

Taking the maximum number of square yards per hour (3, 373), obtained with a 60-in. width and 6-in. lap, as 100 percent and plotting all other values in percent of the maximum, gives Figure 48.

Figure 48 should be of special interest to contractors, as there is a possibility of 100 percent increase in roller capacity. Generally, roller operators arrive at the amount of lap by making it sufficient to prevent displacement. If the roll were of sufficient diameter, it is conceivable that a 6-in. lap would be sufficient. This would be more than double the angle of repose of the material. Many operators questioned by the the author state that the normal lap used is from 1/3 to 1/2 the width of the roll. Reference to the values determined in the three cases previously analyzed will show where the 100 percent increase in capacity with a roller designed for such conditions can be achieved.

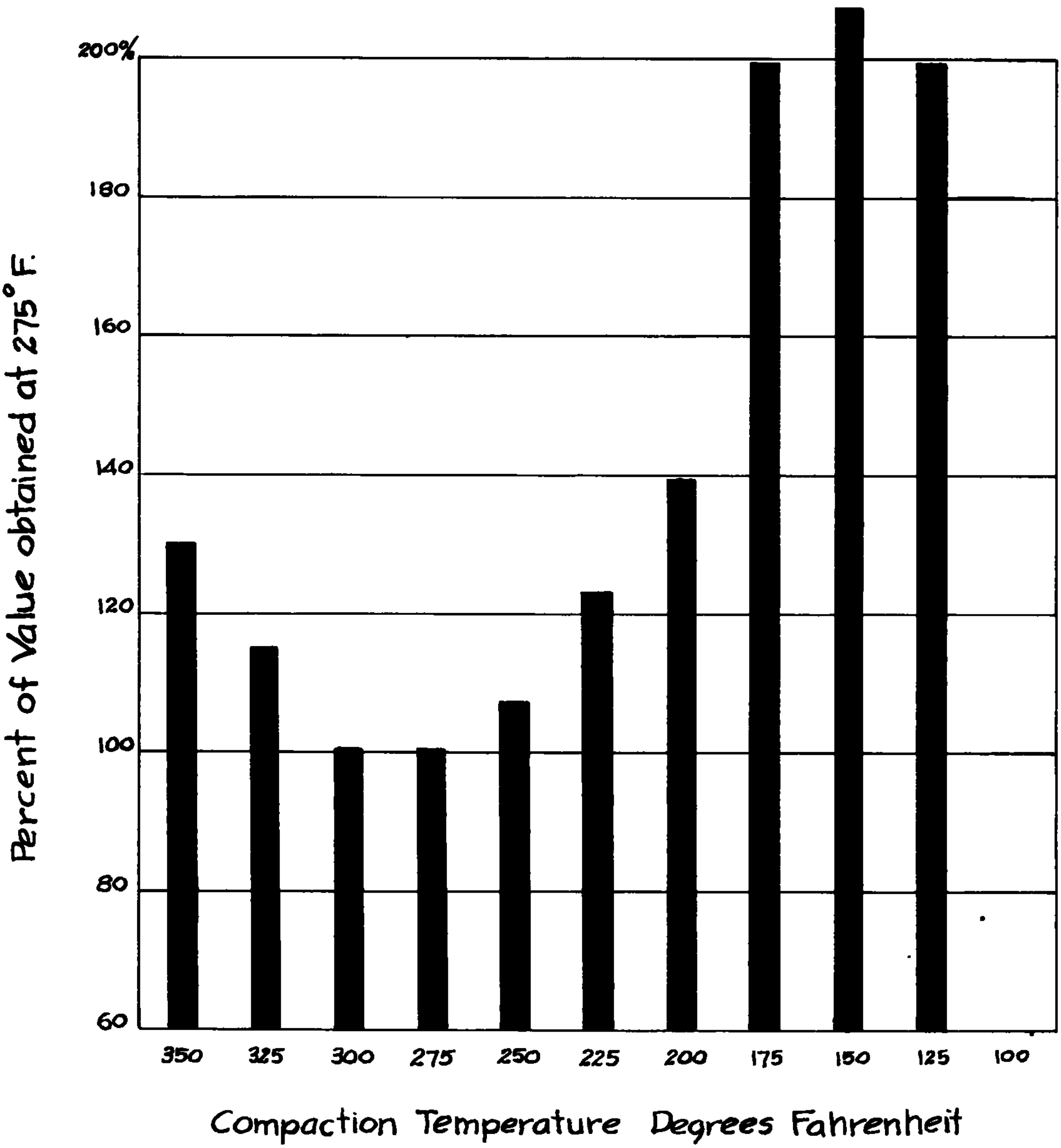


Figure 41. Effect of compaction (Marshall method) at various temperatures on Marshall flow of bituminous concrete binder course.

SUMMARY

1. Sales records from the Bureau of the Census indicate that the sale of steel-tired rollers has remained quite constant over a period of 10 years and that the majority of rollers currently in use in the United States are steel-tired.

The most obvious difference between the performance of tandem and three-wheel rollers is that the tandem was designed as a special purpose roller with considerably less unit compression than the three-wheel unit, due to the wider rolls. The tandem roller is not adapted to the use of scarifiers, and unlike a three-wheel roller cannot roll right up to obstructions on both sides.

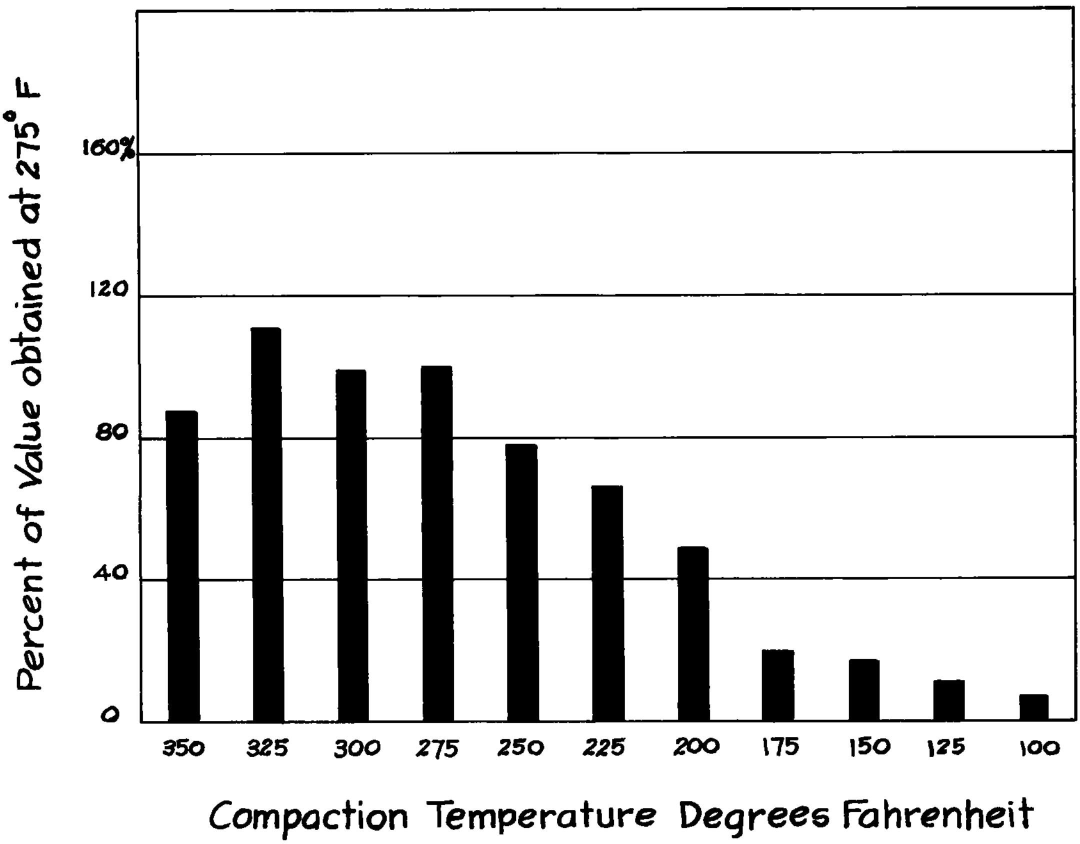


Figure 42. Effect of compaction (Marshall method) at various temperatures on stability ratio (Marshall stability/Marshall flow) of bituminous concrete binder course.

Due to these differences, between 1930 and 1945 few tandem rollers were made. At present, sales of tandem rollers exceed those of three-wheel rollers and the former is becoming more of an all-purpose type, being used not only on bituminous concrete or hot-mix types but also on macadam-type base and surface courses. Improvements in design may lead to further use as an all-purpose roller.

2. Steel-tired rollers are commonly used for earth compaction. The Road Research Laboratory in England has done a great amount of experimental work with various types of rollers on earth compaction.

These investigations were conducted on a covered circular track in which careful control could be maintained over the moisture content of the soils during the process of compaction. Most of the tests were made on 9-in. layers of loose soil, which compacted to a thickness of about 6 in. Some tests were made on thicker layers of soil.

It was found that the two steel-tired rollers were more efficient than the other rollers on the sand and gravel-sand-clay. The pneumatic-tired roller loaded to 12 tons and having a 36-psi tire pressure was less effective than the smooth-wheel rollers on the granular soil. For a complete analysis of these studies, reference should be made to Road Research Technical Papers Nos. 17 (11) and 33 (12).

3. Roller patterns. It was found that skilled roller operators prefer a definite pattern. They all agreed that the stops should be at staggered intervals, but disagreed on the amount of lap. In all cases the lap was decreased when using a three wheel tricycle-type roller with large diameter rolls. Definite rolling patterns should be established and the lap can be a minimum of twice the angle of repose of the material for

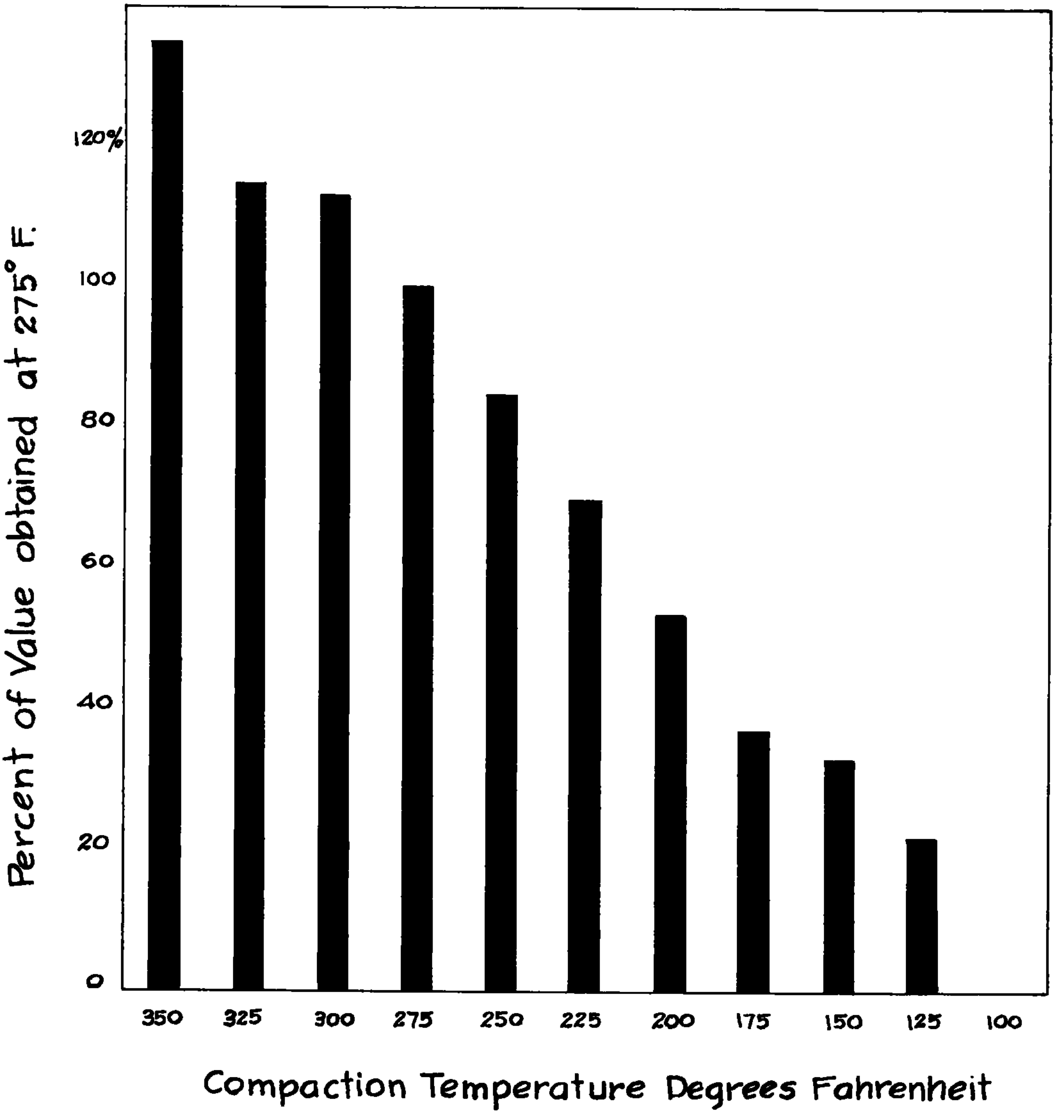


Figure 43. Effect of compaction (Marshall method) at various temperatures on Hveem stabilometer values of bituminous concrete binder course.

the thickness being rolled, provided the roll diameter is sufficient to prevent displacement. Methods of establishing rolling pattern are discussed in detail in the section on "Rolling Procedure."

4. Crushed stone macadam-type pavements also are discussed in detail. "Green rolling" is described and advocated. The importance of maximum size of aggregate and uniformity of gradation in order to roll a dense base course is described. Especially emphasized is the importance of roller diameter and compression in pounds per linear inch of roller.

5. Rolling of bituminous concrete mixtures has been discussed, especially as regards the importance of rolling at specified high temperatures. A practical test conducted in the laboratory, but simulating field conditions, indicates that the knockdown rolling should be completed before the temperature of the mixture has reached 225F and final rolling with the mix temperature not lower than 175F.

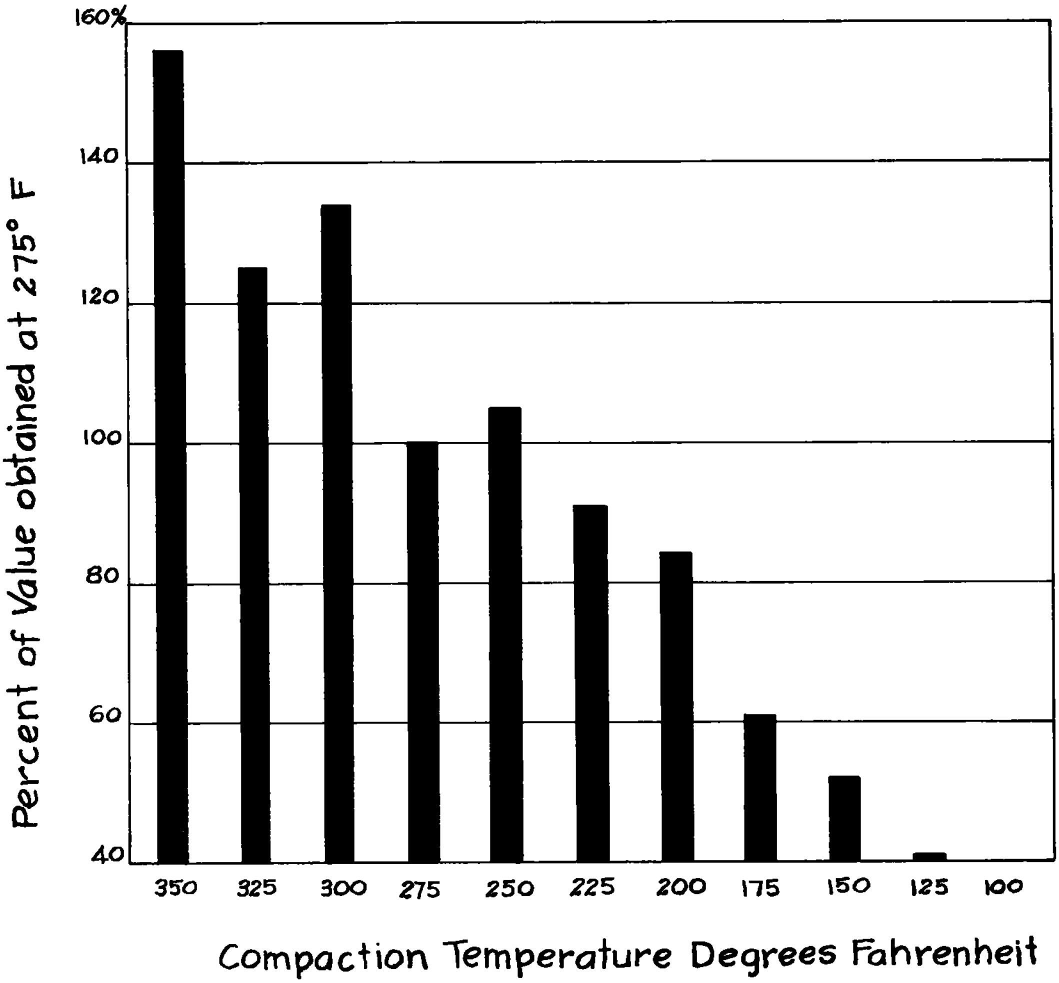


Figure 44. Effect of compaction (Marshall method) at various temperatures on Hveem cohesiometer values of bituminous concrete binder course.

6. Mathematical Analysis. Of special interest in the detailed mathematical analysis is the drawbar pull in relation to the diameter of the roll, including an actual experiment by Buffalo-Springfield. Of interest also is the economic study of rolling with various width rolls and patterns.

7. Ideal Roller. Figures 49 and 50 show an artist's conception of a tandem roller and a three-axle tandem roller as described by the author to artist George J. Elliott, Jr.

Roll diameters should be increased on tandem rollers. Naturally, increasing the diameter of the rolls would increase the size of the roller, which in turn would increase the weight. This could be compensated for to some extent by making the rolls wider, within limitations. Experience has shown that a width of 59 in. proved satisfactory; probably a maximum of 60 in. would be equally as satisfactory. As to the compressive force, a minimum of 250 lb per lin in. would not be excessive and often it may be desired to increase this to more than 350 lb per lin in. This increase could be accomplished by the addition of ballast weights.

Use of water ballast is not considered the most satisfactory type of ballast, as such ballast interferes with the operation of the roller and the amount used is seldom controlled. Frequent damage is done by the use of water ballast, especially during cold weather.

Preference is given to ballast weights that may be inserted inside the rolls at designed locations to give a better balanced operating condition and a known compressive force. Such weights may be arranged to distribute the load on the roller in any desired manner. Aveling and Barford have a patented method (Fig. 51) in the form of a sliding weight that can be adjusted by a simple manual operation to distribute the compressive force in the desired manner.

Normally the weight distribution is such that not more than 70 percent of the total gross weight is carried on the rear axle for three-wheel rollers and not over 68 percent for tandem rollers.

With larger diameters there is an added advantage in rolling bituminous concrete. The larger diameter rolls permit rolling at much higher temperatures than with the

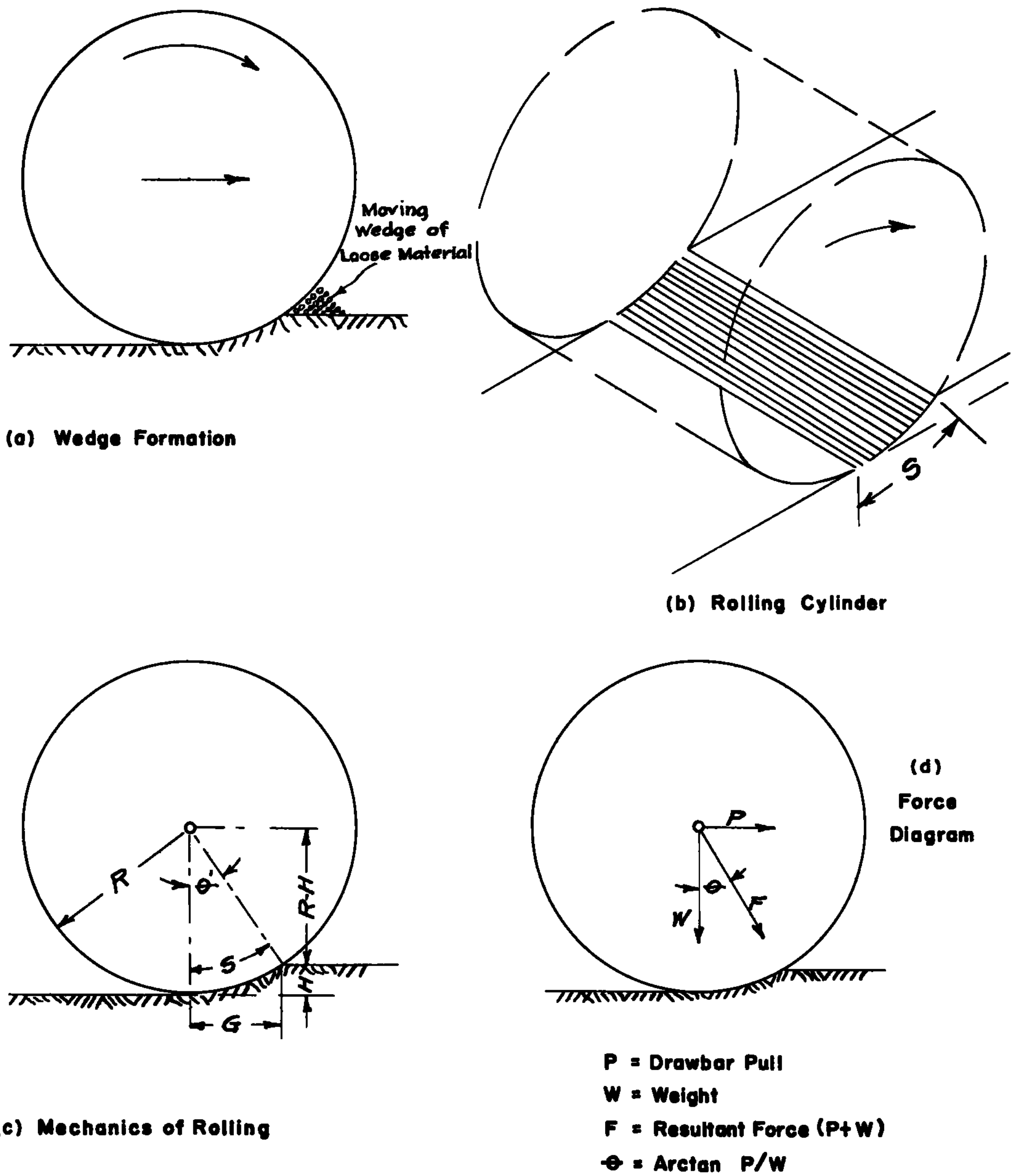


Figure 45. Geometry of rolling, generalized form.

small diameter rolls. This gives added density to the pavement and decreases the cost of rolling. Added width devreases the number of passes per coverage, which is advantageous both structurally and economically. Due to the decrease in horizontal displacement of the mixture there is a reduction in the amount of lap necessary, which in turn decreases the number of passes per coverage.

There also appears to be another advantage in the type of metal used in the tires. Wheel spin occurs much more with cast iron than with steel. Wheel spin also takes place much more quickly with small diameter rolls. By roll spin these rolls can often be ruined, especially for bituminous concrete construction: pits and grooves often result from much spinning. There should be some compromise with the increase in diameter and the use of a harder and longer wearing metal in the steel tires.

Figures 49 and 50 show the operator up front, which gives him a better view of the operations. The increase in roll diameter also gives greater clearance height.

8. The three-wheel tricycle-type roller continues to have many advantages. It is more an all-purpose roller and can be equipped with spikes, scarifiers and attachments that are not adaptable to a tandem roller. In addition, great variations as well as high compressive forces can be obtained with this type of roller. A recent innovation (Fig. 52) patented by Aveling and Barford is a small roll attached to the scarifier for rolling trenches. It is reported that a compressive force about three times as great as the normal rolling can be obtained with this attachment.

CONCLUSIONS

1. Roller patterns should be included in specifications for various types of base and pavement construction. Various patterns should be submitted for approval based on the type and size roller to be used.

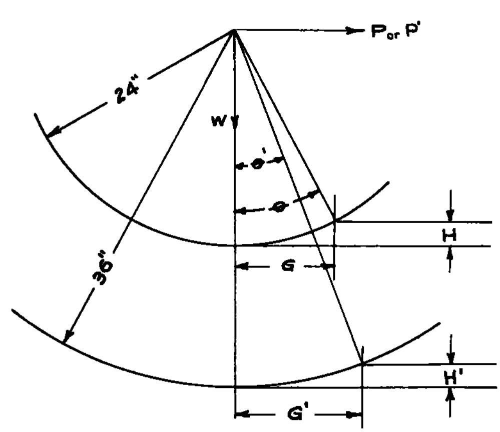
2. Rolling temperatures should be specified for bituminous concrete. The temperature of the mixture is controlled by many factors, including mixing temperature, length of haul, ground temperature, and atmospheric temperature.

3. Consideration should be given to the use of rollers with larger roll diameters and increased widths. The tandem roller was originally designed as a special-purpose roller for sheet asphalt. Although the tandem is not adapted for use with a scarifier, it is becoming increasingly popular for a general-purpose roller, not only on bituminous concrete hot-mix types but also for macadam base and surface courses. Improvements in design, such as are outlined in this paper, may make the tandem roller even more an all-purpose roller.

4. Research should be conducted on the effect of drawbar pull as related to the design of steel-tired rollers.

5. Ballasting should be accomplished by the addition of balance ballast weights inserted inside the rolls. This method would not interfere with the operation of the roller and would provide a method of obtaining the desired weight distribution by a calculated distribution of ballast weights.

6. It is known that the early horse-drawn rollers were mostly cast-iron rolls, although some lighter weight rollers were made from steel plate. The swing to fab-



P = Drawbar pull
W = Weight
u = Coef. of rolling friction = tan θ
R = Radius

$$P = uW = \frac{W \cdot G}{R - H}$$

Assume:
H = 3", H' = 3",
G = 12, G' = 13,
W = 1000 lb

$$24"RP = \frac{1000 \times 12}{24-3} = \frac{12000}{21}$$

$$36"RP = \frac{1000 \times 13}{36-3} = \frac{13000}{33}$$

P = 571 lb
P' = 394 lb

Figure 46. Geometry of rolling for specific roller radii of 24 and 36 inches.

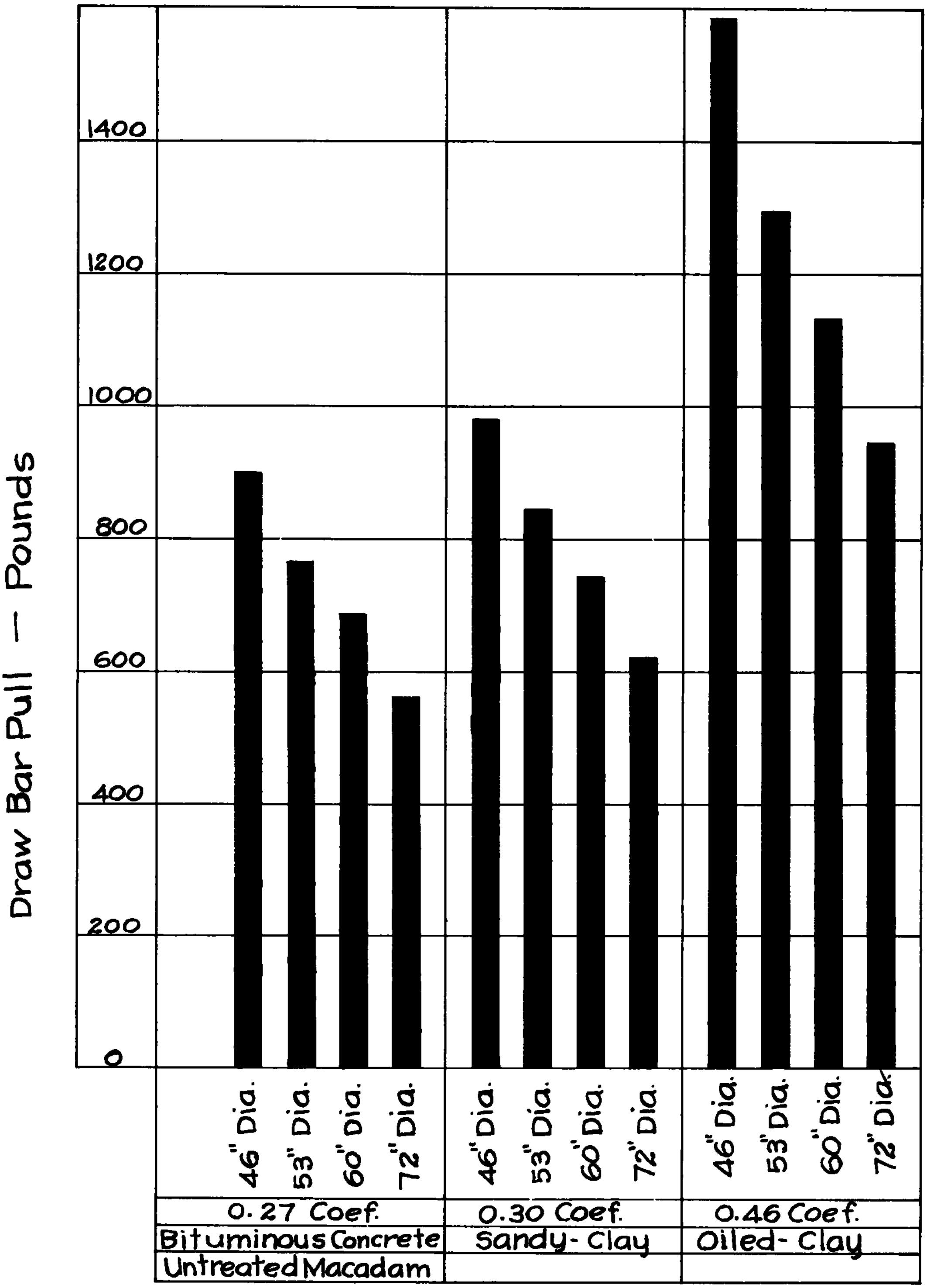


Figure 47. Comparison of drawbar pull for various diameters and conditions.

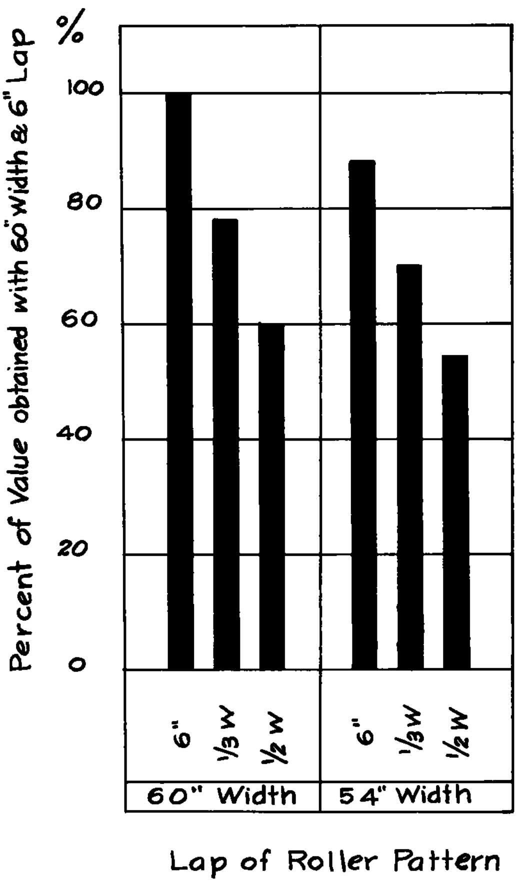


Figure 48. Comparison of coverage (sq yd per hr) with 60- and 54-in. roll widths for various laps (two coverages).

ricated steel rolls began between 1920 and 1930. Steel tires are now used almost exclusively, although at least one manufacturer continues to use cast-iron tires.

7. There are many refinements, such as power steering, torque converter, modern diesel engines, and other mechanical features that are well known today and are not discussed in this paper.

ACKNOWLEDGMENTS

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Aveling and Barford, Grantham, England, through their agent, W. T. Branson, have been most helpful, especially concerning the history of the steel-tired roller. Many of the pictures used are from "The Origin and Development of Aveling-Barford, Ltd." (3), or from other pictures furnished by that company. Mr. Branson has been especially helpful in his lengthy correspondence analyzing many of the author's ideas.

Buffalo-Springfield Roller Co. has been especially helpful, not only concerning the history of steel-tired rollers, but also as regards giving freely of their own experimental data, much of which are given herein. They have loaned the author many out-of-print historical documents giving information that would have been otherwise impossible to obtain.

Austin-Western and Galion contributed greatly in providing historical data, as well as technical information. Several other manufacturers have also been helpful and have cooperated fully in discussing steel-tired rollers.

Of basic help has been on-the-spot conferences with skilled roller operators.

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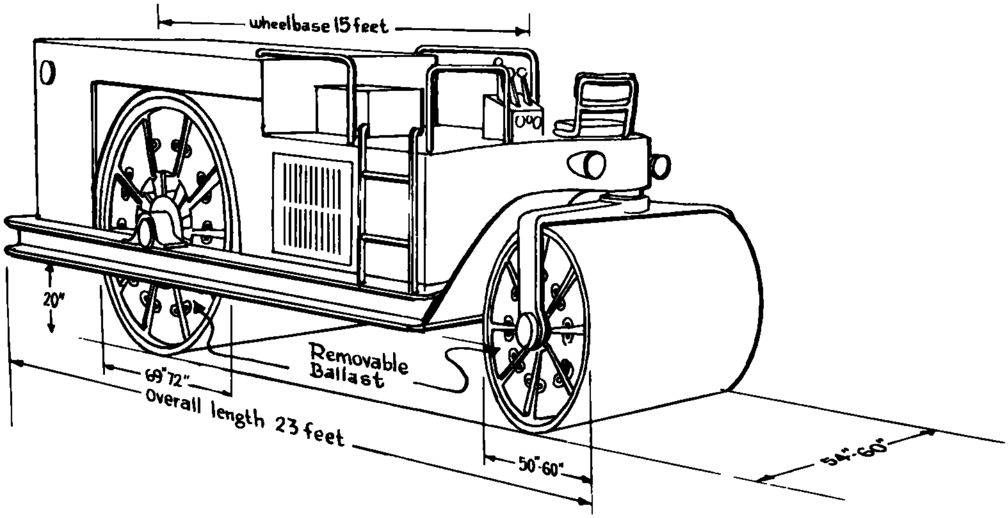


Figure 49. Artist's concept of tandem roller as described by the author.

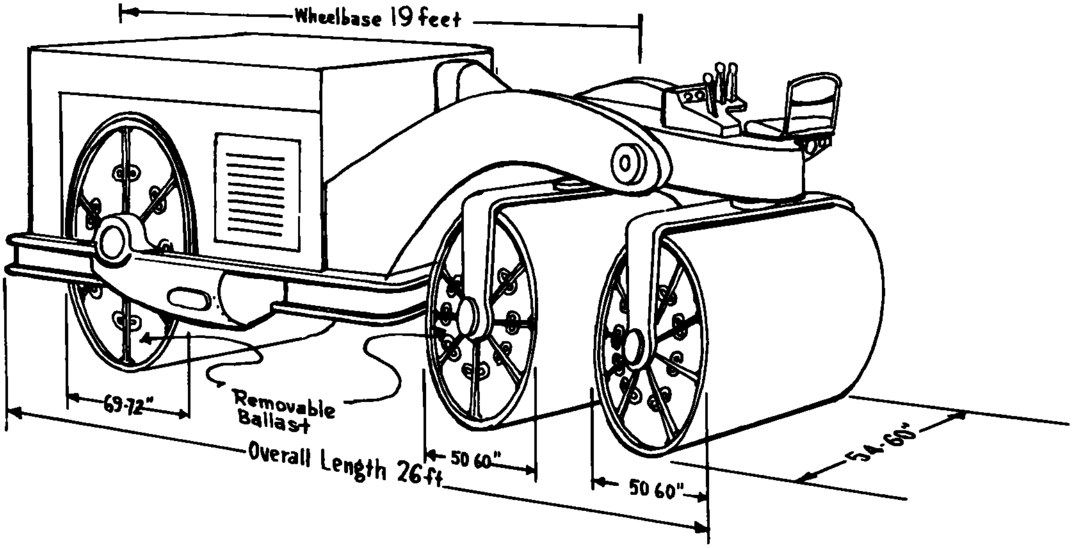
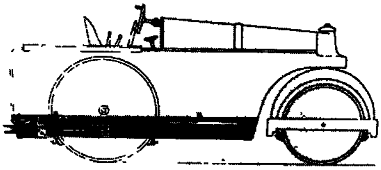


Figure 50. Artist's concept of three-wheel tandem roller as described by the author.



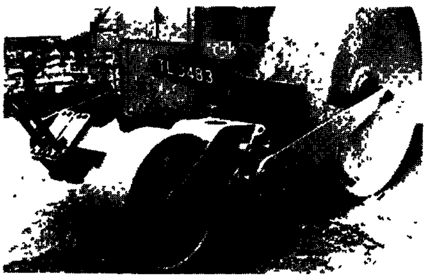


Figure 51. Pressure-balancing device by Aveling-Barford.

Figure 52. Hydraulic pressure roll, Aveling-Barford. ⟶

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