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BUREAU OF PUBLIC ROADS

D. M. BEACH, *Editor*

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

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STUDY AND STANDARD OF QUALITY OF A ROAD SURFACE [1]

FROM THE VIEWPOINT OF (A) ITS SLIPPERINESS OR RUGGEDNESS, AND ITS RESISTANCE TO SKIDDING; (B) ITS PROPERTY OF REFLECTING OR ABSORBING LIGHT (UNDER ARTIFICIAL LIGHTING)

By R. H. BALDOCK, Chief Engineer, Oregon State Highway Commission, Principal Reporter

GENERAL CONCLUSIONS

1. To afford reasonable protection against the dangers of skidding, a road surface should have a static or side-skid friction coefficient of 0.4, or higher, at 40 miles per hour.

2. Pavements with a coarse sandpaper or slightly rough texture are more nonskid than pavements having a rough, knobby texture.

3. As the speed of the vehicle increases, particularly on wet surfaces, the coefficient of friction decreases.

4. The coefficient of friction of wet surfaces of the bituminous type increases with an increase of hardness of the asphalt or tar binder.

5. The coefficient of friction of wet bituminous surfaces varies through a wide range. The coefficients of the high-type, nonskid asphaltic pavements and bituminous macadam surfaces are consistently higher than the coefficients of other wet surfaces. However, unusually low coefficients are obtained on bituminous surfaces when such surfaces are covered by a skin of free asphalt.

6. The coefficients of wet portland cement concrete surfaces are from 15 to 50 percent lower than those of high-type asphaltic surfaces under similar conditions of test.

7. The lower coefficients of friction of wet portland cement concrete surfaces, in comparison with present high-type bituminous macadam and asphaltic concrete surfaces under similar conditions, are unquestionably caused by the film of water retained on the surface of portland cement concrete pavements of current design. Tests indicate that the presence of the water film on the portland cement concrete surfaces is the probable cause of the reflection or glare from approaching headlights as evidenced on this type of pavement in comparison with the noticeable absence of glare afforded by the rough-textured surfaces of modern asphaltic concrete and bituminous macadam.

8. Changes in the design of portland cement concrete pavement surfaces to afford larger grooves to permit the rapid run-off of the water are necessary to increase skid resistance and to reduce the headlight glare of this type of pavement.

9. The larger of two tires of the same tread design will have the greater coefficient of friction. This substantiates the theory that the total frictional resistance of tires on road surfaces is equal to the true frictional resistance of the two materials plus the mechanical resistance which increases with the contact area of the tire.

10. On wet surfaces the squeegee action of the edges of new-tread tires provides a more intimate contact with the area of the road surface than is possible with smooth-tread tires and thus reduces the lubricating effect of the water.

11. Dry, light-colored pavements are from 2 to 4 times as luminous as dry, dark-colored pavements. No pavement has much luminosity when wet.

12. Smooth-textured pavements reflect more light than pavements having rough-textured surfaces.

13. Both smooth pavements and pavements having a fine, sandpaper texture are covered with a film of water, when wet, and this film is a very effective reflecting surface. Coarse-textured surfaces having pits or indentations of from ⅛ to ¼-inch in depth break up the water film and therefore reflect light in considerably lesser degree.

14. Reflective glare from wet surfaces is in the main a function of the texture of the surface and the least glare is given by those surfaces which are so deeply indented that water is not held by surface tension but drains off with sufficient rapidity to prevent the flooding of the entire surface and the formation of a water film to act as a mirror and reflect the lights of approaching vehicles.

15. For a maximum of skid resistance and a minimum of glare, it is necessary to construct pavements having surface indentations or grooves deep enough to prevent the surface tension of water from holding a film of water on the surface. Moreover, the small particles of rock or sand should stand above and screen off the light from the water running in the indentations or grooves above described.

16. The surface texture of the pavement should be as fine as possible to accomplish the above objective inasmuch as a coarse, knobby texture reduces skid resistance.

17. Water film, when present on the surface of a pavement, acts not only as a lubricating medium between the tire and the pavement but also as a mirror to reflect light and cause dangerous glare.

[1] Report for the United States to the Eighth International Road Congress held at The Hague, June 19–July 2, 1938.

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A. SLIPPERINESS OR ROUGHNESS AND RESISTANCE TO SKIDDING

Statistics collected and published by the Travelers Insurance Company of America indicate that about 1,500 persons are killed annually and that 30,000 persons are injured annually in the United States of America, by accidents reported as due to skidding on slippery road surfaces. While many of these accidents were in all probability caused by attempted driving at excessive speed, it must be borne in mind that, to the average motorist, skidding is a menace which causes uneasiness and discomfort even when no accident results. It is quite probable that many such accidents occurred on surfaces so slippery as to afford practically no friction between the tire and the pavement.

Any road surface used by motor vehicles should have sufficient roughness of surface texture to provide that friction between the tires of automotive vehicles and the road surface requisite for the safe starting, steering, and stopping of such vehicles under all reasonable conditions of operation. No road surface should be so slippery that skidding of the vehicle can occur when the vehicle is being operated in a reasonable and proper manner. Investigations have shown that the margin of safety for high-speed driving is small even on dry surfaces where high coefficients of friction are available.

The knowledge of the coefficient of kinetic friction between automobile tires and roadway surfaces now extant is due almost entirely to the work of Professor R. A. Moyer and his associates as reported in Bulletin 120 of the Iowa State College. This report will deal with the findings of Professor Moyer and his associates from numerous tests of the skid-resisting properties of various types of surfaces. It will also make use of the reports and observations contributed by various highway departments and other organizations and individuals.

DEFINITIONS

Coefficient of friction.—The coefficient of friction is the ratio between the force parallel to the road surface and the normal pressure of the tires upon the road when skidding is impending or actually taking place. If skidding is impending, the coefficient is called the coefficient of static friction, while if the movement is actually taking place the coefficient is called the coefficient of kinetic friction. Static friction will control skidding when a vehicle has just started and also the straight skidding in the direction of travel when the brakes are on the point of locking the wheels against rotation. Kinetic friction will control straight skidding in the direction of travel when the wheels are locked, and sidewise skidding in the direction normal to the line of travel with wheels either locked or rotating.

If a great force is necessary to cause skidding, the coefficient will be high, while if a slight force causes skidding the coefficient will be low. In other words, a pavement having a texture which enables the tires to grip the surface will offer great resistance to skidding and will have a high coefficient of friction. It therefore follows that highway surfaces are skid-resistant in the order of the ascending curve of the coefficient of friction.

Integrating dynamometer.—The integrating dynamometer is an instrument for measuring the force exerted by the vehicle when skidding straight ahead after the application of the brakes, or the amount of skid force exerted by the vehicle as it tends to skid sideways. The dynamometer is simple and rugged in construction, measures accurately to within 10 pounds forces ranging from 100 to 2,000 pounds, and its accuracy is not changed by the vibration set up in the test-trailer. This instrument was used in the tests hereinafter described.

TESTS BY PROFESSOR MOYER

Road tests to determine the slipperiness of various road surfaces under various surface conditions, as wet, dry, and snow- or ice-covered, were conducted by the Iowa Engineering Experiment Station in 1924 and again in 1927, under the direction of T. R. Agg. In 1932, the study was renewed and has been carried on continuously since that time under the direction of R. A. Moyer.

In the more recent work, all of the more important phases of skidding relating to highway safety were carefully investigated and analyzed. The resistance to skidding as measured by the coefficient of friction between the tires and the road surface was determined for 25 different types of surfaces. Tests were conducted with new tires of unworn tread design and with similar tires on which the tread had been worn smooth. They were conducted on wet and dry surfaces for both straight-ahead and sidewise skidding, at speeds ranging from 3 to 40 miles per hour, using a two-wheel trailer unit. Tests were made on pavements of brick, asphaltic concrete, portland cement concrete, on surfaces of penetration macadam using asphalt, tar, or road-oil binders, on surfaces treated with both tar and road oil, on gravel and cinder road surfaces, and on bridge floors surfaced with asphalt plank, steel plates, and hardwood plank. Tests were also made on mud-, snow-, and ice-covered surfaces both with and without tire chains.

On the basis of the results of braking-effort tests made with 2,134 cars and an analysis of the frictional requirements when braking, minimum safe-stopping distances were established.

Probably the most important phase of this investigation as far as this report is concerned is that which deals with the tests of the various road surfaces. It is now generally recognized that roads must be smooth-riding and free from large surface inequalities, yet skid-resistant to permit safe operation at the high speeds demanded today and the higher speeds which may be required by traffic in the future.

The Moyer tests indicated that skid-resistance can be provided in road surfaces of any type, and that the greater hazard, caused by snow, ice, and mud, can be materially reduced by maintenance. The tests indicated that practically all roads in the dry condition can provide the requisite friction with a liberal amount to spare for ordinary driving demands or even for emergency demands. Many surfaces in wet condition were found to be almost as safe as the same surfaces in dry condition, but the tests indicated that there is a large mileage of surfaces in the United States today which are dangerously slippery when wet.

In the earlier investigations of the skid-resistance of pavements, tests were conducted at low speeds at which the large uniform tractive forces required of the towing vehicle could be easily provided. In the more recent tests, the more variable effect of speeds ranging from 3 to 40 miles per hour was investigated. The results were startling because they indicated how slippery certain surfaces really are. On certain surfaces in wet condition, it was found that at 40 miles per hour the friction available is only ¼ to ⅕ as great as it is at 10 miles per hour. In fact, under certain conditions, these surfaces were found to be equally as slippery as snow- or ice-covered surfaces.

In theory, which was substantiated by the tests, the total frictional resistance to skidding is equal to the true frictional resistance between the two surfaces plus the resistance which results from a mechanical interlocking of the tire tread with the road surface. This mechanical resistance is brought about by the interlocking of minute particles of rubber with equally small projections in the road surface which tend to shear the rubber as the tire slides over the surface. In extreme cases skid marks are evidenced by the film of rubber left in the path of the skidding tire. The true frictional resistance is theoretically proportional to the normal load supported by the tire. The mechanical resistance, however, is dependent not only on the normal force or load on the tire, but depends also on the area of contact of the tire with road surface.

Surfaces which are smooth and which provide a large and intimate contact area for the tire, as indicated by tests, provide the greatest frictional resistance against skidding. Conversely, surfaces which have a rough knobby surface texture do not provide such an intimate contact, and therefore do not afford frictional resistances as great as those provided by the smooth surface with gritty finish.

On wet surfaces, the water serves as a lubricant if it cannot be squeezed or squeegeed from the surface as the tire rolls over it. At speeds above 25 to 30 miles per hour the tires fairly skim over the surface and it is far more difficult to remove the excess water and to overcome the lubricating effect. If the water is trapped between the tire and the road surface, skidding resistance drops off sharply. On wet surfaces, it is important to recognize that a large area of intimate contact is necessary to develop high frictional resistance; that small grooves should be provided in the road surfaces and in the tire to permit the excess water to escape; and that the aggregate on the surface should be hard and sharp, with many points of contact to grip the tire and prevent skidding. The tests revealed that highly polished or glazed surfaces are certain to be dangerous when wet. Examples of such types of surfaces are smooth steel plates, steel-troweled or highly polished concrete surfaces, and glazed-over asphalt surfaces.

The coefficients of friction of a considerable number of pavement surfaces when both wet and dry and at speeds of from 3 to 40 miles per hour were determined in the Moyer tests. Typical curves resulting from the tests are reproduced in figure 1; and in the following summary of the tests the average values from these curves are used. In figure 2, the results shown in figure 1 have been grouped so that those surfaces which give similar coefficients of friction under the conditions tested are shown by a single curve. Additional data relative to the effect of the condition of the tires are also shown in the lowest section of figure 1.

TESTS ON VARIOUS TYPES OF SURFACE

1. *Portland cement concrete road surfaces.*—Portland cement concrete surfaces of reasonably uniform standard exist in greater mileage than any other type of high-class road surfacing used in the United States today. While the skidding resistance of wet portland cement concrete pavement was found to be not as high as that of certain bituminous surface types, the skidding properties of portland cement concrete were found to be the most consistent for both wet and dry surfaces of all the types considered. The tests indicated the desirability of grooving the surface or of finishing with a canvas belt so as to bring the sharp sand grains to the surface and remove or break up the coating of cement paste which is responsible for the slippery condition certain to develop on a portland cement concrete pavement finished with steel trowels.

The cement paste develops a hard surface finish which is polished smooth by the wearing action of traffic. Excessive manipulation, vibration, or finishing of concrete pavement surfaces draws an excess of cement paste to the surface and makes a slippery surface. Proper brooming or belting will provide a skid-resistant surface. The coefficient of friction of wet portland cement concrete surfaces ranges from 0.4 to 0.9 for straight skidding and from 0.5 to 0.8 for sidewise skidding; the coefficient of friction of dry, rough-textured portland cement concrete surfaces ranges from 0.8 to 1.0 for straight skidding and from 0.9 to 1.0 for sidewise skidding. The ranges given cover the coefficients for both new-tread and smooth tires.

2. *Bituminous road surfaces.*—The frictional resistance of bituminous road surfaces, as measured in the tests, varied more widely than the frictional resistance of any of the other surfaces tested. This general class of surfaces has been generally thought of by the traveling public as dangerously slippery when wet. While the results of the skidding tests on several bituminous surfaces substantiated this belief, the majority of the bituminous surfaces, when tested in the wet condition, gave a frictional resistance appreciably higher than that obtained on any other type of surface. The tests by Professor Moyer substantiate the conclusions of many highway engineers that it is possible to build bituminous surfaces that will be as free from the dangers of skidding as any road surfaces in common use today. The majority of bituminous surfaces built recently in the United States are nonskid in character.

An examination of the bituminous surfaces found in the tests to be slippery revealed that they were covered with an excess of bituminous material. The surfaces which offered high resistance to skidding were covered with sharp, hard sand, or with hard and finely crushed rock particles held in place by the bituminous cement. Such surfaces had a sandpaper-like finish. The coefficient of friction for wet bituminous surfaces varied through a wide range of values. The coefficients for wet, high-type asphaltic surfaces were consistently higher than those for the other wet surfaces tested. However, unusually low coefficients were obtained on some bituminous surfaces, particularly on wet penetration macadam built with a soft seal coat.

It is quite apparent that the coefficient of friction increased with an increase in the hardness of the asphalt or tar binder used in the bituminous surfaces. In this connection it is pertinent to refer to the recent tendency in the practice of State highway departments in the western portion of the United States toward the use of softer binders to overcome cracking of the surface. It is the reporter's opinion that, by and large, the cracking that develops is a function of weak foundations and poor drainage, and that these factors should be corrected before hastily deciding to use softer asphalts. The tests by Moyer indicate that it is a sound practice to construct seal coats with cut-back or emulsified asphalts,

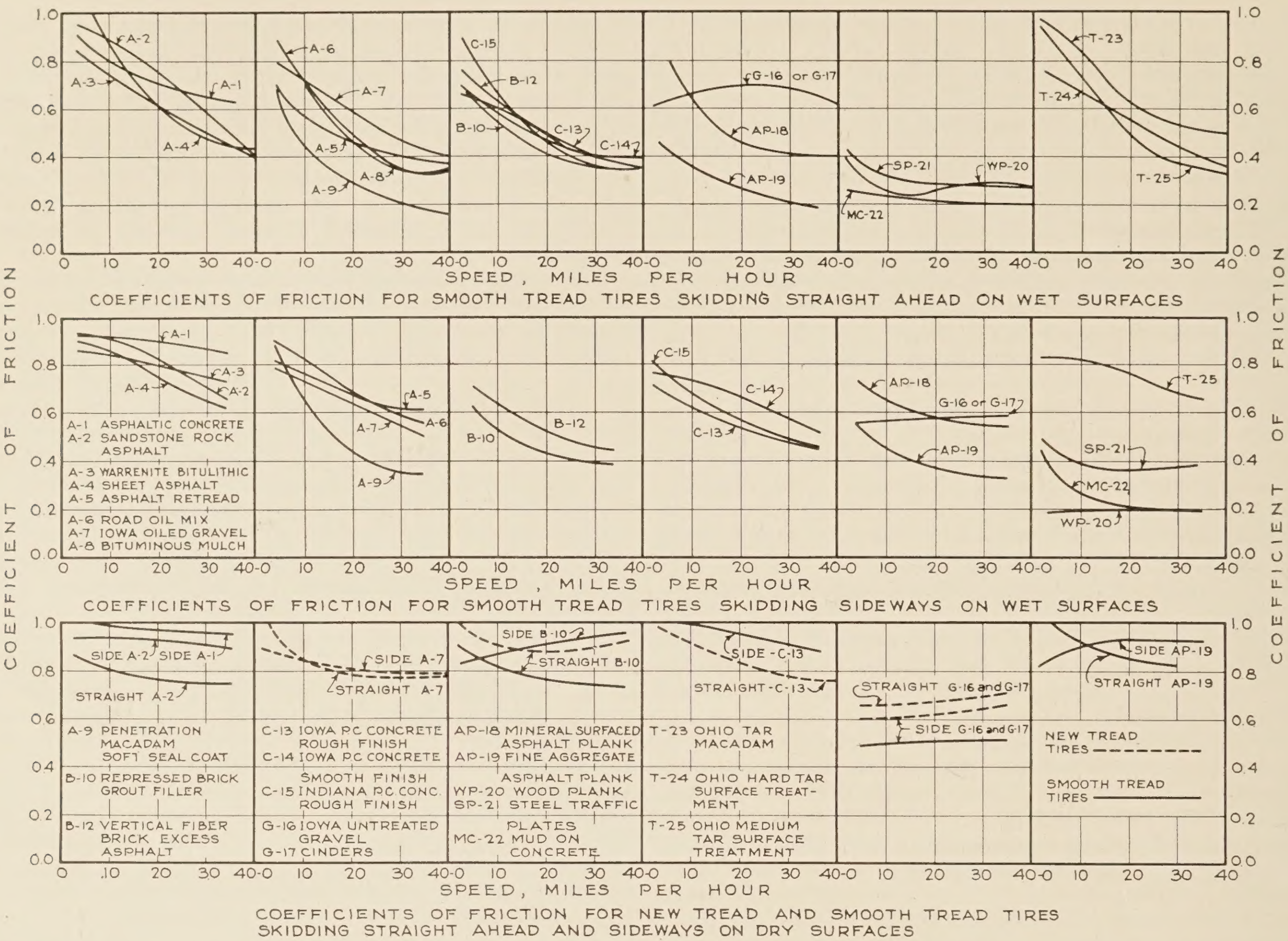


FIGURE 1.—COEFFICIENTS OF FRICTION FOR NEW-TREAD AND SMOOTH-TREAD TIRES SKIDDING STRAIGHT AHEAD AND SIDEWAYS ON VARIOUS TYPES OF ROAD SURFACES.

small amounts of which are sufficient for the thorough coating of the cover aggregate. The thin film of asphalt surrounding the stone particles firmly binds them together and the absence of an excess of asphalt below the cover stone insures a granular surface.

Competent observers are of the opinion that, when hot asphalt is used for sealing, a cover stone of ¾-inch diameter should be employed to prevent flushing of the excess asphalt to the surface. Professor Moyer's experiments have thoroughly demonstrated that a sandpaper surface which takes the wear of traffic directly on the mineral aggregate is the kind of surface it is desirable to construct. Contrary to general observation, sheet asphalt pavement, properly constructed with a sandpaper texture, is quite resistant to skidding. It is, of course, necessary to eliminate the usual surface dusting coat. Since a slight excess of asphalt will destroy the sandpaper finish and produce a glazed surface, it appears necessary in bituminous pavement construction of both the premixed and penetration types to use a hard aggregate and an asphalt with a high melting point. This is particularly true for the top or wearing course. The requisite proportions between the aggregate and asphalt binder should be controlled by careful inspection during construction.

Nonskid asphaltic surfaces can be built either in accordance with the principle of maximum density or by the use of the more open mixes. The latter are perhaps easier to construct and more certain in their results. The methods of building the more open-textured mixes and penetrations are described more thoroughly hereafter in the report on the Oregon practice.

The coefficient of friction of dry bituminous pavement ranges from 0.7 to 0.9 for straight skidding and from 0.8 to 1.0 for sidewise skidding; the coefficient of friction of wet bituminous pavement ranges from 0.2 to 1.0 for straight skidding and from 0.3 to 0.9 for sidewise skidding. Again these ranges cover the use of both new and worn tires.

3. *Brick pavements.*—Brick surfaces, free from excess filler, were found in the Moyer experiments to have skidding resistance slightly lower than that of portland cement concrete surfaces. Brick surfaces with excess filler that exudes or bleeds out of the joints, covering the greater part of the surface with asphalt, were found to be as slippery as bituminous surfaces with seal coats containing an excess of bituminous material. This would be expected since the cause of the slipperiness is the same in both cases—the excess bituminous material on the surface. Recent developments in the manufacture of paving brick and in brick pavement construction have greatly improved the skid-resistant properties of brick pavements. De-aired, vertical-fiber brick with lugs should provide a wear-resisting, gritty finish. Where there is any difficulty in obtaining the gritty

finish, it is possible to face the brick with carborundum or emery grit during manufacture and thereby provide a wear-resisting and skid-resisting surface which should be the equal of any road surface now in general use.

Bleeding of the joints has been practically eliminated by using a blended asphalt joint filler mixed with a mineral flour to provide a stable mix with a low coefficient of expansion. Before applying the joint filler, the brick surface may be sprayed with a separating agent consisting of a clacium chloride solution composed of 35 percent calcium chloride, 1 percent starch, and 64 percent water. By this method any surplus overflow of asphalt from the joints during the filling process may be scraped and peeled off the surface after it has cooled and hardened, leaving a clean surface with flush-filled joints. Lime whitewash may also be used for this purpose. It is prepared by mixing finishing lime and water in the proportions of not less than 1½ sacks of lime to 50 gallons of water. The mixture should be prepared one day in advance of using. Methods for applying these separating agents are described in the report for the United States on brick pavements.

The coefficient of friction of dry brick pavements ranges from 0.7 to 1.0 for straight skidding and from 0.8 to 0.9 for sidewise skidding; the coefficient of friction of wet brick pavements ranges from 0.3 to 0.8 for straight skidding and from 0.4 to 0.7 for sidewise skidding; the ranges in each case covering the use of both new and smooth tires.

4. *Bridge floors.*—Wood plank, smooth steel traffic plates, and ordinary asphalt plank were found in the Moyer tests to be as slippery when wet as icy surfaces. It is particularly hazardous to use these materials on bridge floors. Skidding accidents under such circumstances are more hazardous because of the restricted roadway. Indeed, it is the reporter's opinion that they should not be used under any conditions as a highway surface unless they are provided with some type of nonskid finish. Wood planks may be covered with a bituminous treatment involving the use of cover stone of suitable size so as to give a gritty surface finish. Steel plates should have a stud or grid design providing sharp edges to grip the tires and prevent skidding. Likewise, the surfaces of ordinary asphalt plank should be covered with sharp, gritty aggregate. In general, bridge floors are now covered either with portland cement concrete or high-type asphaltic concrete, both of which afford a satisfactory skid-resistant surface in wet weather.

5. *Sand, gravel, cinder, and macadam surfaces.*—Sand, gravel, cinder, and macadam surfaces all offer a higher resistance to skidding in either the wet or dry condition when the surface is firm and reasonably free from loose material. Loose aggregate, especially sand and gravel pebbles, acts in the same manner as ball bearings under the tires. It causes variations in the skidding resistance, making steering difficult, and in this way causes many accidents. Such surfaces also tend to become dusty in summer, materially reducing visibility, and thus, in another way, creating a hazard. The loose, dusty condition also increases the cost of transportation by causing increased fuel consumption, tire and car repair costs, and road maintenance costs. When there is considerable traffic, the cost of stabilizing the surfaces is unquestionably justified. In parts of the United States clay binder has been used with some success, but it has been clearly demonstrated that the presence of clay in a gravel or macadam surface lowers the chance of success of any subsequent treatment with oil or tar. In the opinion of the reporter, it is much more effective and cheaper in the long run to stabilize such surfaces with an asphalt or tar binder. This can be done either by the road-mix method or by the placing of a mat of oil, asphalt, or tar and screenings, as a wearing course.

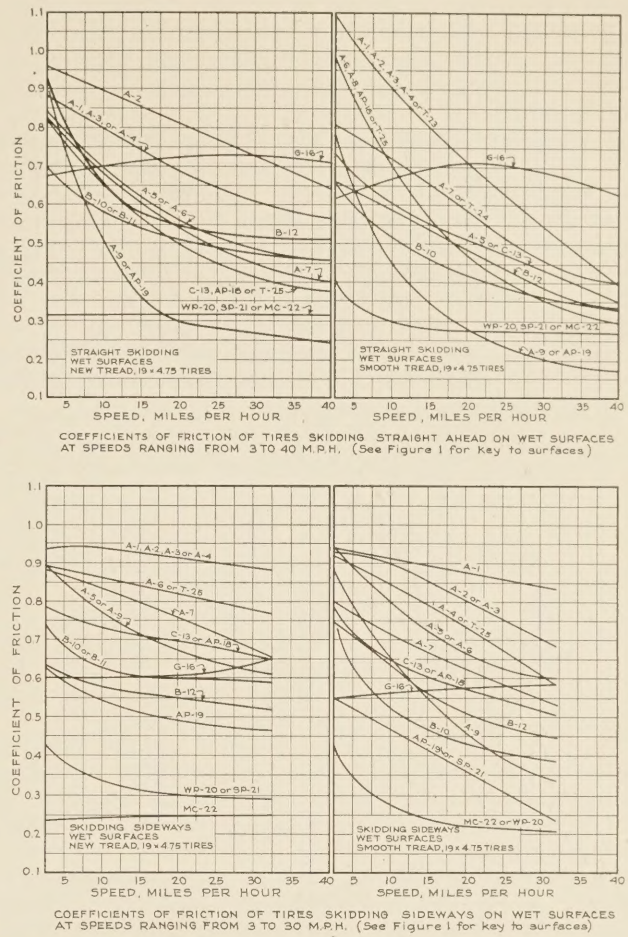


FIGURE 2.—COEFFICIENTS OF FRICTION OF TIRES SKIDDING STRAIGHT AHEAD AND SIDEWAYS ON VARIOUS TYPES OF ROAD SURFACES.

6. *Maintenance.*—The results of the Moyer tests on mud-, snow-, and ice-covered surfaces, regardless of their construction, clearly indicated that these conditions are the most hazardous the motorist is likely to encounter. Ice and sleet were found to be particularly slippery, providing a frictional resistance of only about one-fifth of that provided by a dry concrete surface. The seriousness of the snow and ice problem as related to skidding is indicated by the fact that about 80 percent of all skidding accidents in Iowa, for example, were found to occur in the 4 winter months.

The correction of this slippery condition is clearly a maintenance problem and demands prompt attention if it is to be effective. Ice forms on the road surface at a temperature close to the freezing temperature, and if sand and cinders are applied promptly at that time, the sand and cinders will be embedded in the ice, thus raising its frictional resistance to 3 or 4 times that which it can provide without such treatment. If the application of cinders or sand is postponed until lower temperatures prevail, the sand or cinders may not be embedded in the ice and the wind and traffic may whip them off the road. It is possible to apply the sand or cinders at lower temperatures if they are first heated or premixed with calcium chloride or rock salt. Such treatment causes the sand or cinders to become embedded in the ice the same as if placed at higher temperatures.

In certain States of the United States, notably Michigan, calcium chloride and sodium chloride have been applied directly on ice-covered surfaces. It has been found that such treatment, when applied to ice overlying portland cement concrete surfaces, causes serious damage to pavement and results in a form of scaling and a gradual disintegration of the concrete. For this reason it is suggested that the use of sodium or calcium chloride be avoided and that the sand or cinders be heated before application to ice-covered portland cement concrete surfaces.

Snow (particularly dry snow) has from two to three times the skid-resistance of ice. However, snow may so suddenly change to ice and is so difficult to distinguish from ice that the driver cannot be sure that a snowy surface is free from ice. It is therefore necessary to apply sand and cinders at intersections, on hills, and on curves as soon as the snow becomes packed. The practice of beginning snow removal coincidently with the beginning of the storm and of carrying on the snow removal operations continuously until the storm has ceased has become a standard procedure with State highway departments in the United States.

Mud on pavements constitutes a serious skidding menace. Where possible, the muddying of surfacings should be prevented by placing gravel coatings on shoulders and on muddy side roads, farm drives, or field entrances.

Roads that have glazed surfaces and are known to be slippery when wet should be covered with nonskid treatments of asphalt and mineral aggregate. Attempts have been made to apply heated sand or screenings on glazed bituminous surfaces, but the results have been more or less ineffectual. Usually the rolling operation cracks the stones, with the result that they are soon loosened by the traffic. Under particular conditions, as where soft asphalt with a low melting point has been used, it is sometimes possible to perform this work satisfactorily but, in general, the fact that the treatment can be given on only a few days of the year and a few hours in each day renders the method highly impractical. Likewise the correction of glazed surfaces by cutting back the excess asphalt with volatile solvents and applying gritty cover stone to blot up the excess binder has met with only mediocre success. The nonskid treatment of pavements by the placing of a mat of asphalt and stone chips has been found to be generally satisfactory, but the successful application of this treatment requires long experience and painstaking workmanship. The methods found most satisfactory in Oregon are described elsewhere in this report. The application of nonskid treatment on old concrete pavement is an even more difficult procedure because of the difficulty of successfully binding thin mats to concrete surfaces.

OBSERVATIONS BY STATE HIGHWAY DEPARTMENTS

Wyoming.—The Wyoming Highway Department reports that practically all of its hard-surface roads are of bituminous type built at rather low cost according to a road-mix specification. The Wyoming experience indicates that when slow-curing oils are used there is danger of their softening during hot weather, allowing the aggregate to settle below the surface and leaving a film of asphaltic cement on the top of the wearing surface. The tendency in their present practice is toward the use of harder asphalt and sealing with a rapid-curing cut-back covered with sharp, clean sand.

Virginia.—The Virginia Department of Highways reports a method of making pavements nonskid that it has used recently on a section of U. S. Route No. 1 between Alexandria and Fredericksburg carrying a traffic of well over 6,000 vehicles daily. An original 18-foot concrete pavement had been widened on each side to provide for 3 lanes, and sheet asphalt had been laid over the entire surface. The sheet asphalt proved slippery during periods of heavy fog and rain, and to eliminate the hazardous condition, a nonskid bituminous surface treatment was applied on the grades.

The treatment consisted of an application of one-quarter gallon of cut-back asphalt heated to a temperature of 100° F. This binder was made from an asphalt having a penetration of 85–100 mixed with naphtha in the ratio of 2 parts asphalt to 1 part naphtha. Before the application of the cut-back binder, all cracks in the pavement were patched by hand. A slag covering was immediately applied at the rate of 20 to 22 pounds per square yard. Extreme care was used to effect a uniform distribution and no brooming was permitted. The slag was rolled lightly with a 5-ton roller, and traffic was kept off the road for a period of about 72 hours. The Virginia authorities report that excellent results were obtained on this section which has now been subject to traffic for about 4 months. They are of the opinion that the closing of the section to traffic for a time sufficient to allow the volatile materials in the asphalt binder to escape was one of the major causes of the successful results obtained.

Texas.—The State Highway Department of Texas reports that the quality of a road surface from the viewpoint of slipperiness or roughness and its resistance to skidding has been the subject of considerable study and research by that department for many years. The early concrete pavements built in the State were finished very smooth and they were found to be quite slippery when wet or damp. The condition has been corrected by the use of a belt on the freshly placed concrete at approximately the time it reaches initial set. It has been found that this finishing treatment raises the grains of sand in the mortar and creates light ridges in the surface which afforded a very satisfactory resistance to skidding. The skill of the workmen in the manipulation of the belt determines the type of surface secured; hence this practice has been subjected to careful control by the Texas Department for the past 7 years.

For the "nonskidding" or roughening of asphalt-surfaced roads the Texas department uses both a penetration and a premix type of treatment. In the penetration type treatment the nonskid surface is provided through the use of hard, angular, crushed stone or gravel placed uniformly over the surface as a wearing course. The amount of asphalt used is carefully controlled as are also the proportions and sizes of the lower course of rock. The entire course must be stable, and the amount of asphalt must be less than that which, penetrating upward through the surface course, would fill the voids between the rock and create a smooth surface. When the amount of asphalt is thus properly controlled, a surface affording satisfactory resistance to skidding is provided.

The premix asphaltic treatments are of two general classifications—hot mix and cold mix. In the cold-mix construction the most recent procedure is to place a light surface course of the open-mix type as the last course of the surface construction. This course is not more than ½-inch thick. The aggregate used is ⅜ inch in size and is very hard and sharp. The mix is so designed that the amount of mortar—that is, the portion of the mix below the 10-mesh screen—is not sufficient to fill the voids in the coarser aggregate and, in consequence, the ⅜-inch material is everywhere evident in the wearing course and provides a considerable resistance to skidding.

In the hot-mix construction, the surface course is placed by means of a mechanical finishing machine to a depth of from ⅜ inch to ½ inch. The aggregate is very hard, ⅜ inch maximum size, and the voids are only half-filled with mortar. The mix is placed at a temperature of 375° F. which creates a segregation due to the latent heat in the coarse aggregate. In normal asphaltic concrete construction, segregation is one of the things that is carefully avoided. However, in placing this nonskid surface it was accidentally found that by creating a segregation the type of surface desired was obtained.

The placing of the mix under the mechanical finishing machine in such a thin layer makes it necessary that it be sufficiently warm to work properly. It was found that when the temperature was raised slightly above the normal temperature—in other words to 375° F.—the manipulation of the surface by the finishing machine and the heat in the coarse rock caused the mortar to slip down into the bottom of the course by gravity which left the top open and the lower half of the large rock firmly embedded in the matrix. This provided the most satisfactory nonskid surface that has yet been laid in the State of Texas. It is obvious that the penetration of the asphalt must be low in order that the mix shall be stable. A 55-penetration asphalt has been used and it has been found that the high heat used in mixing and placing decreases this penetration normally to somewhere between 25 and 35.

Arizona.—The Arizona State Highway Department reports that in general its bituminous surfaces are constructed by the road-mix method, using slow-curing road oils and medium-curing cutback asphalt. These surfaces are covered either with a seal coat of 90 to 95 percent road oil and screenings ranging from ½ inch to those passing a 10-mesh sieve, or with 90 to 95 percent road oil premixed with the screenings of the same size. The department reports that it has, in every case, obtained a roughened surface with the requisite nonskid properties, but in some cases the roughened surface has later lost its roughness due to the softening of the surface and gradual embedding of the screenings until a smooth layer of asphalt appeared on the surface. The department is guarding against this condition by a more thorough study of the design of the mix.

Colorado.—The State Highway Department of Colorado reports that in its road-mix construction (bituminous surfaced roads), it guards against the use of too much asphalt. Surfaces are constructed with the minimum amount of asphalt required to supply the essential binder, the main course being followed by a seal coat containing a cover stone which provides a gritty surface resistant to skidding.

Kansas.—The Kansas Highway Commission calls attention to the prevalence of oil drippings along the quarter points of portland cement concrete pavements and to the resultant low resistance to sidewise skidding at those points. The department is attempting to devise ways and means to eliminate this oil streak as a maintenance process. Variations in the skidding characteristics of surfaces of bituminous macadam and other types of bituminous pavement have caused some concern in this State. To correct such conditions, use has been made of light applications of rapid-curing cutback covered with aggregate graded in size between the ¾-inch ring and the No. 8 square-mesh sieve. The Kansas engineers recommend the use of transition curves for highway alinement which will lessen the throw of the car caused by the sudden application of centrifugal force at the point of the curve. On slippery pavements, this throw frequently induces skidding.

Massachusetts.—The Massachusetts Department of Public Works stresses the banking of curves and the lengthening of curve radii as well as the design and construction of nonskid surfaces to prevent the hazard of motor car skidding. It recommends a surface free from depressions and bumps, and providing a maximum amount of angular particles of the mineral aggregate in contact with the tire and particles sufficiently large to resist the force causing the tendency to skid. The Massachusetts portland cement concrete surfaces have been constructed by the well-known method of brooming and afford sufficient angular contact with the tires.

The bituminous macadam surfaces of Massachusetts are known throughout the United States for their excellent quality. Great care is exercised to obtain the proper balance between the amount and kind of bituminous material and the size of the keystone. During the past few years, however, the Massachusetts department has developed a rather coarse, knobby surface texture without any cover of pea or chip stone. The large stones present a rough mosaic, the top of which is free of asphalt. Clean, properly graded broken stone of the resistance to wear and toughness required is used and this, when rolled, affords a firm, interlocking surfacing. Chip stones are used in quantities sufficient only to fill the voids below the top surfaces of the large stones.

The Massachusetts department has been of the opinion that this open, granular type is best from the viewpoint of skid prevention and that such pavements are as durable, if not more so, than the tighter, mat-covered pavements of former years. However, such roads cause an unpleasant rumble in a rapidly moving closed motor vehicle. The department recognizes this disadvantage and plans to return to the former method using a surface of finer texture. It is to be noted that the department's opinion in regard to the skid-resisting properties of the coarse, knobby type of surface does not coincide with the results of the research of Professor Moyer, which leads to the conclusion that all State departments should calibrate their types of pavement by means of equipment similar to that devised by Professor Moyer to the end that they may speak a common language and refer to definite values of the coefficients of straight-ahead and sidewise skidding. It would likewise be desirable if some standard device to measure the nonskid properties of various types of pavements could be universally employed.

Mississippi.—The Mississippi Highway Department reports that it is rolling bituminous-coated chips into both the Topeka and the sheet asphalt types of asphaltic concrete, thereby obtaining a very nonskid pavement surface.

Wisconsin.—The Wisconsin State Highway Commission has had some difficulty in maintaining bituminous surfaces, due to the flushing of the asphalt to the surface. It has remedied this condition by the application of a seal coat of additional asphalt and hard, sharp stone chips. It reports that it has found that ice melts more quickly on bituminous surfaces than on concrete, due presumably to the greater absorption of heat by the darker material. Some difficulty has been experienced in sanding ice covering portland cement concrete pavement because of injurious effects of the salts mixed with the sand and cinders, which salts apparently have caused a later disintegration of the concrete surface.

Oregon.—As has been stated, it is necessary to build and maintain smooth-riding and skid-resisting surfaces. Rough pavements are the direct cause of skidding at high speed. The State Highway Commission of Oregon has devoted a great deal of time and study to devising ways and means for building smooth pavements of various types. It is axiomatic, however, that no matter how smooth pavements may be when originally constructed, they eventually become rough. Grade settlements, slight land movements, occasional weakness in foundations, and faults in drainage all tend to deform the pavement. Sooner or later, therefore, it becomes necessary to patch all pavements. Hence, it would seem to be highly desirable, if not necessary, to develop a technique and workmanship resulting in smooth patches. If patches are smooth, it should be possible to keep pavements in good condition, if not indefinitely, at least over long periods of time.

The Oregon department patches all pavements, regardless of type, with hot asphaltic concrete. The patches are nonskid in character and feathered to paper thinness at the edges. Dark asphaltic concrete patches on portland cement concrete pavements are objectionable to some extent, but they are few in number during the early life of the pavement and disfigure it less than might be supposed.

Portland cement concrete pavements are made smooth at the time of their construction by means of delayed finishing; that is, by delaying a part of the finishing until the shrinkage incident to the initial setting of the concrete has taken place, and by the further procedure of scraping down the high spots with heavy steel scrapers after the initial set has occurred. Very little scraping work is actually performed, however, as contractors, in order to avoid the expense of the scraping, perform the preceding finishing operations with the utmost care. Scraping is objectionable in that it removes the broom finish, leaving the scraped area smooth and less nonskid; but, as stated, the total area scraped is very small.

After extensive trial, the Oregon department has abandoned the mudjack as a means of pavement repair, having found that its use is only partially satisfactory in restoring the smoothness of the surface and that it results in much breakage of slabs into small sections which tend to rock and move under traffic. As the portland cement concrete pavements become progressively rougher, the asphaltic concrete patches increase in number until finally they constitute a complete resurfacing, with the concrete pavement serving as a base for an asphaltic concrete top.

Bituminous pavements constructed in Oregon are of two types, the plant-mix type and the penetration type. All plant-mix construction is of high-type asphaltic concrete of which there are two general classes, the minimum-void or closed-type mixes, and the open mixes. It is the theory of the reporter that it is very difficult to maintain a permanently nonskid surface with the densely graded mixtures for the reason that there are practically no voids for the asphalt to occupy under the influence of heat and the constant pounding of traffic. There is, therefore, the danger of free asphalt exuding upon the surface. It is possible, but rather difficult, to avoid this by a rigid control of the proportions of the aggregate and the percentage of asphalt, using the minimum of asphalt requisite to keep the mixture sealed and to prevent raveling in cold or wet weather. Very good results have been obtained in Oregon by exercising this rigid control, and pavements 5 years of age have retained the nonskid features required for safe driving.

The seal coat is eliminated from this specification and ½-inch screenings coated with 2 percent asphalt cement are rolled into the surface mixture, while it is still warm, at the rate of approximately 5 pounds per square yard. The proportions of aggregate and asphalt binder illustrating this type of construction are as follows:

	Percent
Aggregate:	
Passing 1¼-inch screen	100
Passing 1¼-inch and retained on ¾-inch screen	16–24
Passing ¾-inch and retained on ¼-inch screen	24–36
Passing ¼-inch screen and retained on 10-mesh sieve	12–20
Passing 10-mesh and retained on 200-mesh sieve	20–28
Passing 200-mesh sieve	3–6
Asphalt, 50–60 penetration	4. 5–6. 5

The open-type mix has sufficient voids for any probable expansion of the asphalt. When properly constructed, no evidence of the flushing of the asphalt to the surface has been noted. This construction is used as a wearing course only, and is placed upon an impervious, closed mix as a base. The grading of the materials and the percentage of asphalt are as follows:

	Percent
Aggregate:	
Passing ¾-inch screen	100
Passing ¾-inch and retained on ¼-inch screen	45–55
Passing ¼-inch screen and retained on 10-mesh sieve	30–36
Passing 10-mesh and retained on 200-mesh sieve	8–14
Passing 200-mesh sieve	0–2
Cut-back asphalt (RC–4)	4–6

In closed mixes, an asphaltic cement of 50–60 penetration is employed. In open mix, a heavy-grade cut-back asphalt known as RC–4 is used, in which asphalt of 80–120 penetration is cut back with a maximum of 15 percent of naphtha as determined by distillation at 680° F. All types of asphaltic concrete mixtures are laid with finishing machines. The dense mixtures are laid at a temperature of 325° F. and the open type mixtures at temperatures ranging from 175 to 250° F.

In the early practice of the Oregon State Highway Commission, some rather high-crowned asphaltic concrete pavements, 16 feet in width, were constructed. These pavements were covered with a heavy seal coat of asphaltic cement and sand and they became very slippery in wet weather. It therefore became necessary to eliminate this very definite hazard. The first treatments consisted of one application of asphaltic cement or tar followed by a covering of stone chips or pea gravel. The results were, on the whole, mediocre. The stone tended to whip off the high spots, producing a surface of varying texture. Certain areas were covered with stone chips or pea gravel, affording a nonskid texture, while other areas were entirely bare of screenings and therefore slippery. It was finally found necessary to plane off the excess of asphalt from the surface of the old pavement. The asphalt and fine mineral material had accumulated in bumps and in certain cases had formed rhythmic corrugations.

The planing machine consisted of a heavy trailer of long wheelbase, carrying adjustable chisel-like cutting edges, pulled by a 60-horsepower crawler-tread tractor. The chisels were kept sharp and not only cut off the asphalt-sand mastic, but also sheared through the stones in the underlying mix. Repeated trips with the planer not only removed the excess of asphalt but also produced a very smooth-riding surface. The removal of the excess of asphalt eliminated any chance of its being drawn up into the new wearing course. Upon the planed surface was constructed, by the penetration method, a wearing course approximately 1¼ inches in thickness. Stone of maximum 1¼-inch size was used. The asphalt content was held to the minimum and excellent results were obtained. Surfaces treated in this manner some 8 years ago are practically as skid-resistant as when first constructed.

Probably the most uniform nonskid texture pavement laid in the State of Oregon is the penetration macadam type. The base stone, of 2½-inch to 1¼-inch size, is penetrated by hot asphaltic cement and covered with stone ranging from 1¼ inches to ¾ inch in size. This stone is carefully leveled by long-wheelbase motor graders. After the second application of asphaltic cement, the bituminous macadam is keyed with ¾- to ½-inch stone. This is followed by the first seal coat using ½ to ¼-inch and ¼-inch minus cover stone. Traffic is turned onto the pavement 4 or 5 days before the application of the second seal coat, after which the surface is thoroughly swept and the second seal employing the same size of aggregate is placed. This method effectively seals the penetration macadam against the admission of moisture. Hot asphaltic cement of 120–150 penetration, heated to a temperature of 425° F., is used in all cases with the exception of the last seal coat. A water-soap solution, in the amount of 10 percent of the hot asphalt by volume, is added through separate openings in the spray nozzles. The temporary emulsion formed covers the stone thoroughly. Either cut-back asphalt or emulsified asphalt is used for the second seal coat.

The surface texture of this type of pavement is somewhat coarser than a sandpaper finish, the ½-inch stone and some of the ¼-inch stone being present in the surface. The voids in the base stone act as a reservoir to absorb excessive asphalt in hot weather with the result that this type of pavement seldom bleeds and remains remarkably uniform in texture throughout the years. Oregon has had about 10 years' experience with this type of surfacing. In all, 2 gallons per square yard of bituminous cement, including the cut-back or emulsion, are required. The total aggregate used amounts to 0.111 cubic yards per square yard. Each course of the pavement is thoroughly rolled with 10-ton, 3-wheeled rollers.

B. PROPERTY OF REFLECTING OR ABSORBING LIGHT (UNDER ARTIFICIAL LIGHTING)

In view of the fact that consideration is now being given to the artificial lighting of certain sections of rural highways in the United States to eliminate the hazards of night driving, information concerning the quality of road surfaces in respect to their ability to reflect or absorb light is important. Moreover, since the majority of rural highways will, in all probability, remain unlighted on account of the expense, it is of prime importance that those properties of road surfaces which minimize the glare of approaching headlights, particularly on rainy nights, shall be carefully studied.

The reporter has endeavored unsuccessfully to obtain through published articles data relating to visibility and glare in connection with the various types of pavement surface. Apparently few data of this kind have been assembled in the United States up to the present time. Accordingly a series of experiments of limited scope was undertaken by G. S. Paxson, Bridge Engineer, and J. D. Everson, Designer, both of the Oregon State Highway Department. The character of the equipment and the time available prevented any exhaustive study, but the results obtained give at least qualitatively a comparison between the various pavement surfaces examined.

DESCRIPTION OF INVESTIGATION

Investigations were made to determine the light-reflecting properties of various types of pavements under artificial lighting conditions and to measure the reflection or glare from approaching headlights under both wet and dry conditions. Investigations to determine light-reflecting properties under artificial lighting conditions were made on 7 different types of pavement as follows:

1. A new concrete pavement completed and cured but not yet opened to travel. This pavement is broom-finished. The grooves are between 1/16 and ⅛ inch in depth, running transversely to the pavement. Duplicate tests were made with the incident light across the grooves as would be the case in normal lighting and with the incident light parallel to the grooves simulating a pavement broom-finished parallel to the highway center line. These two conditions are referred to in the accompanying charts as "new concrete parallel with grooves" and "new concrete across grooves," respectively.

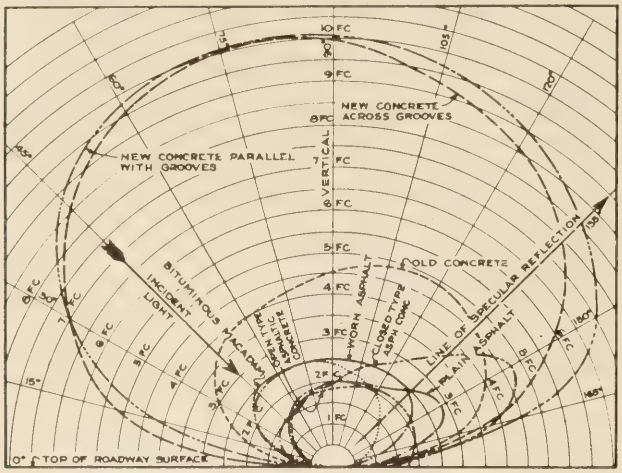
2. A concrete pavement that has been in use 18 years. This pavement was constructed with a smooth surface and has been considerably stained and discolored by oil during service. The pavement is called "old concrete" in the accompanying figures.

3. A section of old asphaltic concrete pavement quite rich in asphalt and showing no aggregate on the surface. This pavement is called "plain asphalt" in the accompanying figures.

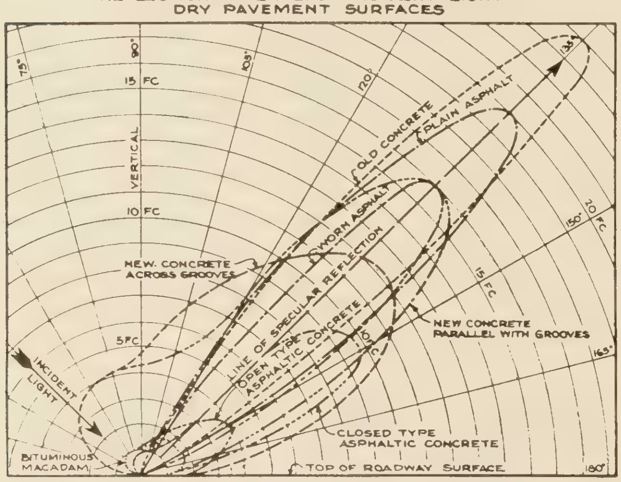
4. An asphaltic concrete pavement that has been in service 15 years. The surface is quite smooth, but over at least 30 percent of the surface small aggregate particles protrude above the shiny asphalt finish. This pavement is called "worn asphalt" in the accompanying figures.

5. A modern asphaltic concrete wearing surface of the "closed type" as described in the first section of this report. This pavement is 3 years old and is called "closed-type asphaltic concrete" in the accompanying figures.

6. An asphaltic concrete pavement of the "open type" as described in the first section of this report. This



LIGHT SOURCE AT 45° TO PAVEMENT SURFACE
REFLECTION IN PLANE OF INCIDENT LIGHT
DRY PAVEMENT SURFACES



LIGHT SOURCE AT 45° TO PAVEMENT SURFACE
REFLECTION IN PLANE OF INCIDENT LIGHT
WET PAVEMENT SURFACES

FIGURE 3.—LUMINOSITY OF VARIOUS TYPES OF ROAD SURFACES WHEN DRY AND WHEN WET, FOR LIGHT SOURCE AT 45° TO PAVEMENT SURFACE.

pavement is 1 year old and is called "open-type asphaltic concrete" in the accompanying figures.

7. A section of bituminous macadam in service about 1 year. The surface of this pavement is composed of stone chips from ¾ to ½ inch in size which project above the body of the pavement about ⅛ inch. This pavement is called "bituminous macadam" in the accompanying figures.

In fixed highway lighting the fixtures are suspended above the roadway surface at a considerable height, and the angle at which the light strikes the surface is controlled by the fixture. With a mounting height of 30 feet and 200 feet between lights, the flattest angle will be about 17°, assuming that each light illuminates the surface halfway to the adjoining light. To simulate these conditions, measurements of the reflected light were made with an incident angle of 45° and with an incident angle of 17°. The light source was a 6-volt incandescent light mounted upon a tripod so that the angle between the light beam and the pavement surface could be accurately determined. The intensity of the light was controlled by a rheostat and voltmeter so that it was kept constant during the entire series of tests.

Reflection readings from the pavement surface, measuring the relative intensity of the light, were taken with a photometer attached to an arm which kept it at a constant distance from the point of reflection on the pavement surface. The intensity was measured in foot-candles. The angle which the axis of the photometer made with the pavement was measured on a dial attached to the frame supporting the photometer arm. The angle of incident light was kept constant and the intensity of the reflection was measured at each 15° around the semicircular arc. Readings were taken in the plane of the incident light.

Readings were first taken on the pavement surfaces when dry. The surfaces were then artificially wetted to simulate conditions during a rain, and the readings repeated.

RESULTS OF THE INVESTIGATIONS

The results obtained with the light at an angle of 45° are shown in figure 3. Those above are for dry surfaces and those below are for the same surfaces when wet. It is interesting to note the regularity of the curves for dry pavement which show almost complete absence of specular reflection or glare except for the three smooth pavements investigated. These were the old concrete, worn asphalt, and plain asphalt. In addition, the closed-type asphaltic concrete, which is a relatively nonskid pavement, shows a decided bulge in the curve of readings taken for dry pavement. The curves for these pavements show a noticeable bulge in the direction of the line of specular reflection.

The difference between the luminosity of the dry portland cement concrete pavement and the dry asphaltic concrete pavement is quite noticeable. The new portland cement concrete pavements show about 4 times the luminosity of the asphaltic concrete pavements, while the old concrete pavements show about twice the luminosity. The rough and irregular bituminous macadam surface shows the property of being more highly luminous in the direction of the incident light than it is away from it.

These surfaces were then wetted and tested, other conditions remaining constant. The characteristics of the pavement have entirely changed and a great amount of specular reflection or glare is apparent. It will be noted that the new smooth pavements give from 4 to 10 times the intensity of glare produced by the rough-textured pavements.

The comparison of the two sets of curves shows that the luminosity of the pavements, except on the line of specular reflection, is one-half or less when wet than when dry; moreover, that in the case of plain asphalt or worn asphalt pavements there is practically no luminosity outside of the glare. This is supported by driving experience which discloses that the pavement appears very bright directly in the line of light sources but practically black at any other angle. It will be noted that while the luminosity of dry bituminous macadam pavement is only about one-fourth that of the new concrete, the glare, when wet, is less than one-sixth as great.

Figure 4 shows the reflection readings on dry and wet pavements with the angle of incident light at 17° with the pavement surface and with the readings taken in the plane of incident light. It should be noted that as the angle of incident light decreases, the glare increases with all types of pavement, wet or dry.

As in the preceding figures, the luminosity of the dry portland cement concrete pavement is from 2 to 4 times that of dry asphaltic concrete types. The spec-

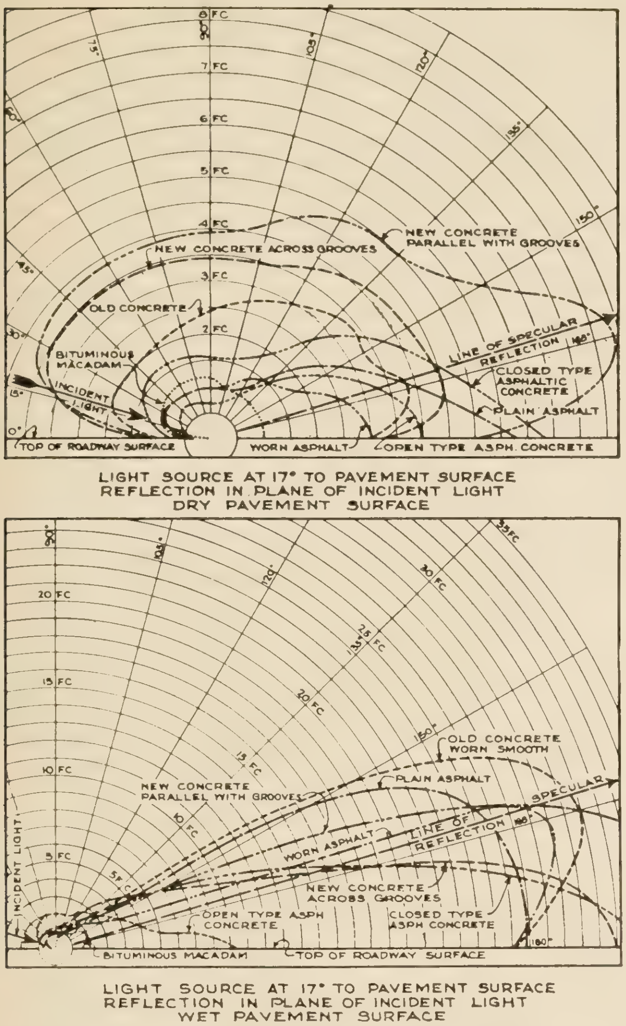


Figure 4.—Luminosity of Various Types of Road Surfaces When Dry and When Wet, for Light Source at 17° to Pavement Surface.

ular reflection or glare from the plain asphalt and worn asphalt types, when dry, is from 2 to 3 times that of the luminosity in other directions. The reflection from concrete pavements, when wet, is 4 to 8 times the luminosity of these same pavements when dry. Bituminous macadam, when dry, shows practically no glare at all.

An examination of the lower part of figure 4 shows that none of the pavements has an appreciable luminosity when wet and that all but the bituminous macadam evidence some glare. An interesting point in this study is the decreased glare from portland cement concrete pavements when the light is across the grooves as compared with the same pavement when the light is parallel to the grooves.

From this study, it appears that under dry conditions, new, clean portland cement concrete pavements are more easily lighted than any of the darker asphaltic types. This is undoubtedly due to the light color of the portland cement concrete pavement. The rough open-textured bituminous macadam surface produces the least glare when wet.

It was noted during the experiment simulating rain that the smooth pavements were covered by a practically continuous sheet of water. Even the new concrete with its shallow broom marks became completely flooded. The high surface tension resulting from the small diameter of the grooves prevented the rapid run-off of the water. This suggests the formation of deeper, wider grooves in concrete pavement to afford quick run-off. The irregularities in the surface of bituminous macadam and new-type asphaltic concrete afford fissures or channels wide and deep enough to minimize the surface tension of the particles of water. Such surfaces are seldom entirely flooded and the stone chips projecting above the water surface break up the reflection and greatly reduce the glare. It is thus apparent that the glare is caused in the main by the reflection of the light from the sheet of water acting as a mirror. Means should be provided for constructing all types of pavement so as to afford rapid run-off of surface water. This is easily accomplished by the standard methods of building penetration macadam and the open-textured asphaltic concrete of the present day.

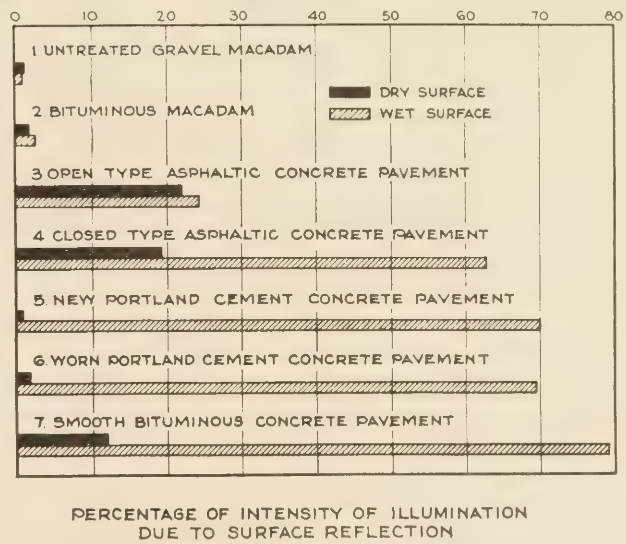


Figure 5.—Percentage of Intensity of Illumination Due to Surface Reflection for Various Types of Road Surfaces.

There is room for improvement in portland cement concrete pavements and it is suggested that consideration be given to the scratching of grooves approximately ¼ inch in depth 1 inch apart, transversely across the pavement surface, while the concrete is still green.

INVESTIGATION OF HEADLIGHT GLARE

In this part of the investigation, a 1937 model automobile with the headlights in the depressed or dim position was used as the light source. In this position the center of the light beam struck the pavement approximately 65 feet from the light. Readings of the intensity of the light at double this distance, or 130 feet, at the same elevation as the headlights, were taken with a photometer. A screen was then placed in the proper position so as to allow only the reflected light to reach the photometer. This eliminated the direct light from the headlights but measured the specular reflection or glare from the pavement surface.

The same pavement types previously described were tested, except that an untreated gravel macadam surface was added and the plain asphalt type was eliminated.

Figure 5 represents graphically the percentage of the total light reaching the photometer which was reflected

(Continued on page 121)

STUDY OF ROAD SUBSOILS

(A) DETERMINATION OF PROPERTIES OF SUBSOILS, TESTING METHODS, EQUIPMENT; (B) INFLUENCE OF THESE PROPERTIES ON ROAD CONSTRUCTION (BASE AND SURFACE) AND ON ROAD MAINTENANCE

By C. A. HOGENTOGLER, Senior Highway Engineer, United States Bureau of Public Roads, Principal Reporter

A STUDY of road subsoils is made quite generally by the individual highway departments of the United States in connection with the design, construction, and maintenance of their highway systems. The experience of the United States Bureau of Public Roads since the inception of its soil research program in 1920, supplemented by numerous contributions from other soil investigators in the highway field, has disclosed three major fields in which soil information and studies have distinct economic value. They are: (1) The use of the subgrade survey and the classification of soils into groups based on performance, (2) the construction of "stabilized" road surface and base courses, and (3) the construction of highway embankments.

SUBGRADE SURVEY AND SOIL GROUPING

The subgrade survey furnishes information which assists in locating the road, selecting the most satisfactory type of surface and eliminating conditions likely detrimentally to affect the serviceability of the pavement.

Examinations of the soil in its natural field condition, in excavations or road cuts or, more commonly, by means of a soil auger, are made at intervals close enough to determine the soil type and to depths sufficient to penetrate the more-or-less nonuniform layers of soil or soil material.

Representative samples obtained as part of the subgrade survey are tested in the laboratory to determine their physical properties.

The principal laboratory determinations used in the classification of subgrade soils are the mechanical analysis, and the plasticity, shrinkage, and moisture equivalent tests.

Procedures for these determinations[1] and for the surveying and sampling of soils[2] have been published by the American Association of State Highway Officials.

The groups into which subgrade soils have been tentatively arranged, are described briefly as follows:

Group A–1.—Well-graded material, coarse and fine; excellent binder. Highly stable under wheel loads irrespective of moisture conditions. Excellent surface course; excellent base course, provided plasticity index is not greater than 6; excellent subgrade for pavements of both flexible and rigid types; excellent fill material.

Group A–2.—Coarse and fine materials, improper grading or inferior binder. Highly stable when damp. Friable varieties become loose and dusty in long-continued dry weather. Plastic varieties likely to soften at high water content caused either by rains or by capillary rise from saturated lower strata when an impervious cover prevents evaporation from the top layer. Satisfactory subgrade for both flexible and rigid pavements under well-drained conditions. Satisfactory fill material.

Group A–3.—Coarse material only, no binder. Lacks stability under wheel loads, but is rarely affected by moisture conditions. Not likely to heave because of frost nor to shrink or expand in appreciable amount. Furnishes excellent support for flexible pavements of moderate thickness and for relatively thin rigid pavements. Excellent fill material if protected from erosion.

Group A–4.—Silt soils without coarse materials and with no appreciable amount of sticky colloidal clay. Has a tendency to absorb water very readily in quantities sufficient to cause rapid loss of stability even when not manipulated. When dry or damp, presents a firm riding surface which rebounds but very little upon the removal of load. May cause cracking in rigid pavements due to frost heave and failure in flexible pavements because of low supporting value. Not satisfactory for surface or base course. Generally satisfactory for subgrade or fill material under controlled conditions.

Group A–5.—Similar to Group A–4, but furnishes highly elastic supporting surfaces with appreciable rebound upon removal of load even when dry. Elastic properties interfere with proper compaction of macadams during construction and with retention of good bond afterwards.

Group A–6.—Clay soils without coarse material. In stiff or soft plastic state absorb water only if manipulated. May then change to liquid state and work up into the interstices of macadams or cause failure due to sliding in high fills. Furnish firm support essential in properly compacting macadams only at stiff consistency. Deformations occur slowly and removal of load causes very little rebound. Shrinkage properties combined with alternate wetting and drying under field conditions are likely to cause cracking in rigid pavements.

Group A–7.—Similar to Group A–6, but at certain moisture contents deforms quickly under load and rebounds appreciably on removal of loads, as do subgrades of Group A–5. Alternate wetting and drying under field conditions leads to even more detrimental volume changes than in Group A–6 subgrades. May cause concrete pavements to crack before setting and to crack and fault afterwards.

Group A–8.—Very soft peat and muck incapable of supporting a road surface without being previously compacted.

The test data limits which identify soils of the different groups have been discussed elsewhere.[3]

Subdivisions of Groups A–5, A–6, A–7, and A–8.—All varieties of Groups A–5, A–6, A–7, and A–8 are unsuitable for surface or base courses. Soils of these groups having liquid limits of 45 or less are suitable for

[1] Methods T–87, T–88, T–89, T–90, T–91, T–92, T–93, and T–99. Standard Specifications for Highway Materials and Methods of Sampling and Testing. American Association of State Highway Officials. Washington, D. C., 1935.

[2] Standard Method of Surveying and Sampling Soils for Use in Place as Subgrades for Highways. Method T–86, Standard Specifications for Highway Materials and Methods of Sampling and Testing. American Association of State Highway Officials, Washington, D. C., 1935.

[3] Subgrade Soil Constants, their Significance and their Application in Practice, part II. A discussion of the Soil Constants and the Soil Identification Chart. C. A. Hogentogler, A. M. Wintermyer, E. A. Willis, PUBLIC ROADS, vol. 12, No. 4, June 1931.

subgrade and fill material under controlled conditions. Soils of these groups having liquid limits greater than 45, but not greater than 65, are poor materials for subgrades or fills and should be used only under rigidly controlled conditions of moisture content and compaction. Soils of these groups having liquid limits greater than 65 are unsuitable for subgrade and fill construction.

STABILIZED ROAD SURFACE AND BASE COURSES

Thousands of miles of "stabilized" road surface and base courses have been built in the United States with results which justify the continuance of this type of construction.

The methods of soil stabilization utilized depend on the materials locally available. In some locations, such as the southeastern part of the United States, nature provided deposits of sand-clay and top soil having the grading and character required in the best of soil roads or base courses.

In other locations, binder soils and aggregates are available for producing mixtures having the properties of the best naturally good soils. At times materials are available for the gradations required in roads, but the binder soil may be of inferior quality. Finally, there are locations where there is a deficiency of the aggregate required for properly graded mixtures.

Studies of the best natural road soils have indicated that the design requirements of stable soil mixtures should include the following:

1. The aggregate should be hard and durable enough to resist weathering, traffic abrasion, and crushing. Sound, tough particles or fragments of gravel, stone, slag, or combinations of them, crushed to the proper size, should prove suitable. Certain types of shales and similar materials that break and weather rapidly when alternately frozen and thawed, or wetted and dried, should not be used.

2. The binder material of the soil, known as fines, should be of a character such as to provide graded mixtures with the proper balance of capillarity and adhesion without risk of detrimental volume change. It is particularly essential that the fines do not swell enough in the presence of moisture to cause the clay to become a lubricant instead of a binder.

3. When local materials are available for the proper proportioning of aggregate and binder soil, but the natural clay does not have the binder value required in highly stable road surfaces, a number of admixtures may be used singly or in some combination. There are, first, the chemical salts, calcium chloride, sodium chloride, and magnesium chloride; and second, the waste products of industry, such as sulfite liquor from the manufacture of wood pulp, sucrate liquor from the molasses industry, and huge accumulations of waste sizes of the mineral aggregate industry.

4. When only fine or poorly graded materials are available, the asphaltic, tar, and portland cement binders may be utilized to provide stable base courses to be covered with bituminous surfacings. In isolated cases, clay soils have been heated to high temperatures by specially constructed furnaces which are moved slowly over the locations to be improved.

GRADED SOIL MIXTURES

The suitability of graded mixtures has been determined by means of sieve analysis of the aggregate retained on the No. 10 sieve, combined sieve and hydrometer analysis (Method T–88, A. A. S. H. O.) of the fraction passing the No. 10 sieve, and the plasticity tests (Methods T–89, T–90, T–91, A. A. S. H. O.) performed on the fraction of the material passing the No. 40 sieve, an effort being made to combine materials in such quantities that the resulting mixture will conform to the requirements of stabilized road surfaces or bases.

Specifications proposed to the American Association of State Highway Officials for both surface and base course materials contain essential requirements as follows:

1. Surface course.

Type A.—Sand-clay mortar.

Passing—	*Percentage by weight*
1-inch sieve	100
No. 10 sieve	65–100

The material passing the No. 10 sieve should have gradings as follows:

Passing—	*Percentage by weight*
No. 10 sieve	100
No. 20 sieve	55–90
No. 40 sieve	35–70
No. 200 sieve	8–25

Type B.—Coarse graded aggregate.

Passing—	*Percentage by weight*
1-inch sieve	100
¾-inch sieve	85–100
⅜-inch sieve	65–100
No. 4 sieve	55–85
No. 10 sieve	40–70
No. 40 sieve	25–45
No. 200 sieve	10–25

Type C.—Crusher run materials.

Passing—	*Percentage by weight*
¾-inch sieve	100
No. 4 sieve	70–100
No. 10 sieve	35–80
No. 40 sieve	25–50
No. 200 sieve	8–25

The fractions of surface course materials, A, B, and C, passing the No. 200 sieve should be less than ⅔ of the fraction passing the No. 40 sieve. The fraction passing the No. 40 sieve should have a liquid limit not greater than 35 and a plasticity index not less than 4 nor more than 9.

2. Base course.

Type A.—Sand-clay.

Passing—	*Percentage by weight*
No. 10 sieve	100
No. 20 sieve	55–90
No. 40 sieve	35–70
No. 200 sieve	8–25

Types B–1 and B–2.—Coarse graded aggregate. (See table 1.)

TABLE 1.—*Grading of base course aggregates, types B–1 and B–2*

Passing—	B–1 1-inch maximum size	B–2 2-inch maximum size
	Percent [1]	*Percent* [1]
2-inch sieve		100
1½-inch sieve		70–100
1-inch sieve	100	55–85
¾-inch sieve	70–100	50–80
⅜-inch sieve	50–80	40–70
No. 4 sieve	35–65	30–60
No. 10 sieve	25–50	20–50
No. 40 sieve	15–30	10–30
No. 200 sieve	5–15	5–15

[1] By weight.

The fraction of base course materials, A, B, and C, passing the No. 200 mesh sieve should be less than ½ of the fraction passing the No. 40 sieve. The fraction passing the No. 40 sieve should have a liquid limit not greater than 25 and a plasticity index not greater than 6.

Type C—Crusher-run materials.

Passing—	*Percentage by weight*
¾-inch sieve	100
No. 4 sieve	70–100
No. 10 sieve	35– 80
No. 40 sieve	25– 50
No. 200 sieve	8– 25

STANDARD METHOD OF TEST FOR DENSITY OF SOIL

In stabilizing fine grained soils with an adhesive binder such as portland cement or bituminous material, it is necessary to compact them to high density. This is best accomplished at a definite moisture content, known as the optimum, for each mixture. The test used to determine the optimum moisture content is known as the density test [4] and is described as follows:

1. *Apparatus.*—The apparatus shall consist of the following: A cylindrical metal mold, known as the density or Proctor cylinder, approximately 4 inches in diameter and 4½ inches in height and having a capacity of 1/30 cubic foot. This mold is fitted with a detachable base plate and a removable extension approximately 2½ inches in height.

A metal tamper having a striking face 2 inches in diameter and weighing 5½ pounds.

A steel straightedge 12 inches long.

A scale of 25-pound capacity sensitive to 1/100 of a pound.

A 100-gram capacity balance sensitive to 1/10 gram.

A suitable drying oven.

Miscellaneous equipment including porcelain dishes for moisture determinations, beakers, etc.

2. *Sample.*—A 6-pound sample, air dried to slightly damp condition, shall be taken from a portion of the material passing the No. 4 sieve.

3. *Procedure.*—The sample is thoroughly mixed and compacted in the cylinder in 3 equal layers, each layer receiving 25 blows from the tamper which is dropped from a height of 1 foot above the soil. The soil is then struck off to the level of the cylinder and the weight determined. A small sample of the compacted soil is oven dried to determine the moisture content. The soil is removed from the cylinder and broken up until it will pass a No. 4 sieve, water is added, and the above procedure is repeated. This series of determinations is continued until the soil becomes very wet and there is a substantial decrease in the wet weight of the compacted soil.

4. *Calculations.*—The moistures shall be computed by means of the following formula:

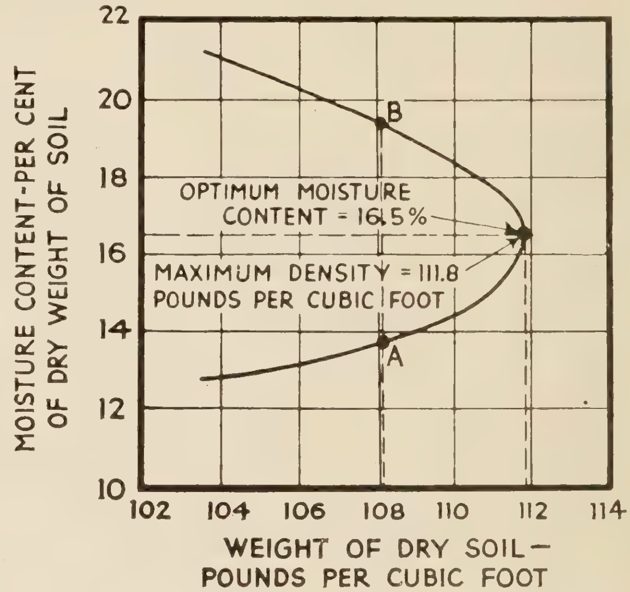
$$\text{Percent moisture} = \frac{\text{weight of water}}{\text{weight of oven dried soil}} \times 100$$

The dry weight shall be computed by means of the following formula:

$$\text{Dry weight} = \frac{\text{wet weight in pounds per cubic foot}}{\text{percent of moisture} + 100} \times 100$$

The results of the compaction test, corrected for weight of moisture and expressed as pounds of dry soil per cubic foot, are plotted against their respective moisture contents and a smooth curve drawn through the resulting points. The peak of the curve represents the maximum density for the given material under the above compaction. The percentage of water at which maximum density is attained is termed the optimum moisture content.

[4] Stabilized Soil Roads. C. A. Hogentogler and E. A. Willis, PUBLIC ROADS vol., 17, No. 3, May 1936.



MOISTURE-DENSITY CURVE SHOWING TYPICAL RESULT OF SOIL DENSITY TEST.

STABILIZATION WITH PORTLAND CEMENT

Soils.—The soils for this work consist of the material in the subgrade within the lines, grades, and cross sections indicated on the plans, except as otherwise designated by the engineer. Soils are sampled and tested in accordance with the requirements of the A. A. S. H. O. methods T–86 to T–94, inclusive. Soils having characteristics which will make pulverization and mixing with cement extremely difficult are removed and replaced with suitable soil obtained from borrow pits shown on the plans.

Design of soil and cement mixture.—The percentage of cement as based on compacted dry soil volume is determined by mixing the soil and cement in several arbitrarily chosen proportions (4.6 and 8 percent cement have been found satisfactory for most soil types).

The optimum moisture content and maximum density for each mixture are found by means of the Standard Method of Test for Density of Soil. When the optimum moisture content for each mixture has been found, 4 specimens of each mixture are prepared in the Proctor cylinder. Two of the specimens are subjected to alternate wetting and drying and 2 to alternate freezing and thawing.

One cycle of wetting and drying consists of 8 hours wetting by immersion at room temperature, 15 hours drying at 300° F. and 1 hour cooling at room temperature.

One cycle of freezing and thawing consists of 8 hours wetting by immersion at room temperature; 16 hours freezing at 20° F. (or lower); 8 hours thawing at room temperature; 15 hours drying at 300° F.; and 1 hour cooling at room temperature.

After each cycle of wetting and drying or freezing and thawing, one specimen is brushed with a wire brush to remove visible loose particles, and the other is left undisturbed.

The weight and dimensions of all the specimens are recorded after each cycle. The volume change of each specimen is calculated and recorded. A loss of 50 percent by volume of any specimen is considered as the point of failure. Failure in less than 15 cycles of wetting and drying and less than 10 cycles of freezing and thawing is considered as the standard for the elimination of any soil-cement mixture for use in base course construction.

The moisture-compaction curve for the cement-soil mixture chosen is used in obtaining the required moisture and compaction during construction.

STABILIZATION WITH BITUMINOUS BINDERS

Bituminous materials used in the stabilization of fine-grained or poorly graded soils for use in road bases may be arranged in 3 groups as follows: (1) emulsions, (2) tars, and (3) road oils and cut-backs.

Soil-emulsion mixtures.—Absorption and stability tests have been largely used in determining the proper amount of bituminous emulsion to be used in the stabilization of fine grained soils.[5]

Preparation of samples.—Samples of soil as received from the field are dried, broken up and passed through a ¼-inch screen. The material passing is quartered and plastic limit, liquid limit, and particle size determinations are made. Mixes are made using various arbitrary percentages of emulsion. The soil is mixed with diluted stabilizer, or first with water and then with stabilizer, until the asphalt is uniformly distributed and the mass is at a consistency between the plastic and liquid limits.

The mixed soil is allowed to dry to a stiff molding consistency and is tamped into 2-inch metal molds 4 inches long. After further drying, but while still slightly damp, it is compressed, usually under a load of 1,000 pounds per square inch, and is then pressed out of the mold and placed in a drying oven or cabinet and maintained at about 140°F. until at a constant weight. Mixing may be done by hand or with any suitable equipment and the details of the tamping and compacting methods are unimportant because the ultimate compaction and density are obtained by shrinkage during the drying operation.

Absorption test.—The specimens prepared and dried are then ready for the capillarity absorption test.

The absorption test is made in a closed cabinet containing pans filled first with a layer of standard Ottawa sand and then a layer of diatomaceous earth covered with blotting paper, with water-feeding apparatus which keeps the water level exactly at the under side of the blotting paper.

Although the humidity within the cabinet remains very high due to the continuous evaporation of water, the individual specimens are wrapped in cellophane on the sides and covered on top with foil or shallow aluminum cups slightly larger in diameter than the specimen. This prevents the escape of any water taken up by capillarity, and is believed to approximate the exposure of any 2-inch cylindrical portion of stabilized soil in a base where it is exposed to water at the under side, where evaporation is prevented by the surrounding stabilized soil, and where surface evaporation is restrained by surfacing.

[5] Soil Stabilization with Emulsified Asphalt. C. L. McKesson. Proceedings Fifteenth Annual Meeting of the Highway Research Board, December 1935.

Specimens are usually removed for daily weighings and the period of test may be 7 to 90 days. It will be found that the absorption decreases rapidly after the first day because the capillarity of stabilized soil is very low.

Great care must be observed in removing specimens from the blotter to prevent loss of weight in the specimen due to portions adhering to the blotter. This is particularly true in the untreated specimens which take up water quickly and become soft and noncohesive. Any portion of the specimen remaining on the blotter must be removed and replaced on the bottom of the specimen before each weighing. The necessity for doing this can be avoided by placing a disk of saturated filter paper under the specimen when it is first placed on the blotter and then weighing the specimen with the filter paper each time. The weight of the saturated filter paper is, of course, added to the initial weight of the dry specimen, which weight also includes the cellophane wrapper and the cover.

The stability test apparatus consists of a heavy steel cylinder 2$\frac{1}{16}$ inches in inside diameter and 4 inches or more high. It is provided with a tool-steel orifice plate at the bottom, the orifice having an area of exactly 1 square inch and beveled downward from the cutting edge. A plunger 2 inches in diameter and a supporting frame complete the apparatus.

To make the test the specimen is placed in the cylinder with the orifice plugged. The equipment is placed in a compression machine and a total load of approximately 3,000 pounds is applied to press the specimen down into contact with the sides of the cylinder and the orifice plate. The plug is then removed, marks are made at ½-inch intervals on the plunger and the load applied at a rate sufficient to move the plunger ½ inch per minute. The load is read as each ½-inch mark is reached, and consequently at the completion of the extrusion of each ½-inch stratum.

The maximum load applied in making the stability test should usually be about 25,000 pounds (approximately 8,000 pounds per square inch), but if desired this may be increased to about 40,000 as the apparatus is designed to withstand this total load. The test is intended to measure resistance to displacement by plastic flow, and a specimen which resists displacement under a load of 8,000 pounds per square inch is virtually a solid and may be so regarded. Test values beyond this limit are not usually significant as an index of plasticity.

Soil-tar mixtures.—Tests for determining the amounts of tar to be used for stabilizing the various types of soil are as yet in a state of development, the most important source of information of this kind being now furnished by studies of experimental road sections. The density tests are largely used for determining the amount of water required in such mixtures.

Road oil and cutbacks.—The amounts of asphaltic oils and cutbacks required to stabilize soils for use in base courses have been determined chiefly from considerable mileages of experimental roads constructed mainly in Missouri.

HIGHWAY EMBANKMENTS

Specifications proposed to the American Association of State Highway Officials for embankment soils contain essential requirements as follows:

Condition 1.—Fills not exceeding 10 feet in height which are not to be placed on steep sloping foundations, and which are not subject to long periods of inundation.

Liquid limit, not greater than 65.

For soil with liquid limits less than 65, the plasticity index should be not less than that determined by the formula 0.6×liquid limit−9.0.

The soils are rated as to maximum dry weights in table 2.

TABLE 2.—*Soils rated as to maximum dry weights for condition 1*

Maximum dry weight (lb/cubic foot)	Approximate Bureau of Public Roads classification	Rating	Minimum field compaction requirement in percentage of maximum dry weight
			Percent
89.9 and below	A-5, A-8	Unsatisfactory	
90.0- 99.9	A-5, A-8	Very poor	95
100.0-109.9	A-6, A-7	Poor	95
110.0-119.9	A-4	Fair	90
120.0-129.9	A-3, A-2	Good	90
130.0 and above	A-1	Excellent	90

Condition 2.—Fills exceeding 10 feet in height, or which may be placed on steep sloping foundations, or which are subject to periods of inundation.

Liquid limit, not greater than 50.

The soils are rated as to dry weights in table 3.

TABLE 3.—*Soils rated as to maximum dry weights for condition 2*

Maximum dry weight (lb/cubic foot)	Approximate Bureau of Public Roads classification	Rating	Minimum field compaction requirement in percentage of maximum dry weight
			Percent
99.9 and below	A-5, A-8	Unsatisfactory	
100.0-109.9	A-6, A-7	Very poor	100
110.0-119.9	A-4	Poor	95
120.0-129.9	A-3, A-2	Fair	90
130.0 and above	A-1	Good	90

ESSENTIAL FEATURES OF CONSTRUCTION

Subgrades.—It has been found economical to separate different classes of materials excavated in grading operations and replace them in the constructed fills in such way that the better materials will be placed next to the pavement. This has been found beneficial for reducing the destructive effects of frost heave in silty soils and the volume change of clay soils.

One of the most successful methods used for overcoming the detrimental heaving due to frost prevalent in the northern part of the United States consists of replacing the material which heaves with selected granular materials. Very fine sands and silts characterized by a lack of cohesion and high water-holding capacity should be replaced generally with the better soils. Such soils are easily identified by visual inspection during the subgrade survey. During the grading operations, the silty soils have been excavated for a depth of as much as 3 feet and the selected material, usually locally available, has been compacted in their place. It has been found necessary to provide proper drainage so that the replaced material does not become saturated.

Several of the States require soils of the A-5, A-6, A-7 and A-8 subgrade groups, which have been found to be inferior materials for the construction of fills and subgrades, to be covered when used as subgrades with better soils. Usually a minimum depth of 1 foot has been required and in many cases, 18 inches to 2 feet.

In some cases plastic soils used for subgrades have been compacted at a controlled moisture content prior to the construction of the surface.

CONSTRUCTION OF STABILIZED ROADS AND BASES WITH GRADED MIXTURES

The essential construction features have to do with the proper mixing of materials, compaction and, in the case of bituminous admixtures, control of moisture content. By road mixing methods, it has been found possible to furnish graded mixtures with a uniformity such that the variation in the plasticity index of the finished road does not exceed 3. It is possible that the same degree of uniformity can be obtained, especially in the more plastic soils, by plant-mixing methods at little or no extra cost. Mixing on the road is facilitated by having the materials dry. It seems that adequate compaction can be attained in chemically treated mixtures with 8 to 12 percent moisture content.

The density of road surfaces can be expected to increase under traffic after construction. In bases an effort should be made to obtain a high degree of compaction during construction if the tops are to be applied soon afterward. It seems that the dry weight per cubic foot of the compacted materials should be at least 130 pounds before the application of the bituminous surface treatment.

When a highway is built on a new location, a sufficiently wide roadbed or subgrade is first constructed, using available materials. Loose, sandy subgrades should be improved by the addition of soil binder; soft, unstable subgrades should be improved by the addition of granular material. The added material should be thoroughly mixed into the subgrade by harrowing or blading, after which the subgrade is brought to true alinement and grade by blading and rolling. Excess subgrade material that is suitable for use as binder for the wearing course can be bladed to the shoulders of the road and left in windrows during the preparation of the subgrade.

When an existing highway is improved, material is added or taken away to obtain the desired width, grade, and alinement. Soil binder or granular material is added in sufficient amount to obtain a stable mixture, and is thoroughly mixed into the subgrade by harrowing or blading.

There are two methods for obtaining the desired mixture—plant mixing and road mixing.

Plant mixing.—The essential requirements for plant mixing are a source of satisfactory binder in close proximity to the supply of coarse aggregate to be used; means for drying and pulverizing the binder; apparatus for measuring the quantities of binder and aggregate to obtain the proper proportions; and equipment for thorough mixing of the combined materials.

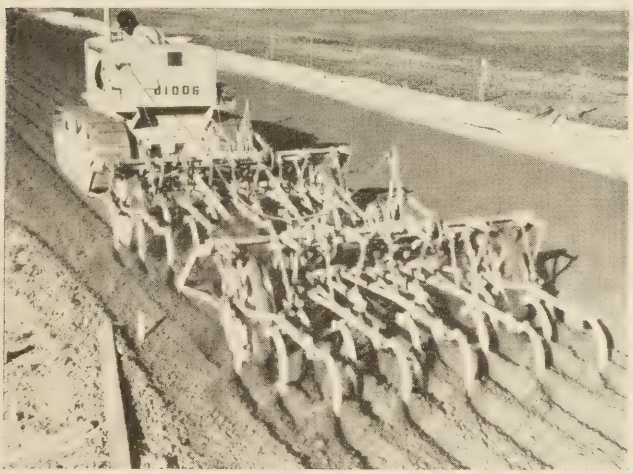
An ideal location for a mixing plant is one near a place where the overburden consists of a clay soil having satisfactory binder properties. This overburden may be stripped and stockpiled in windrows so that it will dry sufficiently to be pulverized under a roller. The clay should then be combined with an aggregate of proper grading in such proportions that the resulting mixture will conform to the specifications. Thorough mixing should be provided by means of a pugmill or rotary-type mixer.

In some plant mixes, bank-run gravel and the existing overburden have been used and the drying and pulverizing steps have been eliminated by passing the combined materials through a rotary screen or over a grill to remove oversize material.

The mixture is hauled to the road, spread, sprinkled, shaped, and rolled. The principal advantage of the plant-mix method is that it effects a thorough mixing of the binder and aggregate.

Road mixing.—The necessary equipment for mixing materials on the road includes tractor-drawn or self-propelled blade graders, scarifiers, harrows, and other apparatus for mixing, moistening, spreading, and compacting the base- and wearing-course materials.

Scarifiers may either be mounted on special four-wheel vehicles or may be attached to the roller. Disk harrows should be so designed that unintended cutting into the subgrade can be avoided. Either the spring- or spike-tooth harrows, that assure positive control of the depth to which the teeth will penetrate, are satisfactory. For mixing and shaping, power-drawn blade graders with a wheelbase of not less than 16 feet are satisfactory.



A Spring-Tooth Harrow Which Permits Positive Control of the Depth of Penetration of the Teeth.

The surfaces of existing roads should be scarified deep enough to eliminate all irregularities of the surface and to permit reshaping to grade. After the loosened material is shaped to grade, the surface should be scarified to a uniform depth. New material, if required, should be spread on the loosened surface in amount sufficient to furnish a compacted layer of approximately 3 inches. If greater surface thickness is desired, additional layers should be constructed.

The material should be mixed, until uniform throughout, by means of harrowing and turning with blade graders. The water required to obtain the proper moisture content in the wearing course should then be supplied in the following manner: The dry mixture of binder and gravel should first be bladed onto the shoulders of the road. The exposed base should then be moistened uniformly using a suitable sprinkler, and approximately one-fourth of the material from the shoulder windrows should then be bladed immediately onto the moistened base. The newly distributed road material should then be similarly moistened and covered as before with one-fourth of the original windrowed mixture, and similar operations repeated until the last fourth of the dry mixture has been placed.

A Pneumatic-Tired Roller Especially Devised to Consolidate Stabilized Soil Surfaces.

Any means of applying adequate load, whether it be a flat-wheeled roller, a crawler-type tractor, truck graders, other trucks, or any vehicular traffic, will assist in the compacting of graded mixtures. After shaping and initial compacting are completed, the road should finally be thoroughly dampened and again compacted.

During the period of final compaction, loose material should be kept distributed over the road surface by means of a road drag or blade grader. The amount of crown maintained by blading operations should be sufficient to provide for the rapid run-off of rain and prevent the formation of pools of water on the road surface. Pitting of the surface is an indication that the crown is too slight.

Chemical admixtures.—In plant mixing, calcium chloride is generally added to the mixture at the plant. In road mixing, calcium chloride is applied in the following manner:

After the new and old soil materials have been spread over the prepared base in sufficient thickness, they should be covered uniformly with flake calcium chloride in the amount of ½ pound per square yard per inch of thickness, with a maximum of 2 pounds per square yard. The spreaders should be capable of spreading the chemical uniformly and in the desired quantities. The calcium chloride is then thoroughly worked into the soil by harrowing and blading until the surfacing material is uniform throughout. Sprinkling and shaping into a finished surface is then accomplished in the same manner as in the case of the untreated roads already described.

Calcium chloride should not be applied during periods of cold, wet weather. The most favorable time for a surface application of calcium chloride is during the drying period just following a rain, after the surface has been bladed to proper smoothness. The moisture in the road at that time hastens solution and penetration. In the absence of rain, application in the early hours of the day, when the air has high relative humidity, is very desirable. Calcium chloride applied just prior to a rain will probably be washed off the road and consequently afford little or no benefit. When blading of the calcium-chloride treated road is required, it should be done after rains or commenced near the end of a rain. At other times, the surfaces may be too hard. For patching holes an admixture of 100 to 150 pounds of calcium chloride per cubic yard of graded soil is recommended.

Need for extensive patching of stabilized soil surfaces during dry weather can be minimized or eliminated by periodic maintenance with light applications of calcium chloride during the dry season.

In the use of calcium chloride as a dust palliative, it has long been known that this material remains effective for much longer periods in gravel having a clay binder than in gravel having a sandy filler. It has also been apparent that the presence of loose gravel tends to shorten the useful life of a treatment. The intermittent movement of such loose gravel by traffic and maintenance operations exposes new surfaces to the air and promotes evaporation.

Sodium chloride may be added at the plant for a plant-mix or to the mixture on the road for a road-mix. Rock salt has been used most generally, but any commercial type of pure salt or salt brine is satisfactory. The coarser grades of rock salt are well adapted for stabilization, as they remain free-flowing and can be more uniformly spread than the finer gradations, which will absorb mositure and cake when stockpiled along the road. The salt should contain not less than 98 percent of pure sodium chloride.

When sodium chloride is applied in the form of brine, any gradations of the salt may be used, since the condition of the salt before it is dissolved is unimportant. The stabilized mixture will remain plastic longer if all of the salt has been dissolved, thus permitting rolling and compacting to be continued over a long period of time with the possibility of attaining greater ultimate compaction. There should be enough water to moisten the soil somewhat above the plastic limit.

Water is usually added by means of pressure distributors, sprinkler wagons, or gravity tank trucks. It is preferable to make several trips over the section under construction, sprinkling lightly on each trip. This gives the moisture a chance to penetrate sufficiently and does not create a sloppy condition on the surface. The amount of salt used varies somewhat in the different States. The usual amount is about 2 pounds per square yard per 3-inch thickness of road constructed.

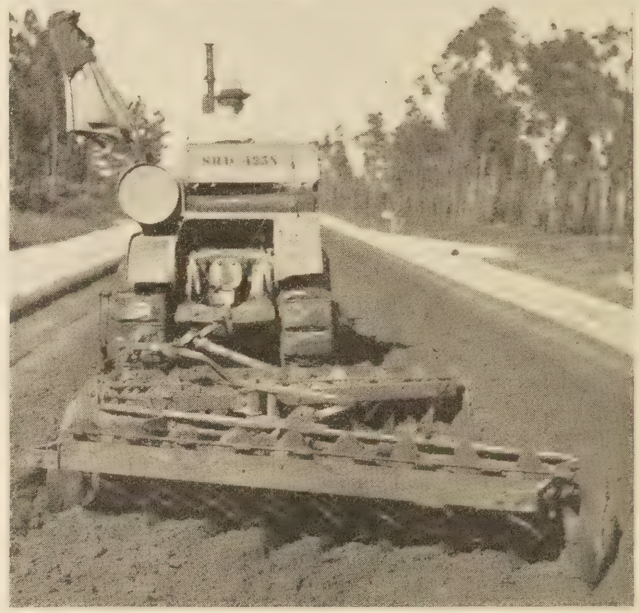
During prolonged dry periods, the fine aggregate may wear off of a sodium chloride treated surface, leaving the larger aggregate particles protruding. This condition can be corrected by covering the surface to a depth of about ½-inch with properly proportioned soil mixtures containing about 100 pounds of sodium chloride per cubic yard. When damp the mixture makes a satisfactory bond with the worn surface without scarification.

If, during periods of rainfall, the top eighth or quarter of an inch of stabilized roads becomes plastic, crushed aggregate should be added to the surface in amounts of about 50 to 70 tons per mile. This aggregate should have a maximum size of about ½-inch and should be free from dust and sand. The material should be spread over the surface and kept uniformly distributed as long as the surface is wet. The thin surface layer of fine material acts as a cementing agent for the coarse aggregate that has been added. This results in a satisfactory driving surface, adds some additional thickness to the road, fills up any depressions that may have developed, and reduces the tendency for pot holes to form.

CONSTRUCTION OF CEMENT STABILIZED BASES

The construction of a cement stabilized base, recently developed experimentally in South Carolina, is summarized as follows:

1. *Pulverizing the soil.*—The soil on the road was effectively scarified to the desired depth with a tooth-scarifier and then pulverized with a disk harrow assisted by a sheepsfoot roller where dry, hard lumps of soil were encountered.



A TRACTOR-DRAWN DISK HARROW.

2. *Spreading cement.*—The cement was spread by means of a sand spreader; which was attached to and pulled by loaded dump trucks containing a known quantity of loose cement. Considerable time was lost in spreading as each time a truck was emptied, it was necessary to unfasten the spreader and attach it to the next loaded truck. The moisture content of the soil should be below the optimum required for compacting, as high moisture contents cause the cement to form into balls.

3. *Mixing cement with dry soil.*—A disk harrow was first run slowly over the freshly spread cement in order to mix it partially with the loose soil. The cement flowed into the furrows cut by the disks, and if the disks were allowed to cut below the depth to be treated, the cement would flow into the bottom of the furrows and be lost, as the other mixing equipment would not cut into the hard subgrade. Mixing was completed by using a road machine and multiple-blade drag simultaneously. The drag followed the road machine and mixed the roll of material turned up by the road machine blade. Mixing in this way was first performed on the edges and continued through the middle. Approximately 12 trips of each machine were required for the dry mixing.

4. *Application of water.*—Water was applied with an asphalt distributor of 1,000 gallons capacity. This quantity of water was spread uniformly over the surface in one trip. The distributor was filled at each end of the section by feeder trucks.

5. *Mixing.*—After each application of water the materials were partially mixed with a 20-inch disk harrow pulled as rapidly as possible by a 75-horsepower crawler-tread tractor. For most efficient mixing, it was found that the disk harrow should be operated at a high speed so that the disks would throw the material instead of merely cutting into it. On sections 6 inches thick, it was necessary to store approximately ⅓ of

the dry mixture on the shoulders and apply the mixing water to that remaining in the bottom layer, then bring in the stored material from the shoulders and mix water with it. In order to wet the mixture efficiently at the edges of the road, approximately 3 feet of the mixture near the edges was pulled toward the center of the road when the stored material was brought in from the shoulders. After the water had been mixed with this material, the mixture was spread back to the edges before compaction was started. The entire section was then loosened to the bottom with a disk harrow so that the sheepsfoot roller could begin compaction at the bottom.

6. *Compaction.*—The sheepsfoot roller used for this operation was pulled by a tractor which was operated slowly for the first few trips so that the feet of the roller could penetrate the mix easily and compact the material from the bottom upwards. The roller was then operated at a higher speed in order to obtain the benefit of dynamic forces in the compaction. It usually required about 3½ hours for one roller to work itself to the surface of an 800-foot section of road. It was found that the moisture content of the soil below the treatment and of that on the shoulders must be at the optimum or below to obtain satisfactory compaction. The operation of the sheepsfoot roller on soft subgrades produces numerous fine cracks throughout the compacted surface. Usually about 1 inch of loose material remained on the surface when the sheepsfoot roller had compacted the mix as much as possible, and this loose material was shaped with a road machine to the correct cross section and rolled with loaded trucks.

7. *Finishing.*—The finishing operation consisted of blading the surface to the correct grade and cross section with a hand-operated road machine. This operation determined the riding quality of the section and was done by very skillful operators. This work was partly done during compaction and completed before the trucks had finished rolling the surface. It was found that the road machine blade would not cut the surface of the hardened base the day after it was constructed, and, therefore, it was necessary that the surface be finally shaped as soon as possible after compaction.

CONSTRUCTION OF TAR STABILIZED BASE

The construction of an experimental road in South Carolina in which coal tar was used as a stabilizing agent,[6] has been described as follows:

The soil in this project, practically all of which passed the No. 10 sieve, contained about 16 percent silt and 28 percent clay (by elutriation). Other characteristics were approximately as follows: Liquid limit 28, plasticity index 13, field moisture equivalent 19, shrinkage limit 15, specific gravity 2.57, and volume change 23.

The total amount of tar used was 3.73 gallons per square yard of base 6 inches in compacted thickness. Of this quantity of tar 1.48 gallons was 4 to 8 viscosity (Engler) and the remainder 26 to 36 viscosity (Engler). The lighter tar was applied and thoroughly mixed with the soil before the heavier tar was used.

It was found that small lumps of clay soil did not cause trouble if the lumps were surrounded by material impervious to water and protected from traffic.

It was noticed that soil mixed with low-viscosity tar alone repelled water so completely that rain for from 2 to 9 days did not penetrate windrows of the mixture more than ¼ inch.

Three different sections contained, respectively, 2.9 percent, 7.5 percent, and 5.8 percent moisture when mixed with the low-viscosity tar. It was noticed that the section with 7.5 percent moisture had a "slightly grayish tinge" during mixing rather than the "deep black cast" that had been observed on the section containing 2.9 percent moisture. Furthermore, it appeared to be lean and dusted under traffic. It was thought that the differences in appearance and behavior of these two sections undoubtedly were due to the fact that the greater moisture content of the second section caused the tar to penetrate the soil, and particularly lumps of soil, more completely in that section.

The equipment used on this project consisted of a disk harrow, tractors and blade graders, retread machine, pressure distributor, and trucks.

Soon after this project was completed the heavier tar was applied to the surface at the rate of 0.26 gallon per square yard and covered with sand. No other cover has been applied since completion 2 years ago.

CONSTRUCTION OF EMULSION STABILIZED BASE

The construction of a soil surface with admixture of bituminous emulsion [7] has been described as follows:

Laboratory studies indicated that the natural adobe clay soil could be stabilized to a depth of 3 inches with about 3 gallons of 55 percent emulsified asphalt. By adding 2 parts of quarry waste to 1 part of the clay, stabilization was accomplished with 1 gallon of emulsion per square yard, a saving after paying for the quarry waste of about 5 cents per square yard. The construction methods were as follows:

The quarry waste was uniformly spread on the clay subgrade to a loose depth of 1¼ inches and scarified into the natural clay. The loose mixture was 4½ inches thick. The clay and quarry waste were well mixed by harrowing.

The soil mixture was first dampened with about 2 gallons per square yard of water and the water was mixed in by harrowing. The emulsified asphalt was then applied, after dilution with 4 parts of water. The diluted emulsified asphalt was applied in 6 applications. After the first application, the mixture was harrowed and the top inch and a half of the mixture was bladed to the sides. These operations were repeated after the next 2 applications. The soil mixture was then in 2 windrows on the sides and was distributed back over the road in 3 spreads with application of dilute emulsion to each.

To obtain thorough mixing, the soil-emulsion mixture was again bladed into windrows, then brought back in thin layers, and finally shaped to the required cross section. The tractor used to pull the mixing equipment had by this time fairly well compacted the road surface.

One gallon of emulsion and 6.2 gallons of water were used per square yard, including the water used in the preliminary dampening operation. This completed the soil stabilization and there remained only the surface treating.

The surface was then given an application of approximately ¼ gallon per square yard of the emulsion, diluted with an equal part of water and immediately covered with 40 pounds per square yard of ½ to ¼-inch crushed stone. This was followed by rolling of the surface which embedded the crushed stone in the

[6] Soil Stabilization with Bituminous Materials in South Carolina, J. S. Williamson, Convention Proceeding 1935-36 of the American Road Builders' Association.

[7] New Developments in Asphalt Construction, C. L. McKesson, Association of Highway Officials of the North Atlantic States, New York City, February 26, 1937

stabilized soil mixture. A final application of 0.64 gallon per square yard of undiluted emulsified asphalt was then spread and immediately followed with 15 pounds per square yard of ¼ inch to No. 10 sieve crushed stone, followed by brooming and rolling.

STABILIZATION WITH CUTBACKS AND ASPHALTIC OILS

An experimental stabilized road in Jackson County, Missouri, was compacted by traffic. Asphaltic materials used as stabilizers were introduced at desired depths below the surface of the loose road mix by means of a specially constructed "sub-oiler." [8] This device is essentially a tooth scarifier having an oil line attached to the back of each tooth and running nearly to its point.

The theory underlying this procedure has been that as moisture evaporates from the overlying soil, the moisture films will be replaced by liquid asphalt. Roads consisting of heavy, sticky clay or gumbo types of soil became water resistant after treatment in this way and were unaffected by rains.

Another method for incorporating the asphalt into the soil was tried in Missouri during 1935.[9] The clay surface was scarified and the loosened material windrowed and mixed with the desired percentage of bituminous material by means of a traveling mixing plant.

Varying quantities of coarse aggregates were added to the soil to obtain information as to the physical and economical effects of the use of such materials. The conclusion reached was that percentages of aggregate may be varied to obtain economy dependent upon the relative costs of aggregate and bituminous materials, since the addition of material larger than the No. 40 sieve permits a proportional decrease in oil.

About 35 gallons of water per cubic yard of mixed material were added to facilitate mixing in the pug mixer. The sections that had time to dry prior to freezing carried traffic with little or no sign of distress, although there was some evidence of a sponginess or rubbery action indicating that future additional consolidation would and should take place.

SUMMARY

The study of road subsoils has been utilized in the following ways in the United States:

1. The subgrade survey and subgrade classification has been used in the location and design of highways and particularly in the prevention of (*a*) frost heaving and (*b*) excessive pavement breakage and faulting.
2. The testing methods described have been employed in the design and construction of stabilized road surfaces and base courses of (*a*) the graded type and (*b*) the fine-grained type in which an adhesive binder such as portland cement or bitumen has been used.
3. The density tests as described have been used for the selection and control of construction of fills.
4. Special investigations have been made for the solution of foundation problems.
5. The problem of constructing stable bases for light bituminous surface treatment has been extensively investigated by the State Highway Department of the State of Missouri. This work has included mechanical stabilization (clay-aggregate stabilization), portland cement, bituminous, and mixed bituminous and mechanical stabilization.

(*a*) It is indicated that all the methods employed may be successful but the relative economy of various methods depends on local conditions associated with the project. Mechanical stabilization assumes the availability of an ample aggregate supply. Economy limits cement stabilization to soil types requiring a relatively small amount of cement. In other cases, bituminous treatments will generally prove more economical and adaptable.

(*b*) In bituminous stabilization three methods of treatment—machine mixing, sub-oiling, and road-mixing—have all been successfully employed. The sections of road-mixed material are of too recent date to be fairly compared with the other sections, but the results obtained so far give no indications of inferiority.

(*c*) Machine mixing as carried on in Missouri produced complete diffusion of the treatment. The presence of fine material in the mix promoted the formation of a clay emulsion as indicated by the appearance and action of the material discharged by the pug mixer. Tar-treated material in particular instances has not shown any such action but diffusion and coating have appeared complete.

(*d*) Asphalt emulsions because of their ability to diffuse through the roadbed materials worked to best advantage in conjunction with the sub-oiling operation. However, cheap road oils of the slow curing grades were successfully used when dispersed by supplementary blade mixing after the application of oil by means of the sub-oiler.

(*e*) The necessary quantity of portland cement for use is apparently easily determined by use of the Proctor density tests in combination with durability tests consisting of freezing and thawing and alternate wetting and drying tests.

(*f*) In the case of bituminous treatments there is apparently a rather flexible range of quantity of treating agents which may be successfully used. This quantity ranges from approximately 6 to 10 percent by weight of the soil fraction. As judged by the behavior, mixtures near the upper limits of the range mentioned appear to be more critical than those near the lower limits, no radical failures being noted in sections approaching excessive leanness whereas an excess of bitumen has immediately produced plasticity and loss of stability.

(*g*) Under the conditions used, and based on the length of service thus far observed, no appreciable difference has been noted in the stability produced, or the durability obtained, with the various bituminous agents used. Unless additional length of exposure develops differences in durability or behavior, economy in cost of treating agents will probably be the governing factor in selection.

(*h*) One of the results of planning and carrying out the research projects is the conclusion which immediately becomes apparent, that there is little or no fundamental information available on which to base thickness design.

ACKNOWLEDGMENTS

The Principal Reporter acknowledges the very valuable data and papers furnished him for the preparation of this report. The contributors were Miles D. Catton, Development Department, Portland Cement Association; W. W. Johnson, State Highway Commission of Kansas, and F. V. Reagel, Engineer of Materials, Missouri State Highway Department.

The Principal Reporter quoted freely from all the information furnished.

[8] Soil Stabilization Work in Jackson County, Missouri: Frank V. Gilmore: Roads and Streets, 68: 313-316, 1935.

[9] Use of Cutbacks and Road Oils in Soil Stabilization, F. V. Reagel and R. C. Schappler, Proceedings of 16th Annual Meeting Highway Research Board, vol. 16, p. 359, 1936.

(Continued from page 111)

light from each type of pavement tested both in a wet and a dry condition.

Attention is called to the fact that the wetting of the surface of the bituminous macadam and the open-type asphaltic concrete has little effect upon glare. This is borne out by driving experience over these types of surfacings. On the contrary, smooth and fine sandpaper-textured surfaces show a greatly increased glare when wet. Such surfaces, when wet, are covered with a film of water which becomes the reflecting surface, while the irregular surfaces, having pits or indentations ¼ inch or more in depth, break up the water film. It is thus apparent that the relative glare from wet surfaces is in the main a function of the texture of the surface, and the least glare is given by those surfaces which are so deeply indented that the water will drain off with sufficient rapidity to prevent the flooding of the entire surface and the formation of a water film which acts as a mirror in reflecting the lights of oncoming vehicles.

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The outstanding contribution of Professor R. A. Moyer of the Iowa State College forms the basis of the first section of this report. The Principal Reporter quoted freely from all the information furnished.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF JULY 31, 1938

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 18,600	$ 9,300		$ 7,180,388	$ 3,583,440	290.6	$ 2,755,844	$ 1,374,955	121.8	$ 3,782,495
Arizona	1,038	747		1,710,711	1,294,548	91.9	227,955	146,378	14.9	1,734,296
Arkansas				914,892	904,226	74.5	2,046,596	2,043,355	125.9	2,224,424
California	638,168	336,189	17.1	10,947,077	5,743,959	200.5	3,742,136	1,999,794	91.8	1,912,982
Colorado	268,441	142,332	13.1	2,413,481	1,326,808	75.4	708,171	393,822	16.6	2,853,299
Connecticut				1,189,000	579,991	13.1	405,970	201,510	3.6	1,531,972
Delaware	54,130	27,065		782,314	385,679	22.3	480,998	241,791	1.4	1,184,277
Florida				2,942,251	1,471,126	61.2	2,666,856	1,058,828	33.9	2,815,962
Georgia	886,329	443,164	50.9	6,592,734	3,296,367	307.1	2,078,040	1,039,020	109.0	5,518,798
Idaho	267,078	158,698	16.5	1,973,726	1,176,262	184.0	581,165	345,748	7.5	1,227,141
Illinois	317,000	179,284	10.3	10,231,338	5,110,255	217.4	4,025,790	2,012,895	124.9	3,201,711
Indiana	1,000,000	500,000	19.2	5,032,417	2,510,140	131.5	2,120,340	1,059,950	39.3	2,511,545
Iowa	701,727	319,146	17.1	6,993,809	3,137,683	225.3	2,158,879	1,014,673	76.7	1,162,647
Kansas	13,330	6,665	.5	4,871,879	2,392,192	320.1	5,555,486	2,777,727	631.5	3,120,023
Kentucky	436,832	218,416	32.3	4,908,412	2,454,206	157.4	3,301,496	1,638,006	76.5	2,114,640
Louisiana	256,047	128,000	9.3	11,647,244	2,221,315	46.2	2,155,846	971,631	41.5	2,399,773
Maine	452,048	226,529	10.3	2,152,782	1,069,101	48.5	1,077,544	538,771	18.3	415,972
Maryland	54,000	27,000	1.2	1,937,567	967,021	29.5	1,230,411	602,830	18.1	1,992,916
Massachusetts	122,568	61,284	.8	2,675,881	1,337,937	9.9	580,222	290,109	8.7	2,659,435
Michigan	687,200	343,600	25.4	6,335,138	3,097,169	128.2	2,495,890	1,244,000	53.3	2,455,712
Minnesota	236,204	106,916	5.9	5,144,493	2,546,079	250.4	2,534,846	1,262,167	130.0	2,935,473
Mississippi	121,400	60,700	6.2	7,255,460	3,091,525	325.5	2,946,200	777,840	130.1	3,223,880
Missouri	275,580	137,790	13.2	4,850,897	2,395,786	125.2	4,535,941	1,929,031	163.0	3,635,997
Montana	351,319	197,613	18.3	1,396,200	784,993	52.5	252,912	142,262	8.4	4,481,815
Nebraska	419,442	209,721	63.7	5,865,800	2,924,429	491.3	3,874,158	1,302,084	166.3	2,656,210
Nevada	647,806	561,764	65.8	830,919	719,392	60.5	515,844	442,570	59.5	1,366,464
New Hampshire	175,316	86,246	5.8	983,694	490,088	15.1	171,212	85,534	5.1	1,162,941
New Jersey				2,852,361	1,424,918	21.2	211,060	104,010	.5	2,672,543
New Mexico	381,352	232,583	46.3	1,955,111	1,292,584	164.7	820,802	500,603	53.9	852,860
New York	697,231	344,860	9.8	16,061,399	7,860,712	283.8	3,827,230	1,455,115	54.8	3,570,039
North Carolina	765,500	382,750	59.4	7,150,106	3,447,615	317.9	1,196,893	577,116	70.3	2,899,077
North Dakota				2,565,531	2,487,301	160.5	478,270	420,003	59.4	3,825,290
Ohio	1,460,130	728,110	19.2	8,157,002	4,050,010	82.7	3,748,010	1,863,673	25.4	7,206,088
Oklahoma	948,402	499,098	39.4	4,200,204	2,176,400	152.3	2,847,939	1,495,258	93.9	3,214,684
Oregon	250,986	109,495	1.1	2,245,956	1,331,925	85.0	703,886	429,550	15.7	2,129,944
Pennsylvania	1,894,299	946,100	31.7	5,418,749	2,687,106	82.0	5,579,134	2,788,573	57.8	4,410,663
Rhode Island				1,085,102	542,551	14.8	360,400	180,200	3.2	1,021,049
South Carolina	461,039	210,900	36.2	5,105,356	2,259,535	206.0	951,695	429,290	52.9	1,878,384
South Dakota	128,610	71,130	6.0	3,731,162	2,066,250	370.8	1,214,550	679,480	92.3	3,340,076
Tennessee	385,560	192,780	13.0	5,184,534	2,592,267	153.2	913,400	456,700	19.7	4,747,348
Texas	2,617,918	1,299,835	166.3	10,306,467	5,105,482	589.3	4,862,157	2,377,080	225.1	7,575,569
Utah	3,300	2,360		1,294,470	927,400	108.4	581,880	415,673	36.1	1,459,499
Vermont	147,643	67,887	3.1	1,447,682	659,520	39.4	241,698	105,199	6.9	292,304
Virginia	1,091,814	545,907	41.0	5,008,991	2,502,515	167.7	1,916,636	956,033	47.8	1,033,162
Washington	7,917	3,600		4,573,308	2,386,214	75.3	615,217	322,300	13.9	1,296,312
West Virginia	115,250	92,300	9.2	1,705,746	1,131,733	45.8	1,362,406	771,578	34.5	2,220,246
Wisconsin	669,468	321,477	17.0	6,917,676	3,208,835	193.1	2,011,961	878,880	62.7	1,879,276
Wyoming	210,330	127,920	27.4	1,884,027	1,157,562	202.3	336,631	207,960	66.2	798,986
District of Columbia										
Hawaii	103,405	51,703	1.9	795,285	394,357	16.5	776,440	380,075	8.8	1,198,792
Puerto Rico				1,128,739	562,390	20.5				671,985
TOTALS	20,741,757	10,718,964	930.9	220,535,468	109,266,899	7,508.3	90,785,043	44,731,630	3,379.4	126,476,976

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF JULY 31, 1938

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama				$ 459,700	$ 229,750	30.2	$ 192,005	$ 94,750	13.7	$ 728,472
Arizona				196,056	129,008	11.4	92,929	63,940	7.2	463,534
Arkansas				19,426	12,863					851,245
California	$ 146,008	$ 84,753	16.7	827,590	454,517	41.0	738,150	395,006	28.6	910,656
Colorado				688,486	381,243	33.5	141,044	76,430	14.8	463,895
Connecticut							76,090	38,025	1.3	280,253
Delaware							21,700	10,850	4.0	236,025
Florida				20,122	10,061					664,791
Georgia	71,680	35,840	8.4	277,418	138,709	36.4	487,417	243,708	62.9	840,308
Idaho	105,529	52,041	8.0	306,022	133,494	33.6	12,569	5,080	3.5	280,884
Illinois	95,000	47,500	10.3	1,269,832	580,916	88.8	1,279,800	639,900	94.9	758,599
Indiana				772,200	305,700	77.9	746,153	369,800	71.7	566,938
Iowa										1,298,449
Kansas	43,670	21,835	.5	63,694	31,847	.7	163,886	81,942	40.1	1,183,445
Kentucky	109,248	33,608	16.4	662,226	193,254	53.4	1,445,259	407,476	127.5	180,088
Louisiana				21,670	10,835		498,299	191,750	39.0	521,551
Maine	122,600	61,300	8.4	198,936	99,468	11.2	201,000	100,500	11.5	67,305
Maryland				6,264	3,132					409,344
Massachusetts				5,300	2,650					643,750
Michigan				23,362	11,681		764,500	382,250	49.5	1,141,608
Minnesota				381,352	171,027	37.1	27,946	11,610	8.7	1,196,943
Mississippi										888,927
Missouri	97,410	47,800	17.4	250,250	124,735	19.5	526,360	183,745	61.9	708,808
Montana				13,983	7,865					1,027,170
Nebraska	13,984	6,992	2.2	435,186	217,593	60.3	250,776	116,812	45.7	654,655
Nevada	57,038	49,463	6.3	199,291	172,542	27.9	139,080	120,539	19.9	148,900
New Hampshire				208,761	103,578	4.5	39,820	19,880	1.5	123,417
New Jersey							181,060	86,875	2.5	585,898
New Mexico	102,849	62,727	10.7	438,545	267,466	20.0				476,579
New York	416,600	208,300	26.7	1,757,260	878,630	116.9	801,000	341,350	34.2	930,181
North Carolina				866,220	433,110	94.2	73,044	36,500	3.4	611,983
North Dakota				33,860	18,135	5.5	149,990	80,332	29.5	688,785
Ohio				184,400	92,200	3.8	11,100	5,000	.9	1,734,441
Oklahoma				84,588	45,008	4.1	486,490	248,819	45.7	891,088
Oregon	74,302	44,310	11.5	256,003	155,342	24.9	179,494	100,610	24.3	452,860
Pennsylvania	215,152	107,576	15.5	1,303,619	632,461	79.6	792,965	385,994	51.1	989,857
Rhode Island	21,730	10,865	.6	112,106	56,053	5.5				120,973
South Carolina				514,080	219,862	57.8	469,018	197,754	53.8	261,064
South Dakota				11,300	6,250					816,436
Tennessee				243,946	121,973	12.6	442,580	154,230	19.9	783,287
Texas	131,830	65,390	27.2	1,801,796	833,699	221.2	1,194,610	485,190	151.5	1,740,246
Utah	50,570	25,000	3.8	202,455	115,790	18.8	250,575	120,530	27.5	289,050
Vermont	140,880	60,675	8.3	59,176	27,178	3.3	55,100	15,247	2.2	106,440
Virginia	66,100	33,050	6.9	535,227	265,398	44.8	529,390	202,909	33.9	390,642
Washington				423,079	222,378	31.6	474,906	249,800	50.6	258,378
West Virginia				208,000	104,000	16.5	118,200	59,100	9.4	386,574
Wisconsin				641,365	304,965	24.6	310,170	121,580	15.0	785,683
Wyoming	221,060	136,590	22.9	157,360	97,230	20.9	61,500	38,000	5.1	313,373
District of Columbia										
Hawaii				56,250	28,125	2.4				218,750
Puerto Rico				244,000	121,950	13.7				124,925
TOTALS	2,303,240	1,195,615	228.7	17,441,762	8,573,671	1,390.1	14,425,975	6,483,813	1,268.4	31,197,453

U. S. GOVERNMENT PRINTING OFFICE: 1938

PUBLICATIONS of the BUREAU OF PUBLIC ROADS

Any of the following publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C. As his office is not connected with the Department and as the Department does not sell publications, please send no remittance to the United States Department of Agriculture.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1931. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1933. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1934. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1935. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1936. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1937. 10 cents.

HOUSE DOCUMENT NO. 462

Part 1 . . . Nonuniformity of State Motor-Vehicle Traffic Laws. 15 cents.

Part 2 . . . Skilled Investigation at the Scene of the Accident Needed to Develop Causes. 10 cents.

Part 3 . . . Inadequacy of State Motor-Vehicle Accident Reporting. 10 cents.

Part 4 . . . Official Inspection of Vehicles. 10 cents.

Part 5 . . . Case Histories of Fatal Highway Accidents. 10 cents.

Part 6 . . . The Accident-Prone Driver. 10 cents.

MISCELLANEOUS PUBLICATIONS

No. 76MP . . The Results of Physical Tests of Road-Building Rock. 25 cents.

No. 191MP. . Roadside Improvement. 10 cents.

No. 272MP. . Construction of Private Driveways. 10 cents.

No. 279MP. . Bibliography on Highway Lighting. 5 cents.

Highway Accidents. 10 cents.

The Taxation of Motor Vehicles in 1932. 35 cents.

Guides to Traffic Safety. 10 cents.

Federal Legislation and Rules and Regulations Relating to Highway Construction. 15 cents.

An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.

Highway Bond Calculations. 10 cents.

DEPARTMENT BULLETINS

No. 1279D . . Rural Highway Mileage, Income, and Expenditures, 1921 and 1922. 15 cents.

No. 1486D . . Highway Bridge Location. 15 cents.

TECHNICAL BULLETINS

No. 55T . . . Highway Bridge Surveys. 20 cents.

No. 265T. . . Electrical Equipment on Movable Bridges. 35 cents.

Single copies of the following publications may be obtained from the Bureau of Public Roads upon request. They cannot be purchased from the Superintendent of Documents.

MISCELLANEOUS PUBLICATIONS

No. 296MP. . Bibliography on Highway Safety.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y . . Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).

Report of a Survey of Transportation on the State Highways of Vermont (1927).

Report of a Survey of Transportation on the State Highways of New Hampshire (1927).

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).

Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).

Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

UNIFORM VEHICLE CODE

Act I.—Uniform Motor Vehicle Administration, Registration, Certificate of Title, and Antitheft Act.

Act II.—Uniform Motor Vehicle Operators' and Chauffeurs' License Act.

Act III.—Uniform Motor Vehicle Civil Liability Act.

Act IV.—Uniform Motor Vehicle Safety Responsibility Act.

Act V.—Uniform Act Regulating Traffic on Highways.

Model Traffic Ordinances.

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to the U. S. Bureau of Public Roads, Willard Building, Washington, D. C.

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF JULY 31, 1938

STATE	COMPLETED DURING CURRENT FISCAL YEAR		NUMBER			UNDER CONSTRUCTION		NUMBER			APPROVED FOR CONSTRUCTION		NUMBER			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	
Alabama						$ 541,798	$ 541,724	7			$ 595,610	$ 595,110	6		6	$ 848,685
Arizona						4,718	4,718									625,495
Arkansas						279,639	278,482	7			348,844	348,462	6			1,131,825
California						1,206,964	1,206,389	3	4		348,426	338,944	3			2,154,876
Colorado	$ 18,855	$ 18,855	1		1	19,348	19,348				58,956	55,196	1		3	1,194,643
Connecticut																844,490
Delaware											77,270	77,270			23	416,480
Florida						10,616	10,616				178,800	178,800	1			1,216,381
Georgia						18,346	18,346				27,460	27,460	1			2,371,581
Idaho	87,825	87,652	1			12,342	12,342				106,037	99,220	2			623,656
Illinois						814,675	814,675	4			775,080	775,080	7	1	29	3,614,888
Indiana	97,500	97,500		2		687,000	660,100	5	3		720,260	683,600	1	1	86	971,506
Iowa	17,747	16,100			5	985,329	931,300	12	1	4	247,051	230,400	1		12	1,384,766
Kansas	112,408	112,408	3		2	460,089	458,089	8		2	566,699	566,699	8		3	1,435,607
Kentucky						145,000	145,000	1			374,266	374,266	2	1	31	1,294,779
Louisiana						146,486	146,478	2			327,021	293,050	6			1,137,543
Maine						293,297	293,297	3	2		124,010	124,010	2		1	273,896
Maryland						64,586	64,586	1								962,247
Massachusetts						70,420	70,420		1		162,480	162,480	1			1,680,388
Michigan	110,000	110,000	1	1		568,152	568,152	3		45	759,200	759,200	8			1,847,833
Minnesota						720,196	720,196	2	6	1	100,140	100,140	1			1,601,146
Mississippi						356,800	356,800	4								1,227,351
Missouri	19,380	19,380	1			239,130	239,130	3			149,140	149,140	2			2,617,603
Montana						365,654	360,772	4			276,614	276,614	2			687,085
Nebraska						311,783	311,783	11			13,880	13,880	2			1,438,747
Nevada	5,626	5,626			2	91,561	91,561		2		52,574	52,574		1		308,880
New Hampshire						69,138	68,831		1							424,919
New Jersey						210,005	204,779	2	1							1,765,478
New Mexico						122,441	122,441	4			77,677	77,677		1		651,373
New York						1,831,201	1,825,600	8	4	2	440,868	439,518		3		4,504,811
North Carolina						414,060	414,060	3	2		202,950	202,950	1	4		1,827,384
North Dakota						545,688	545,688	1	1		62,630	62,630	1	1		970,903
Ohio						32,120	32,120				267,110	267,110	4			3,929,938
Oklahoma						17,343	17,343									2,264,166
Oregon	95,263	94,614		2		220,687	220,687	1			9,754	9,754				650,276
Pennsylvania						299,116	283,910	2								5,448,625
Rhode Island						227,553	227,553	1			67,326	67,326		2		198,871
South Carolina						73,933	51,147	1	1		397,131	397,131	1	1	34	1,040,824
South Dakota						125,508	125,508	1	1		258,290	256,150	3	1	10	936,215
Tennessee						14,381	14,381				16,450	16,450		1		1,861,202
Texas	38,798	38,100	2			598,642	598,642	6			402,850	402,515	3	2		4,301,811
Utah	1,760	1,760			1	121,173	121,173	3			25,400	25,400	1		3	424,655
Vermont	151,590	151,590	3	1		85,148	75,868	3	1		18,220	18,220			7	233,875
Virginia	18,730	18,730		1		279,985	279,985	12	1		385,931	385,931	4		8	1,111,384
Washington						419,518	417,418	5	2	2	382,348	382,348	3	2	2	584,033
West Virginia						369,189	368,169	4			87,870	87,870			5	868,059
Wisconsin						922,873	911,633	8			207,138	175,000	2			1,386,876
Wyoming						159,644	159,644		2		14,530	14,530			6	502,556
District of Columbia																325,431
Hawaii						33,230	33,230	1			163,920	163,920	2	1		296,600
Puerto Rico						61,900	61,550	2			151,661	150,580	2			518,170
TOTALS	775,482	772,315	12	7	11	15,668,405	15,505,664	148	36	56	10,029,872	9,884,605	90	23	269	70,940,812