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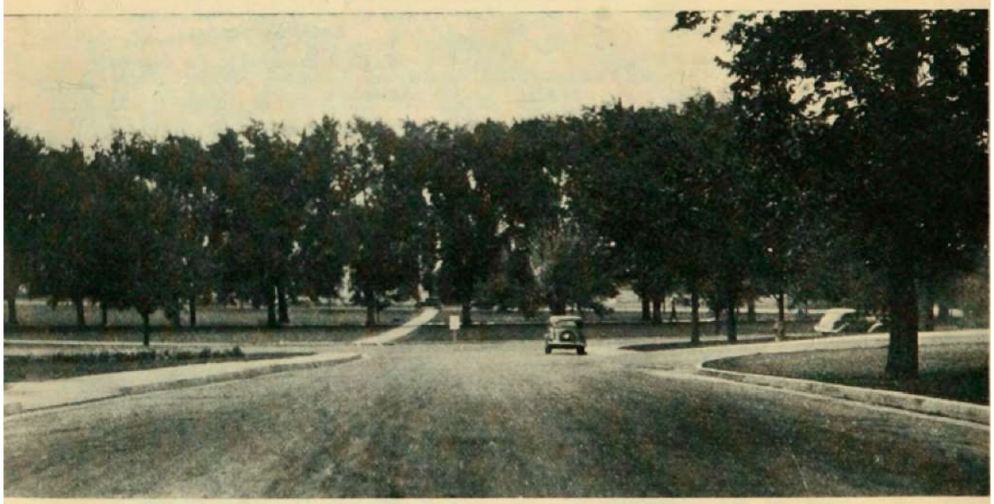
Oiled-Gravel Roads of Colorado

E. B. HOUSE



Oiled-Gravel Roads, Colorado State College Campus

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OILED-GRAVEL ROADS OF COLORADO

E. B. HOUSE

THE experience with oiled-gravel roads has often been unsatisfactory from the viewpoint of maintenance and durability. This result has been due largely to improper mix, incorrect oil content, use of inferior aggregates, and poorly compacted subgrades. In fact, most of the fundamentals in proper road construction have been violated, with the net result that the roads so constructed have constantly to be repaired or even rebuilt.

This study of oiled-gravel roads of Colorado was undertaken some 4 years ago.* Most of the construction studied had been done by the road-mix process. Gravel was hauled and spread on the road surface, the oil applied, and the mixing done by blade machines. When mixed the gravel was spread and left for the traffic to compact. In some instances it was lightly rolled. Some of our roads have been constructed by the penetration method, but no great success has been attained here.

In recent years portable mixing machines have been used on some roads. The machine picks up the gravel from a windrow, adds the oil, mixes the aggregate and oil, and deposits it in a windrow behind the machine. Blade machines then spread it, and the traffic compacts it. The advantage here is that the matrix is more thoroughly mixed, and the oil content is more constant.

In a very few instances the plant-mix process has been used, but as this is more expensive it has been tried more as an experiment than otherwise. So far as we know the results have been good.

Our first investigation was to determine the percentage of oil in the matrix by analyzing samples taken from our roads. This was followed by a subsoil investigation and moisture determination, as we thought that one or the other or both of these conditions might be the cause of rolling of the sheet into corrugations, alligator cracking, or rutting and raveling of the finished roadway.

Oil Analysis

SAMPLES of the road surfacing were taken at places where the road was wearing well and at places nearby where any type of failure was manifestly present. These samples were taken into the laboratory and the oil washed from them in an extractor developed by the New York Testing Laboratory. The process is as follows:

*Laboratory and field work reported in this bulletin were done by three graduate engineers: D. A. Wigle, E. A. Lawver, and Adrian Legault. Each has held the position of Testing Engineer of the Colorado State College of Agriculture and Mechanic Arts. Mr. Wigle collected and analyzed the matrix and sub-grade samples taken from the oiled highways of Colorado. Mr. Lawver started the work of investigating and testing the effect of water in the aggregate when the oil is applied. He also designed and superintended the oiled roads on the campus and designed and laid the experimental road. Mr. Legault has completed the work of Mr. Lawver and has arranged and tabulated the data. The author of the bulletin is Dean of Engineering at the college.

Preparation of Sample.—The sample of oiled-gravel mat taken from the roadway is broken up and mixed thoroughly. A 200-gram sample is taken for the oil-extraction test, and a 100-gram sample is taken and tested at once for water content. The procedure of testing for water will be given later.

The sample for the oil-extraction test is carefully weighed and put into an 80-mesh wire basket lined with filter paper; the weight of basket and filter paper is carefully determined. A piece of felt cut to fit the basket is put over the top of the sample.

The apparatus consists of a brass cylinder 6 inches in diameter supported 3½ inches above a base, to which is attached a 16-candle power, incandescent, carbon-filament electric bulb. The entire bulb projects through the bottom of the cylinder and supplies the necessary heat for vaporizing the solvent used. An inverted conical condenser serves as a top for a second cylinder 4 inches in diameter sitting inside the large one above the lamp. The basket containing the sample is suspended in this second cylinder; the solvent (carbon disulfide) is poured over it; the condenser top, through which a continuous stream of cold water circulates, is put in place; the lamp is lighted, and the assembly is complete.

The heat from the lamp vaporizes the carbon disulfide. It rises, is condensed on the inverted cone above the basket, and drips down through the sample, dissolving the oil as it passes through. The felt over the top of the samples serves to distribute the dripping solvent over the entire surface, thus preventing a channel forming through the material in the basket, which would result in only part of the oil being removed. The process of the solvent vaporizing, condensing, revaporizing, and again condensing is continued until the drippings from the basket leave no stain on a piece of filter paper. The basket is then removed, the carbon disulfide allowed to evaporate, and the material dried to a constant weight in an oven. The net weight of the sample now compared to its original weight gives the loss due to oil, water, and fine aggregate material washed out. To get the weight of the oil alone it is necessary to correct for the water and mineral matter.

The water content is determined by placing the 100-gram sample previously mentioned in a metal still and pouring 100 cc of "water-free gasoline" over it. The top of the still is fastened, and heat is applied. As the gasoline and water, if any, vaporize they pass off through an opening in the top of the still to which a water-cooled condenser is attached. The vapors condense and drop into a graduated trap. If any water is present it settles to the bottom of the trap, where its amount may be read on the graduated scale. The condensed gasoline fills the trap, overflows, and returns to the still, where it is revaporized and the process repeated.

When the reading of water becomes constant the distillation is complete, and the percentage of water which the sample contained may be determined from the two weights.

The amount of fine mineral material which was removed with the oil is found by weighing the material washed from the sample and igniting it, thus burning out the oil and evaporating the water, then reweighing. The amount of material remaining after ignition is mineral matter and consists of the fines washed from the sample.

(The foregoing is the standard A. S. T. M. method for oil extraction.)

A mechanical analysis was then made of the dried aggregate of the sample to determine the grading of it. Some 200 samples of road surfacing were worked over in this way, and the results tabulated.

After arranging and tabulating these results it was found that they varied so greatly it was impossible to construct graphs which did more than zigzag aross the sheet, overlapping and varying so greatly that no conclusions could be drawn except that a successful road could be constructed in places and with certain aggregates with an oil content varying from 3 percent to 8 percent of the aggregate by weight. Many samples taken from places where the road was in perfect condition showed these percentages.

At the same time samples taken from sections of surfacing in the near vicinity where the road was failing contained the **same** percentage of oil as that found in the samples taken nearby where the road was standing up as it should. It was, therefore, evident that something more than the oil content of the matrix was causing the failure.

Our highway department has done considerable experimenting on our roads with different kinds of oil obtained from different refineries. The same condition concerning oil content and failure seemed to exist regardless of the **kind** of oil used or its grade and curing qualities.

Some of the samples tested had been in place for 5 years and ranged all the way from that age to those from roads only a few months old. In **all** cases it was possible to find good roads containing as low as 3 percent of oil, and failure sections containing the same amount of oil. The same thing was true when the matrix contained 4, 5, 6, 7, and 8 percent of oil.

The oil content was extremely variable due to the method followed in applying it with oil distributors on the road. An even distribution of oil cannot be obtained by this method of application.

It was thought that perhaps the oil content changed with the age of the road due to evaporation of the volatile parts of the oil. Several hundred cylinders 4 inches in diameter and 2½ inches thick were made, compressed with 1,500 pounds pressure per square inch, and placed outdoors in a test lot to weather. (Heavier compaction tended to break the aggregate.) There were 21 cylinders in each set. Care was taken to have the percentage of oil in each set of cylinders the same; but the percentage of oil was varied in different sets of cylinders, and different kinds of road oils were used.

In placing these test cylinders in the test lot care was used to have as nearly as possible the same exposure as would be the case were the same material a part of an oiled-road surface. This was accomplished by filling in the spaces between cylinders with tamped sand, leaving the bottom of each cylinder in contact with the ground and the top in contact with the air. No protection of any kind was provided.

A test cylinder was tested for oil content at intervals of 1 week for the first month and one each month thereafter. The twenty-first cylinder of each set was tested 18 months after being placed outside.

It was found that the percentage of oil lost by volatilization was very small. In fact it may be said to be negligible for all practical purposes. In our work it ranged from 0 to 0.2 percent, with a few showing slightly more than this amount. The apparatus used for this work certainly would give a probable error of this amount with the most careful work.

The inconsistencies in results of evaporation tests made on the cylinders of oil and aggregate were attributed to lack of uniformity in mixing oil and aggregate, and to unavoidable error in determining the percentage of oil remaining in the sample by the extraction process previously described.

In an attempt to eliminate as far as possible the factors believed to be causing these inaccuracies, samples of the oil to be observed were put in open dishes and exposed to the same conditions to which the cylinders had been exposed. Care was taken to prevent dust or other foreign materials from getting into the oil. From time to time the weights of the samples were taken, and thus the loss due to volatile material passing off was determined.

The samples used were 65-70 and 75-80 road oils and two cutbacks: one a heavy asphaltic oil cut back to a viscosity to permit its use at ordinary temperatures; the other, one of much lower asphaltic content, and recommended for surface treatment.

The results of these tests conformed very well, however, with general conclusions drawn from the tests on the cylinders. The 65-70 and 75-80 oils showed a very slight loss, averaging two-tenths of 1 percent in 40 days.

The cutbacks, however, were much higher in percentage of loss. They averaged 27 percent in 10 days. This increase of loss is, of course, to be expected due to the higher volatility of the flux in the cutbacks. In these cutbacks 23 percent of the 27 percent loss occurred in **2 days,** and at the end of 40 days there was an increase of only two-tenths of 1 percent over the loss at 10 days.

We feel that it is safe to say the oil-content analyses of the road samples made are correct within a limit averaging 0.2 percent, and that they represent within that limit the amount of oil placed in the road at the time the oil was applied.

Subgrade Analysis

THE subgrade samples were taken with the oiled-matrix samples and represented about every kind of soil found in Colorado. They ranged from disintegrated granite and gravel to the clay of disintegrated shale and river silt. The tests for moisture were made in the usual way: namely, weighing before and after drying. The moisture content of these samples ranged from 2 percent to 15 percent.

The notable fact revealed by this analysis of water content of the subgrade was that in nearly **every** case where failure of the oiled mat was taking place the subsoil moisture was above 5 percent; and the more pronounced the failure, the wetter was the subgrade.

It is our opinion that the water in the subsoil softens it, and the matrix has not a stable foundation at those places. It may also be that the water floats the oil in the tack coat and matrix, causing a parting, and the matrix slips into waves and corrugations.

Some work has been done upon the emulsion of the oil by the water, but to date the results are not such as to warrant publication.

Proper attention to drainage is necessary on Colorado roads. They must be graded sufficiently high above the water table. It is poor economy to construct oiled-gravel roads knowingly too low for the water table at any time during the year. The surface of the road should always be placed beyond the capillary limit of that particular soil. Our tests conclusively show that construction of an oiled road upon a wet subsoil is a mistake. A road is practically sure to fail if so constructed. If money is not available for properly grading the road, it is far better to delay oiling until it **is** available.

Mechanical Analysis

GRADING of the aggregate used is an important item, as is shown by our mechanical analysis of the aggregate of the matrix samples from which the oil had been extracted. The aggregates should be so proportioned that they conform reasonably close to the curve developed by the Kansas Highway Department. The grading of aggregate used in our test cylinders was done on this basis.

TABLE 1—*Basis of grading aggregate for cylinders*

Sieve number Passed	Sieve number Retained	Grams on each sieve	Percent on each sieve	Percent coarser
1	3	204	17	17
3	10	264	22	39
10	20	132	11	50
20	30	66	5.5	55.5
30	40	66	5.5	61.0
40	50	67	5.6	66.6
50	80	101	8.4	75
80	100	32	2.7	77.7
100	200	134	11.2	88.9
200	...	134	11.1	...

The grading indicated in table 1 gives a straight-line curve similar to the curve developed by Kansas. It is called a curve for maximum density.

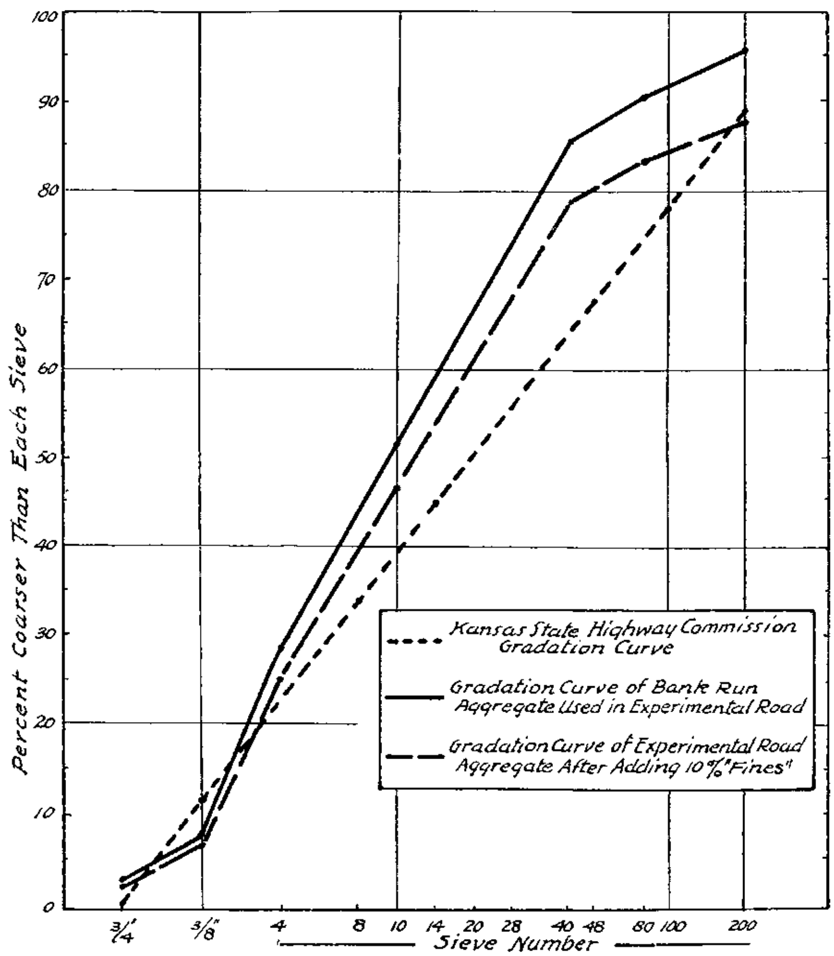
The percentage of oil required to cover the surface of the aggregate with this grading when figured by the New Mexico formula is 6 percent.

We have followed this grading in the oiled roads on the Colorado State College campus, adding enough "fines" (passing 200 sieve) to make the total fines equal 12 percent. The percentage of oil used was cut to 4.5 percent, and a seal coat of cutback asphalt was then applied.

This surfacing is now 2 years old and is in perfect condition. It is wearing far better than the rock asphalt paving used to surface the campus oval. This oval carries about the same traffic and the same grade of traffic. Rock asphalt was used instead of the oiled gravel, as it was thought the gravel would not stand up on the curves of the oval.

From the mechanical analysis of the many samples of aggregate taken from highways it would seem that available material along the route has been used without adequate testing and mixing with other aggregate to provide the deficiencies and secure the proper grading. In nearly every case the aggregate was seriously deficient in fines. All our Colorado natural gravels are deficient in fines. These run between 3 and 5 percent, whereas an aggregate suitable for oiled roads should contain more than 10 percent of this fine material. Our clays even do not generally contain this amount of fines; it is, therefore, inadvisable to use clay for this purpose.

A suitable material can be obtained from ore mills at Colorado City. Ninety-seven percent of this material will pass a number 200 sieve. It is pulverized rock from the ores treated at the mill. It is inexpensive, and the principal cost is the transportation charge from Colorado Springs to the road site. It is certainly more advisable to obtain and use the small amount of this material necessary to make a suitably graded aggregate than to get along without it. It is not economy to skimp on these things because they are not available at the road site. Far better to haul material from a greater distance that **is** suitable and thereby obtain a good road, than to use



unsuitable material hauled a shorter distance and have a poor road. With the truck transportation of today the length of haul cuts a far less figure than it formerly did.

Roads can be made that will stand up **fairly** well with an ungraded aggregate, and usually they are cheaper roads but poorer.

Effect of Moisture in Aggregate on Stability

IN constructing oil-gravel cylinders in the laboratory it was observed that when oven-dry aggregate was used, or when the percentage of moisture in the aggregate was very low, a great deal of difficulty was experienced with the cylinders crumbling when pressed from the molds. The appearance of the cylinders indicated sufficient oil, but there was a decided lack of bond.

Since the oil content appeared high enough, the consideration of lack of moisture in the aggregate seemed worth while to determine if possible the cause for the lack of bond in certain cylinders.

Consequently cylinders were constructed of the same type of aggregate and having the same oil content, but varying in percentage of moisture present in the aggregate. Some test cylinders were constructed with varying amounts of water present in the aggregate before the oil was added. In others the oil and oven-dry aggregate were mixed, and then water in the desired amount was added and the mixing continued until the mass was homogeneous.

After mixing the cylinders were formed by compressing in 4-inch cylindrical molds under a load of 1,500 pounds per square inch. They were then pressed from the molds. It was at once found that the added water solved the problem of cylinders crumbling when pressed from the mold. These cylinders were then put out-of-doors in sand, as described in the discussion of storage of cylinders made in connection with the evaporation tests.

After 15 days the specimens were tested for compressive strength in a testing machine. After rupture they were re-mixed, compressed, and again placed in the test lot. This procedure was repeated four times. The oil and water content, and strength of each specimen, are shown in table 2.

Another group of cylinders was constructed in a manner similar to that used in construction of those just discussed, except that this group was tested for compressive strength in from 1 to 4 days after construction. The results of these tests are shown in table 3.

From the results shown by these tables it will be seen that in every case where moisture was present in the aggregate a higher strength resulted than when there was no moisture. This increase was manifest not only shortly after the samples were constructed but also at the end of a 60-day period, and after the cylinders had been broken and re-compressed three times.

The variation in strength when the percentage of moisture varied between 1 percent and 6 percent was not always consistent. The average, however, showed that a moisture content of from 4 percent to 6 percent gave the highest strengths.

The conclusions drawn, therefore, are that the theory of having the aggregate very dry, with a maximum moisture content of 2 percent at the time of mixing, is erroneous. Moisture contents of as much as 6 percent were beneficial so long as the materials were thoroughly mixed. At least 1 percent of moisture was essential for good results. It is somewhat more difficult to mix properly the oil and wet aggregate, but when this is accomplished there is no doubt that the moisture present improves the finished product.

TABLE 2—*Oiled-gravel cylinders with varying percentages of water*

Specimen number	Percent oil used	Percent water in aggregate when mixed	Percent water added immediately after mixing	Total Compressive Strength Trial 1 *Pounds*	Trial 2 *Pounds*	Trial 3 *Pounds*	Trial 4 *Pounds*
4.5-458-1	4.5	0.0	3.0	2,020	1,550	1,150	1,080
4.5-458-2	4.5	0.0	3.0	2,000	1,580	1,240	1,360
4.5-458-3	4.5	0.0	3.0	2,150	1,630	1,320	1,550
4.5-458-4	4.5	0.0	0.0	500	Fell apart	....	....
4.5-458-5	4.5	0.0	0.0	Fell apart	....	....	....
4.5-458-6	4.5	0.0	1.0	1,640	1,280	1,210	1,410
4.5-458-7	4.5	3.74	0.0	2,420	2,150	1,460	1,610
4.5-458-8	4.5	3.68	0.0	2,530	2,360	1,350	1,670
4.5-458-9	4.5	3.79	0.0	1,840	2,635	1,640	1,720
4.5-458-10	4.5	0.0	3.79	1,810	2,340	1,150	1,400
4.5-458-11	4.5	0.0	3.83	1,990	2,470	1,370	1,470
4.5-458-12	4.5	0.0	3.80	1,620	2,410	1,610	1,500
4.5-461-1	4.5	1.07	0.0	1,460	1,120	1,080	1,880
4.5-461-2	4.5	1.18	0.0	1,400	920	970	1,750
4.5-461-3	4.5	1.47	0.0	1,270	1,320	1,210	1,970
4.5-461-4	4.5	4.80	0.0	2,510	1,770	1,630	1,940
4.5-461-5	4.5	4.77	0.0	2,760	1,830	1,420	2,080
4.5-461-6	4.5	4.75	0.0	2,320	1,570	1,180	1,970
4.5-461-7	4.5	6.10	0.0	1,570	2,040	1,380	1,880
4.5-461-8	4.5	5.91	0.0	1,660	1,720	1,180	1,950
4.5-461-9	4.5	6.00	0.0	1,380	3,630	1,310	1,970
4.5-461-10	4.5	2.48	0.0	1,850	1,370	1,200	1,770
4.5-461-11	4.5	2.10	0.0	1,730	1,120	1,150	1,740
4.5-461-12	4.5	2.32	0.0	1,770	1,220	1,160	1,470

Experimental Road Section

AFTER concluding the above experiments on oiled samples it was thought that a stretch of experimental road under actual traffic would be desirable in helping to prove the correctness of the conclusions based upon the laboratory tests.

A section of oiled-gravel surfacing was laid on a drive of the Colorado State College campus. The section was laid in September 1934. Its length is 600 feet, and it has a width of 20 feet. The compacted thickness of oiled mat is 2 inches.

The section is composed of 35 mixtures, each varying from the others in one or more of the following respects: (1) oil content; (2) moisture content at time of mixing; (3) grading of the aggregate; (4) percentage of fines added to the mix.

TABLE 3—*Tests 1 to 4 days after construction*

Specimen number	Date compressed	Date tested	Percent oil	Percent water	Total compressive strength
6-320-1-1	Nov. 16	Nov. 17	6.0	0.65	1,030
6-320-1-2	Nov. 16	Nov. 17	6.0	0.65	Fell apart
6-320-1-3	Nov. 16	Nov. 17	6.0	0.65	Fell apart
6-320-1-4	Nov. 16	Nov. 17	6.0	0.65	895
6-320-1-5	Nov. 16	Nov. 17	6.0	0.65	840
6-320-1-6	Nov. 16	Nov. 17	6.0	0.65	880
6-320-2-1	Nov. 16	Nov. 17	6.0	2.50	1,620
6-320-2-4	Nov. 16	Nov. 17	6.0	2.50	1,140
6-320-2-5	Nov. 16	Nov. 17	6.0	2.50	1,170
6-320-2-6	Nov. 16	Nov. 17	6.0	2.50	1,490
4-328-1-1	Nov. 24	Nov. 27	4.0	0.50	1,080
4-328-1-2	Nov. 24	Nov. 27	4.0	0.50	700
4-328-1-3	Nov. 24	Nov. 27	4.0	0.50	940
4-328-1-4	Nov. 24	Nov. 27	4.0	0.50	875
4-328-1-5	Nov. 24	Nov. 27	4.0	0.50	730
4-328-1-6	Nov. 24	Nov. 27	4.0	0.50	885
4-328-2-1	Nov. 24	Nov. 27	4.0	4.70	1,450
4-328-2-2	Nov. 24	Nov. 27	4.0	4.70	1,210
4-328-2-3	Nov. 24	Nov. 27	4.0	4.70	990
4-328-2-4	Nov. 24	Nov. 27	4.0	4.70	985
4-328-2-5	Nov. 24	Nov. 27	4.0	4.70	1,050
4-328-2-6	Nov. 24	Nov. 27	4.0	4.70	1,290
4.5-332-1-1	Nov. 28	Dec. 1	4.5	1.70	1,180
4.5-332-1-2	Nov. 28	Dec. 1	4.5	1.70	965
4.5-332-1-3	Nov. 28	Dec. 1	4.5	1.70	920
4.5-332-2-1	Nov. 28	Dec. 1	4.5	3.00	1,090
4.5-332-2-2	Nov. 28	Dec. 1	4.5	3.00	960
4.5-332-2-3	Nov. 28	Dec. 1	4.5	3.00	1,050
4.5-332-3-1	Nov. 28	Dec. 1	4.5	4.20	1,440
4.5-332-3-2	Nov. 28	Dec. 1	4.5	4.20	1,370
4.5-332-3-3	Nov. 28	Dec. 1	4.5	4.20	1,170
4.5-332-4-1	Nov. 28	Dec. 1	4.5	5.50	1,400
4.5-332-4-2	Nov. 28	Dec. 1	4.5	5.50	1,280
4.5-332-4-3	Nov. 28	Dec. 1	4.5	5.50	1,435
4.5-341-1-1	Dec. 6	Dec. 8	4.5	3.70	2,380
4.5-341-1-2	Dec. 6	Dec. 8	4.5	3.40	1,845
4.5-341-1-3	Dec. 6	Dec. 8	4.5	3.00	2,350
4.5-341-2-1	Dec. 6	Dec. 8	4.5	0.00	700
4.5-341-2-2	Dec. 6	Dec. 8	4.5	0.00	805
4.5-341-2-3	Dec. 6	Dec. 8	4.5	0.00	740
4.5-342-3-1	Dec. 7	Dec. 9	4.5	2.00	1,630
4.5-342-3-2	Dec. 7	Dec. 9	4.5	1.90	1,780
4.5-342-3-3	Dec. 7	Dec. 9	4.5	2.50	1,780
4.5-342-4-1	Dec. 7	Dec. 9	4.5	1.30	1,470
4.5-342-4-2	Dec. 7	Dec. 9	4.5	1.30	1,850
4.5-342-4-3	Dec. 7	Dec. 9	4.5	1.30	1,620
4.5-342-5-1	Dec. 7	Dec. 9	4.5	1.70	860

The oil used throughout was the product of one refinery and met specifications for the MC-2 type of liquid-asphaltic road materials.

The aggregate consisted of bank-run material passing a 1-inch mesh screen and grading close to the Kansas curve except in fines, which were 4.3 percent. To this was added zero, 6, or 10 percent of fines, 95 percent of which passed a 200-mesh sieve. The bank-run material was chiefly feldspathic in nature, with a specific gravity of 2.60. The same gravel was used on all sections. The fines added were silicious, being ore-mill tailings from the dump. The specific gravity of the fines was 2.70.

The natural grading of this material is shown in table 4.

TABLE 4—*Mechanical analysis of aggregate used in experimental road*

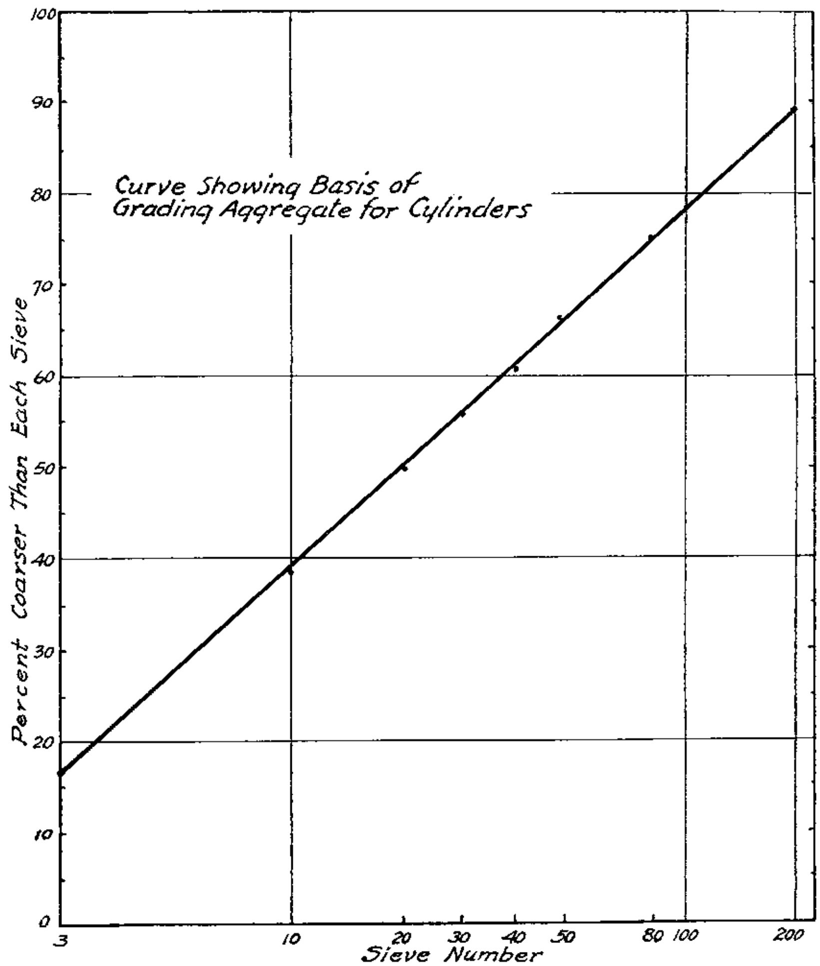
Sieve	Percent passing each sieve	Cumulative percent retained on each sieve
1″	100.0	0
¾″	97.9	2.1
⅜″	92.4	7.6
No. 4	71.5	28.5
No. 10	48.6	51.4
No. 40	14.6	85.4
No. 80	9.1	90.9
No. 200	4.3	95.7
Wash	2.0	98.0

In order to control more closely the proportioning of the various ingredients and to insure well-defined boundaries for each different mix, the same general method of mixing and placing was employed as would have been used for concrete. The proper quantity of the bank-run material was placed in a concrete mixer. To this was added the fines, if used, and the whole was thoroughly blended. If water was to be added it was poured in and several minutes allowed for its absorption and uniform distribution. Lastly the oil was slowly introduced and the mixing process completed. All proportioning was done by weight.

The subgrade had been compacted thoroughly by traffic. At one place there was a 2-foot fill to bring the surface to grade. The surface was bladed smooth and the bank-run aggregate placed upon it and spread. After 5 weeks under traffic the aggregate was bladed into a windrow from which it was taken for the mix. A prime coat of MC-1 oil was applied to the subgrade just before the oiled mat was spread.

As the oil mix left the mixer it was spread on the subgrade and puddled into place with a strike board. The excess was struck off to the forms, and the following day preliminary compaction was given with a 600-pound hand roller.

After the whole section was completed it was opened to traffic, which gave the final compaction. The traffic over the section is light, probably not over 200 cars per day. There is little heavy-truck traffic to which it is subjected.



Because there were not enough experienced men available to carry on extensive laboratory tests at the same time the experimental road was being constructed, there was no laboratory work undertaken until after the road was completed. No doubt, it would have been more desirable, had it been possible, to have taken test specimens from each road section on the day that particular mix was laid, and to have tested them in the laboratory at once. Since this was not possible, the test cylinders were constructed later.

The construction of the cylinders was begun sometime after completion of the road. They consisted of a series of oil-gravel cylinders in groups of three. Each group duplicated the mix used for one of the 35 sections of the road, and there was one group for each

TABLE 5—*Tests for compressive strength after nine months*

Cylinder group number	Percent mill-fines to oven-dry aggregate	Percent oil to total dry aggregate	Percent water to total dry aggregate	Total compressive strength of cylinders made for section
1	10.0	6.0	0.6	870 pounds
2	10.0	6.5	0.6	725 pounds
3	10.0	5.5	0.6	1,240 pounds
4	10.0	5.1	0.6	905 pounds
5	10.0	7.0	0.6	650 pounds
6	10.0	8.6	0.6	350 pounds
7	10.0	4.6	0.6	760 pounds
8	9.8	4.0	0.2	780 pounds
9	10.0	5.1	5.8	1,935 pounds
10	10.0	5.0	4.2	2,330 pounds
11	10.0	5.0	2.1	900 pounds
12	6.0	5.1	0.6	770 pounds
13	6.0	5.6	0.6	590 pounds
14	6.0	6.1	0.6	595 pounds
15	6.2	6.2	1.7	820 pounds
16	6.0	6.5	0.5	605 pounds
17	6.0	4.0	0.5	600 pounds
18	6.0	4.5	0.5	540 pounds
19	6.1	4.5	0.6	780 pounds
20	6.1	5.1	0.6	840 pounds
21	6.1	3.6	0.6	580 pounds
22	6.1	3.0	0.6	995 pounds
23	6.1	4.6	3.3	1,605 pounds
24	6.0	4.6	2.6	850 pounds
25	6.0	4.6	3.6	1,600 pounds
26	6.0	4.5	4.5	765 pounds
27	6.0	4.5	5.5	Broken in test lot
28	6.0	4.5	6.2	1,600 pounds
29	0.0	4.0	0.2	620 pounds
30	0.0	4.0	1.2	1,000 pounds
31	0.0	4.0	2.3	840 pounds
32	0.0	4.1	1.3	1,040 pounds
33	0.0	4.0	3.1	1,245 pounds
34	0.0	4.0	3.9	1,260 pounds
35	0.0	4.0	5.0	1,370 pounds

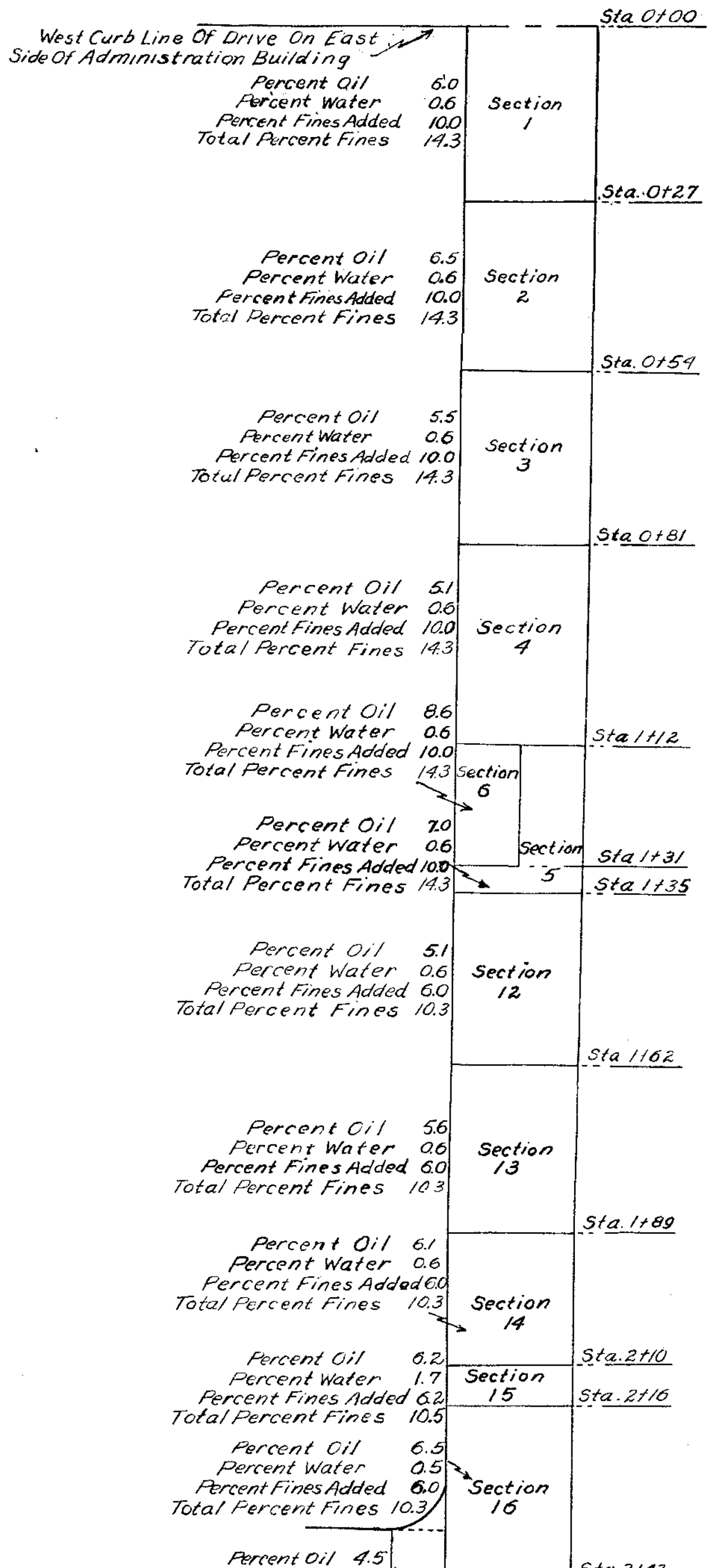
Note: The cylinder group number is the same as the section number of the experimental road. These cylinder tests are classed in four groups in table 6.

section. They were constructed by re-combining aggregate, which had been separated by sieving, in proper proportions to give the grading as designed for that section in the road. One thousand grams of oven-dry aggregate were used for each cylinder, and the proper amounts of water and oil were added. The oil and aggregate were mixed thoroughly, put in 4-inch cylindrical steel molds, and compressed under a load of 1,500 pounds per square inch. The cylinders were then pressed from the molds and put in the test lot out-of-doors. They were placed about one-half inch apart and covered with sand. Then the surface of each was brushed clean, so that it was exposed to the weather.

TABLE 6—*Group classification of cylinder tests*

	Cylinder number	Percent oil content	Percent water at time of mixing	Percent fines added	Percent total fines in mix	Total strength of cylinders
						Pounds
	9	5.1	5.8	10	14.3	1,935
Outstanding strength,	10	5.0	4.2	10	14.3	2,330
1,600 pounds to 2,330	23	4.6	3.3	6.1	10.4	1,605
pounds	25	4.6	3.6	6.0	10.3	1,600
	28	4.5	6.2	6.0	10.3	1,600
	Average	4.76	4.62		11.92	1,814
	3	5.5	0.6	10	14.3	1,240
	30	4.0	1.2	0	4.3	1,000
	32	4.1	1.3	0	4.3	1,040
Good strength, 1,000	33	4.0	3.1	0	4.3	1,245
pounds to 1,600	34	4.0	3.9	0	4.3	1,260
pounds	35	4.0	5.0	0	4.3	1,370
	Average	4.27	2.52		5.97	1,192
	1	6.0	0.6	10	14.3	870
	2	6.5	0.6	10	14.3	725
	4	5.1	0.6	10	14.3	905
Class 1	5	7.0	0.6	10	14.3	650
	6	8.6	0.6	10	14.3	350
High oil content,	11	5.0	2.1	10	14.3	900
above 5 percent	12	5.1	6.6	6.0	10.3	770
	13	5.6	0.6	6.0	10.3	590
Low-strength cylin-	14	6.1	0.6	6.0	10.3	595
ders, 350 pounds to	15	6.2	1.7	6.2	10.5	820
1,000 pounds	16	6.5	0.5	6.0	10.3	605
	20	5.1	0.6	6.1	10.4	840
	Average	6.07	.80		12.32	718
	7	4.6	0.6	10	14.3	760
Class 2	8	4.0	0.2	9.8	14.1	780
	17	4.0	0.5	6.0	10.3	600
Below 5 percent oil	18	4.5	0.5	6.0	10.3	540
	19	4.5	0.6	6.1	10.4	780
Low-strength cylin-	21	3.6	0.6	6.1	10.4	780
ders, 350 pounds to	22	3.0	0.6	6.1	10.4	995
1,000 pounds	24	4.6	2.6	6.0	10.3	850
	26	4.5	4.5	6.0	10.3	765
	29	4.0	0.2	0.0	4.3	620
	31	4.0	2.3	0.0	4.3	840
	Average	4.11	1.2		9.94	755

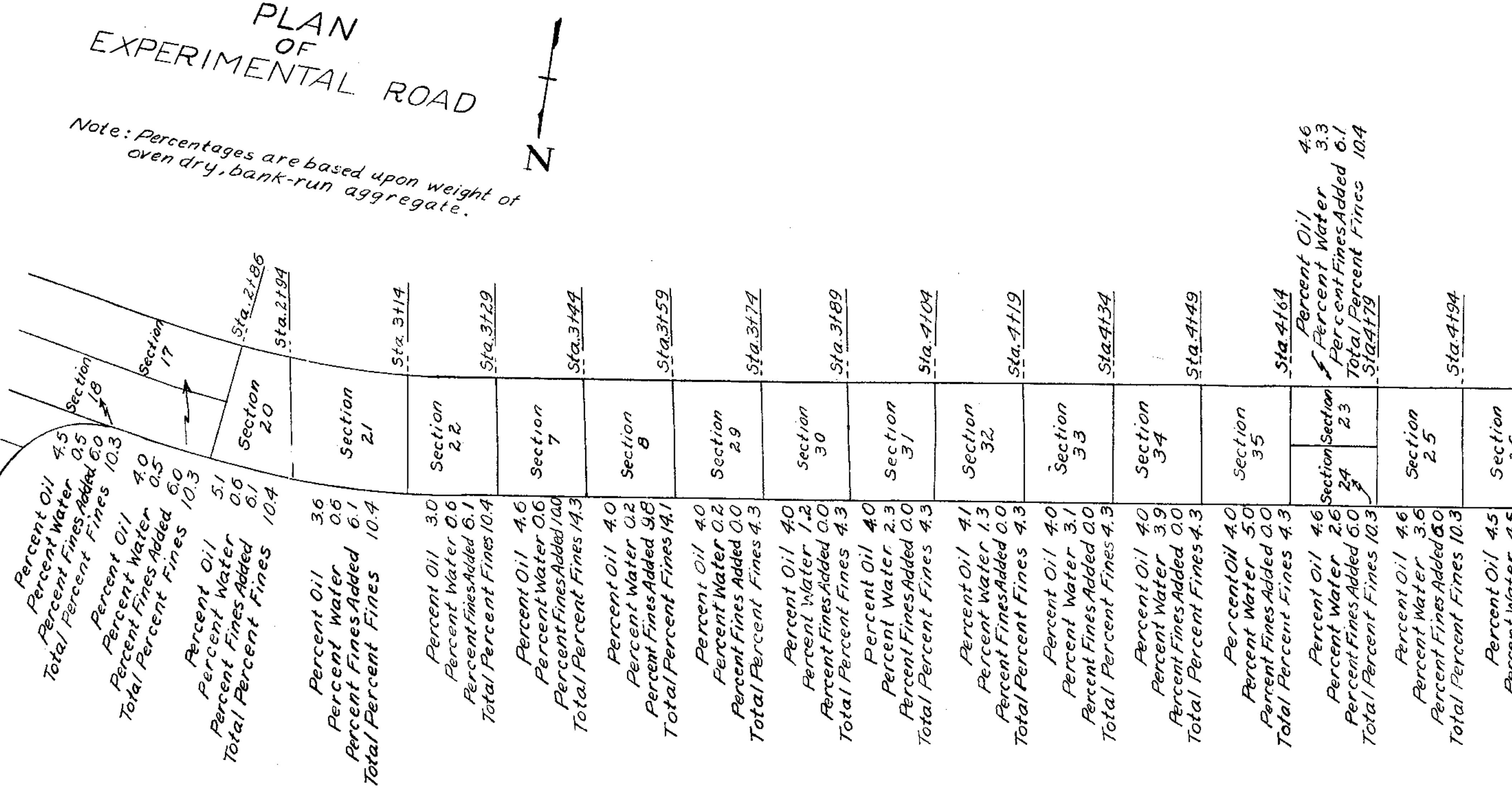
After the cylinders had been in the test lot for about 9 months they were removed and tested for compressive strength. Table 5 shows the results of these tests. The **total** load sustained was recorded, rather than the loads in pounds per square inch. This recorded load is the average load sustained by each group of three cylinders.



Sta 0+00
West Curb Line Of Drive On East Side Of Administration Building
Percent Oil 6.0
Percent Water 0.6
Percent Fines Added 10.0
Total Percent Fines 14.3
Section 1
Sta. 0+27
Percent Oil 6.5
Percent Water 0.6
Percent Fines Added 10.0
Total Percent Fines 14.3
Section 2
Sta. 0+54
Percent Oil 5.5
Percent Water 0.6
Percent Fines Added 10.0
Total Percent Fines 14.3
Section 3
Sta 0+81
Percent Oil 5.1
Percent Water 0.6
Percent Fines Added 10.0
Total Percent Fines 14.3
Section 4
Percent Oil 8.6
Percent Water 0.6
Percent Fines Added 10.0
Total Percent Fines 14.3
Sta 1+12
Section 6
Percent Oil 7.0
Percent Water 0.6
Percent Fines Added 10.0
Total Percent Fines 14.3
Section 5
Sta 1+31
Sta 1+35
Percent Oil 5.1
Percent Water 0.6
Percent Fines Added 6.0
Total Percent Fines 10.3
Section 12
Sta 1+62
Percent Oil 5.6
Percent Water 0.6
Percent Fines Added 6.0
Total Percent Fines 10.3
Section 13
Sta. 1+89
Percent Oil 6.1
Percent Water 0.6
Percent Fines Added 6.0
Total Percent Fines 10.3
Section 14
Sta. 2+10
Percent Oil 6.2
Percent Water 1.7
Percent Fines Added 6.2
Total Percent Fines 10.5
Section 15
Sta. 2+16
Percent Oil 6.5
Percent Water 0.5
Percent Fines Added 6.0
Total Percent Fines 10.3
Section 16
Percent Oil 4.5

PLAN OF EXPERIMENTAL ROAD

Note: Percentages are based upon weight of oven dry, bank-run aggregate.



Condition of Road After 21 Months

INSPECTIONS of the experimental road have been made from time to time. After it had been in service for a period of 21 months an inspection was made on June 6, 1936 which showed it as a whole to be in fair condition. Some sections containing the most oil were soft, with some rolling indicating an excess of oil. Had the rich sections been longer, there probably would have been more rolling.

A few of the rich sections contained alligator cracking. Other sections showed a roughening of the surface due to insufficient oil. On these sections the aggregate at the surface had been separating from the mat due to the action of traffic and wind. The pitting, however, was in most cases over the whole surface and not in holes.

Only a few sections showed holes forming. The surface appears hard and firm except on the rich-oiled sections, and a good seal coat will stop the separation of aggregate from the matrix and produce a good and lasting road surface.

A few sections have raveled and worn and have holes in the mat averaging about 1 foot in diameter and about one-half inch deep. In one section there are two holes 2 to 3 inches in depth.

The subsoil under the entire road is dry and in good condition.

Following is the condition of the road section by section on June 6, 1936, about 21 months after construction:

Section 1.—Oil 6 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 870 pounds.

This section was evidently too rich in oil. It has been soft from the start. There is alligator cracking over an area 18 feet long by 9 feet wide. It is somewhat rutted. On the south half there are two rolls. The surface of this south half is black in color. The north half of this section is much better than the south half. The mat on this half has a very different appearance. It is much lighter in color on the whole, although there are a number of black spots caused by "bleeding." These spots will average 8 inches in diameter. Some traffic hits this section on a curve at the place where cracking and rolling occurs.

Section 2.—Oil 6.5 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 725 pounds.

This section, although it contains one-half percent more oil and the same water and fines as section 1, is in better condition. There is no rutting and no cracking. There is one roll at the southwest corner. Were the section longer there would probably be more rolling, as the south four-fifths of the section is soft on warm days. The surface here is jet black.

Similar to section 1, the north one-fifth of this section is much lighter in color, and there are four black spots along the north edge due to bleeding.

Section 3.—Oil 5.5 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 1,240 pounds.

This section is in much better condition than sections 1 and 2. Most of the surface has the same light color of the north parts of the two previous sections. Bleeding has formed a black strip averaging 3 feet wide the entire length and at the center of the section. There are black spots varying in size on each side of this strip. There are no cracking, rolls, or rutting, and no pitting. The section is in fair condition.

Section 4.—Oil 5.1 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 905 pounds.

This section is in good condition. It has a light color over most of its area. There is a narrow, black strip 6 inches wide along the center and a few black spots on each side of the strip. There are no cracks, no rolls, and no ruts. A very slight loosening of pebbles at the surface has caused a slight roughness. A seal coat is needed to stop this, and were this applied the section would be in "A-1" condition.

Section 5.—Oil 7 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 650 pounds.

This section is in bad condition. Although it contains 1.6 percent less oil than the following section, number 6, it is in worse condition. It has "bled" less but shows cracking and rolling. Section 5 is better on the north side than on the south side, as are most of the sections on this stretch of road. The reason for this is unknown. This is probably the worst section on the road.

Section 6.—Oil 8.6 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 350 pounds.

This section contains the greatest amount of oil of any section on the road, and the test cylinder from it showed the least strength.

The section is better on the north side than on the south side. It has a jet-black surface and shows much bleeding. It has bled so badly that oil has run on the surface. It has slight rolls, and with heavier traffic would surely rut and roll more, as it is still soft and spongy. There is no cracking visible, and if cracks have formed they have been sealed by the bleeding.

Section 6 is one of the really poor sections of the road.

Section 7.—Oil 4.6 percent; water 0.6 percent; total fines 14.3 percent; cylinder strength 760 pounds.

This section is in good condition. There is no bleeding, and it has about the same color throughout. Some aggregate has loosened at the surface, and the entire section is slightly rough. The pitting is worst near the west end. A seal coat would stop this and is needed on this section. There are no rolling, rutting, or cracking.

Section 8.—Oil 4 percent; water 0.2 percent; total fines 14.1 percent; cylinder strength 780 pounds.

This section is not as good as section 7. The pitting is much worse, and holes are starting. The holes are only about one-fourth inch deep and about 1 foot in diameter.

The section will fail in time by raveling. There are no ruts, rolls, or cracks. The section needs a seal coat badly.

Section 9.—Oil 5.1 percent; water 5.8 percent; total fines 14.3 percent; cylinder strength 1,935 pounds.

This is one of the best sections on the road. There are no ruts, rolls, or cracks, and the only fault is a very slight separation of the surface pebbles, causing a slight roughness. A seal coat would put this section in perfect condition.

Section 10.—Oil 5.0 percent; water 4.2 percent; total fines 14.3 percent; cylinder strength 2,380 pounds.

This is another good road section. Slightly smoother than section 9, otherwise it appears about the same. Sections 9 and 10 are among the very best on the entire road. It would seem that the increased water content and correspondingly increased cylinder strength of the matrix are also evident in the increased wearing qualities of the matrix in these two sections.

Section 11.—Oil 5.0 percent; water 2.1 percent; total fines 14.3 percent; cylinder strength 900 pounds.

This is the last section on the road and next to section 10. It contains the same amount of oil and fines but only half as much water. Its cylinder strength is only about half as great as that of number 9 cylinder, and yet from all appearances it is wearing just as well. It has the same surface appearance, and a seal coat would improve it. We list it as one of the good sections of the road. There are no rolls, cracks, or pitting.

Section 12.—Oil 5.1 percent; water 0.6 percent; total fines 10.3 percent; cylinder strength 770 pounds.

The only difference between section 4 and this section is in the percentage of fines. The oil and water content is the same.

The two sections (4 and 12) have about the same appearance. Section 12, however, is slightly more pitted. It would seem that the reduction of fines has decreased the cylinder strength somewhat and gives less binder to help hold the larger pebbles, hence the increase in pitting. A seal coat would help this section very much. There are two spots where it has bled a little, but there are no rolls, no cracks, and no ruts.

Section 13.—Oil 5.6 percent; water 0.6 percent; total fines 10.3 percent; cylinder strength 590 pounds.

An increase of 0.5 percent of oil in this section has caused more bleeding than in section 12. The bleeding has occurred at the center, and the strip is 5 feet wide. The surface of this strip is black. Both sides of the section are much lighter in color. The pitting is slightly less, and we rate the section as in good condition. On neither side of the central strip is there any bleeding. There are no rolls, no cracks, and no ruts in section 13.

Section 14.—Oil 6.1 percent; water 0.6 percent; total fines 10.3 percent; cylinder strength 595 pounds.

This section is not very good, and the increase of the oil content has been detrimental. There is more bleeding at the center than in sections 12 and 13. The black strip here is 12 feet wide. It appears to be soft on warm days. There are some cracks in places. It is slightly rutted in one place, and a slight roll is at the side of the rut near the south side of this section. It is very slightly pitted near the edges, where the oil seemingly has escaped in some way.

Section 15.—Oil 6.2 percent; water 1.7 percent; total fines 10.5 percent; cylinder strength 820 pounds.

In this section the increase in the water content and the slight increase in fines has raised the cylinder strength. The section is in about the same condition as section 14, with bleeding at the center where it is soft when warm. There are slight ruts and rolls, and some cracks.

Section 16.—Oil 6.5 percent; water 0.5 percent; total fines 10.3 percent; cylinder strength 605 pounds.

The decrease in water content in this section has decreased the cylinder strength. The slight increase in the oil content has made the section black all over its surface to within 6 feet of the south edge. It has bled badly but has not rutted, rolled, or cracked. Much traffic hits this section on a curve, and it has held up well under adverse conditions.

Section 17.—Oil 4.0 percent; water 0.5 percent; total fines 10.3 percent; cylinder strength 600 pounds.

This section is in only fair condition. The west 10 feet contains slight depressions which will in time form holes. Traffic hits the section on a curve where the holes have started. There is slight pitting over the entire section, and it needs a seal coat to strengthen the surface. There are no bleeding, no ruts, no rolls, and no cracks.

Section 18.—Oil 4.5 percent; water 0.5 percent; total fines 10.3 percent; cylinder strength 540 pounds.

This section is fair to good. It is better than section 17, although the cylinder strength was slightly less. It shows less pitting and no holes starting. There are no rolls, ruts, or cracks.

Section 19.—Oil 4.5 percent; water 0.6 percent; total fines 10.4 percent; cylinder strength 780 pounds.

This section is in fair to good condition. It is better than sections 17 and 18. It has not rolled, rutted, or cracked. Traffic hits it on a curve, and it shows some wear on the east and west sides.

Section 20.—Oil 5.1 percent; water 0.6 percent; total fines 10.4 percent; cylinder strength 840 pounds.

This is a very small section. It is on a curve, and traffic hits it on a curve. The narrowest part of it is on the sharpest curve. As far as appearance goes it is standing up as well as any section on the road. There is no cracking, rolling, or rutting, and no perceptible pitting. Being so small where the traffic hits it, we have not considered it a fair section and have, therefore, discarded it.

Section 21.—Oil 3.6 percent; water 0.6 percent; total fines 10.4 percent; cylinder strength 580 pounds.

This section is rated in the poor list. Pitting is pronounced along the south side, and two holes have started at the west end. Slight pitting extends over the entire section, although it is not as pronounced as along the south side. There is evidently too little oil in this section.

Section 22.—Oil 3.0 percent; water 0.6 percent; total fines 10.4 percent; cylinder strength 995 pounds.

This is a poor section, one of the worst on the road. It is badly pitted over the entire section and very rough. Holes have started in many places, and two of them extend clear through the oiled mat. Appearances show it to be too lean in oil. There is no rutting, rolling, or cracking.

Section 23.—Oil 4.6 percent; water 3.3 percent; total fines 10.4 percent; cylinder strength 1,605 pounds.

This is an excellent section, one of the best on the road. There is no rolling, rutting, or cracking. The surface is slightly rough, but there is no perceptible pitting. A seal coat would put this section in perfect condition.

Section 24.—Oil 4.6 percent; water 2.6 percent; total fines 10.3 percent; cylinder strength 850 pounds.

This section is not as good as section 23, but there is not very much difference as far as appearances go at this time.

The decrease in water of 0.7 percent has decreased the cylinder strength to 53 percent that of section 23. It is not wearing as well as section 23 and should be classed as a good section in the second class of sections.

Section 25.—Oil 4.6 percent; water 3.6 percent; total fines 10.3 percent; cylinder strength 1,600 pounds.

This is another good section. The increase of 1 percent in the water content has brought the cylinder strength up to 1,600 pounds. The section is a little rough along the edges, but as a whole it is one of the best on the road. It is grey in color and well bound except at the extreme edges. There are no rolls, no ruts, no cracks, and no bleeding.

Section 26.—Oil 4.5 percent; water 4.5 percent; total fines 10.3 percent; cylinder strength 765 pounds.

The surface of this section has worn slightly rough, and it is slightly pitted. It is far from being a poor section but is not as good as section 25. Probably the slight decrease in oil content has caused this. It shows need of a seal coat, and when this is applied it will be one of the best sections. This section should be rated high in the second class of sections, although the cylinder strength places it in the third class. There are no rolls, no ruts, no cracks.

Section 27.—Oil 4.5 percent; water 5.5 percent; total fines 10.3 percent; cylinder strength ....

The cylinders for this section were accidentally broken in the test lot. We believe they would have tested well, as the percentage of water is higher by 1 percent than in the preceding section. It is difficult to see much difference between this section and section 26, except that it is somewhat better at the edges. It should be rated in the first class of sections. There are no ruts, no rolls, and no cracks. A seal coat is needed.

Section 28.—Oil 4.5 percent; water 6.2 percent; total fines 10.3 percent; cylinder strength 1,600 pounds.

This section is slightly better than sections 26 and 27, and the only difference is the extra water used. There is no question that water in the aggregate improves the oiled matrix; it is shown progressively in these three sections (26, 27, 28). This section is one of the best on the road. A seal coat would put it in perfect condition. It has no rolls, ruts, pits, or cracks.

Section 29.—Oil 4.0 percent; water 0.2 percent; total fines 4.3 percent; cylinder strength 620 pounds.

In this section the reduction of oil, water, and fines has cut the cylinder strength to 39 percent of the former section where more oil, water, and fines were used. Over the south half of this section the surface is rough due to loosening of the surface gravel by traffic. The pitting is not as bad over the north half. It is in about the same condition as section 8, next to it. It needs a seal coat badly. It has no rolls, ruts, bleeding, or cracks.

Section 30.—Oil 4 percent; water 1.2 percent; total fines 4.3 percent; cylinder strength 1,000 pounds.

In this section the increase of water has again raised the cylinder strength, and the section shows a decided improvement over section 29, next to it. The pitting is less, but it shows need of a seal coat to make it a good section. There is no bleeding, and there are no ruts, rolls, or cracks.

Section 31.—Oil 4.0 percent; water 2.3 percent; total fines 4.3 percent; cylinder strength 840 pounds.

This section is not quite as good as section 30. The increase of 1.1 percent of water is not manifest in either the cylinder strength or the wearing qualities of the matrix. There is a slight pitting, and it shows need of a seal coat. When that is applied it will be a good section. It has no bleeding, ruts, rolls, or cracks. It should be rated very high in the second-class sections.

Section 32.—Oil 4.1 percent; water 1.3 percent; total fines 4.3 percent; cylinder strength 1,040 pounds.

This section is a good section, slightly better than section 31 as far as pitting is concerned, and should be classed low in the first-class sections, or at least as one of the best in the second class. It needs a seal coat. There is no bleeding, and there are no ruts, rolls, or cracks.

Section 33.—Oil 4.0 percent; water 3.1 percent; total fines 4.3 percent; cylinder strength 1,245 pounds.

The increase of water in this section is shown in the increased cylinder strength. The only fault to be found with the section is the pitting, which is slightly more than in section 32 and about the same as in section 31. It needs a seal coat. No other faults are to be found in this section.

Section 34.—Oil 4.0 percent; water 3.9 percent; total fines 4.3 percent; cylinder strength 1,260 pounds.

This section is pitted slightly more than section 33 along the north side; otherwise it is, from all appearances, about the same. It needs a seal coat badly. Otherwise there are no faults in the section.

Section 35.—Oil 4.0 percent; water 5.0 percent; total fines 4.3 percent; cylinder strength 1,370 pounds.

This section is better than section 34, and the only difference is the increase of 1.1 percent of water in the aggregate. There is a slight pitting or loosening of the surface gravel under traffic, making a rather rough surface. Otherwise there is no fault to find with this section. A seal coat, however, is needed.

The last seven sections show that acceptable oiled roads may be constructed with some natural Colorado gravels, deficient in fines though they are. Added fines are advisable, but we believe that a seal coat will hold the surface gravel in place.

Analyzing the Data

IN ANALYZING the foregoing data from the experimental road we group these sections into four classes: first class, second class, third class, and fourth class.

First-class sections are those which were in excellent condition at the time of this inspection, June 6, 1936.

Second-class sections are those which were in good condition on that date. We have this class divided into two parts: those sections of high oil content, containing more than 4.5 percent; and those of low oil content, containing 4.5 percent or less.

Third-class sections are those in **fair** condition after 21 months under traffic; and these are also divided into high and low oil content on the same basis.

Fourth-class sections are those sections in **poor** condition at this time and are divided into high and low oil content.

This classification is shown in table 7.

TABLE 7—*High and low oil content of sections*

First-class sections	Second-class sections		Third-class sections		Fourth-class sections	
Excellent	Good High oil	Good Low oil	Fair High oil	Fair Low oil	Poor High oil	Poor Low oil
9	4	8	3	17	1	21
10	7	19	16	18	2	22
23	11	26	..	..	5	..
25	12	29	..	..	6	..
27	13	30	..	..	14	..
28	24	31	..	..	15	..
..	..	32	..	..	..	..
..	..	33	..	..	..	..
..	..	34	..	..	..	..
..	..	35	..	..	..	..

First-Class Group.—In analyzing these different groups it should be noted that in the first-class group: The oil content in the six first-class sections runs between 4.5 percent and 5.1 percent, and averages 4.7 percent; the water content ranges between 3.3 percent and 6.2 percent, and averages 4.7 percent; the fines in these six sections lie between 10.3 percent and 14.3 percent, and average 11.6 percent.

It is also to be noted that five of these six best sections of the experimental road also showed the highest cylinder strength, averaging 1,814 pounds, and the fines were all above 10 percent.

It would seem only fair to conclude that:

1. High cylinder strength of a matrix indicates a lasting and well-wearing one, and this test for strength should always be made when the matrix is being designed.

2. Water in the aggregate up to 6 percent is **beneficial** to the matrix.

3. The grading of the aggregate should conform closely to the Kansas curve of "maximum density."

4. With this grading the oil content should be between 4.5 percent and 5 percent for the **best** results.

It is difficult to classify some of these road sections. There is no distinct dividing line. The good sections of one class are so nearly the same as the poor sections of the next higher class that probably no two men would exactly agree on classifications. We have, therefore, placed all sections which could not be called **excellent** in the group of second-class sections. These second-class sections are good oiled-road sections, but each shows some slight defect which keeps it out of the first class.

Second-Class Group.—There are 16 sections in this group, of which six are in the high oil content class. The oil content of this class is between 4.6 percent and 5.1 percent, and averages 5.0 percent. The water content is between 0.6 percent and 2.6 percent, and averages 1.2 percent. The fines vary between 10.3 percent and 14.3 percent, and average 12.3 percent.

The low oil content class has an oil content ranging from 4.0 percent to 4.5 percent, and averages 4.1 percent. The water content varies from 0.2 percent to 5.0 percent, and averages 2.2 percent. The fines run from 4.3 percent to 14.3 percent, and average 6.4 percent.

From this it would seem that a satisfactory road may be constructed from a well-graded, disintegrated-granite aggregate with an oil content from 4 percent to 5.1 percent, a water content from 0.2 percent to 5 percent, and fines from 4.3 percent to 14.3 percent. The greater percentages of fines require the higher percentages of oil.

Third-Class Group.—There were four sections only in this group, two in each class. In the high-oil class the percentage of oil was 5.5 percent and 6.5 percent, the water content .06 percent and 0.5 percent, and the fines 14.3 percent and 10.3 percent.

In the low class the oil was 4.0 percent and 4.5 percent, the water was 0.5 percent, and the fines were 10.3 percent.

We feel that the high oil content and low water content caused the deterioration of this group of sections.

Fourth-Class Group.—There are eight sections in this group, which is rated decidedly poor oiled road.

In the high-oil class of poor sections the oil content varied from 6 percent to 8.6 percent, and averaged 6.7 percent; the water content varied from 0.6 percent to 1.7 percent, and averaged 0.8 percent; and the fines varied from 10.3 percent to 14.3 percent, and averaged 13 percent.

In the low-oil class of poor sections there were only two sections with oil content 3.0 percent and 3.6 percent, water content 0.6 percent, and fines 10.4 percent.

All that can be said of this group of sections is that the excessive oil content in the one class caused them to roll, rut, and crack; while in the other class there was so little oil that they have failed by raveling.

Determining Amount of Oil

IT IS, of course, important to determine the proper and most economical amount of oil to use in designing any matrix. A number of methods have been suggested for this. Probably the outstanding one is known as the "surface area method" suggested by F. N. Hveem of the California Highway Department. His research work showed that the proper amount of oil in an aggregate is the amount necessary to cover the surface of all particles of the aggregate. It therefore depends upon the surface area of these particles and also upon the fact that the film thickness of oil must diminish as the diameter of the particle diminishes.

Different kinds of aggregates contain different-shaped pebbles which have different surface areas. Different kinds of aggregates have different absorption properties, and so different equations must be used for different kinds of aggregates with varying degrees of roughness of the pebbles.

Mr. Hveem has worked out tables from which the surface area of an aggregate can be found from the sieve analysis and, when that is known, a chart of curves from which the weight of oil necessary per pound of aggregate is obtained.

These have been published, and those interested are referred to the Asphalt Institute, 801 Second Avenue, New York City, for bulletins containing full details of this method.

As the surface area of **fine** particles in an aggregate is much greater per pound of material than the surface area of the larger particles per pound, the grading of the aggregate, and especially the percentage of fines in the aggregate, has a tremendous influence upon the percentage of oil required for the matrix.

Wyoming Formula.—A formula suggested by the Wyoming Highway Department for computing the proper percentage of oil for an aggregate, which is the old California formula changed for Wyoming aggregates, is as follows:

$$P = (0.015a + 0.03b + 0.17c)\ 1.4$$

Here P = percentage of oil required in terms of the dry weight of aggregate.

a = percentage of aggregate retained on number 10 sieve.

b = percentage of aggregate passing number 10 sieve and retained on number 200 sieve.

c = percentage of aggregate passing number 200 sieve.

This formula gives satisfactory results as far as performance of the mix is concerned but slightly high results from the standpoint of economy.

New Mexico Formula.—The New Mexico Highway Department suggests the following formula:

$$P = 0.02a + 0.07b + 0.15c + 0.2d$$

Here P = percentage of oil by weight to dry weight of the aggregate.

a = percentage of aggregate retained on a number 50 sieve.

b = percentage of aggregate passing number 50 and retained on number 100 sieve.

c = percentage of aggregate passing number 100 and retained on number 200 sieve.

d = percentage of aggregate passing number 200 sieve.

The results from this formula are quite similar to those of the middle curve or average of the surface area method of determination.

It is our opinion, based upon the results of our experimental road, that it is better and more economical to design the mix a little dry in oil and then hold the surface pebbles from raveling by a seal coat of cutback asphalt than to use the full amount of oil throughout the matrix.

The sections of road so prepared by us show better compaction and are more stable; the only fault in them is the slight loosening of pebbles at the surface under traffic. These pebbles will all be held in place by the seal coat.

Colorado State College Formula.—We suggest the following formula:

$$P = 0.012a + 0.055b + 0.08c + 0.19d$$

Here P = percentage of oil by weight.

a = percentage of aggregate retained on number 14 sieve.

b = percentage of aggregate passing number 14 and retained on number 100 sieve.

c = percentage of aggregate passing number 100 and retained on number 200 sieve.

d = percentage of aggregate passing number 200 sieve, including loss in decantation.

From the mechanical analysis of the aggregate in the "excellent" sections of the experimental road, and for a comparison of the actual oil used in each with the different formula results of the correct percentage to use, table 8 has been prepared.

TABLE 8—*Oil used in various formulas*

Section number	Percent oil actually used	Percent oil surface area method	Percent oil by Wyoming formula	Percent oil by New Mexico formula	Percent oil by recommended formula
9	5.1	5.20	5.50	5.01	5.1
10	5.0	5.20	5.50	5.01	5.1
23	4.6	5.15	5.05	5.03	4.7
25	4.6	5.15	5.05	5.03	4.7
27	No mechanical analysis taken for this section				
28	No mechanical analysis taken for this section				
Kansas maximum density grading		5.34	5.33	5.96	5.37

Conclusions

CONDITIONS necessary for first-class oiled roads are:

1. A well compacted, dry subgrade.

2. Adequate drainage to obtain this.

3. Even distribution of oil throughout the matrix. This cannot be accomplished without adequate machinery; an oil distributor and blade mixing give a very irregular oil content. Use of mixing machines, in which oil is under constant control, and thorough mixing are essential.

4. Oil content of the mix must be changed for different aggregates and aggregate grading.

5. The formula recommended will produce a slightly dry matrix which, as soon as compact, should be treated with a seal coat sufficient to well cover the road surface and to be evenly distributed.

6. Water in the aggregate up to 6 percent **improves** the matrix and makes a stronger and better wearing road surface, provided the materials are well mixed.

7. The proper grading of aggregate is advisable, and a fairly close coincidence between the "Kansas Maximum Density" curve and the aggregate used is necessary for first-class oiled roads.

8. Fines in the aggregate are especially important and should not be less than 10 percent. If these are not present in the bank run of aggregate, they should be supplied by adding mill fines or mixing with other aggregates to produce the proper grading.

9. No aggregate should be used without making frequent mechanical analyses.