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16. ABSTRACT

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The grading of aggregates may be judged by several unrelated criteria such as economy, permeability, workability, surface texture of finished pavements, oil demand, and stability. Grading curves, with tolerance limits wide enough for average plant production, are given to show gradings which have proven satisfactory.

Formulae for determination of oil content involve surface area analysis. The report describes a method and gives a table of surface area constants and curves. The surface area is multiplied by the bitumen index to get the amount of oil required. A bitumen index chart is shown with curves which apply for particle surface textures with different degrees of roughness from glassy to vesicular.

A machine has been devised to test the stability of bituminous mixtures. Deformation of the specimen results in pressure on a liquid. Laboratory tests with this "Stabilometer," have been correlated with pavement service. For susceptibility to moisture of oil roads, the laboratory uses modified procedures of methods developed by the Arizona Highway Testing Laboratory. A water-asphalt preferential test has been adopted to determine the water-resisting properties of a filler to be used in a bituminous mixture. A swell test is used to determine the effect of water on oil mixes. This test is considered to be the most reliable for predicting the effect of water on the road surface.

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RÔLE OF THE LABORATORY IN THE PRELIMINARY INVESTIGATION AND CONTROL OF MATERIALS FOR LOW COST BITUMINOUS PAVEMENTS

RÔLE OF THE LABORATORY IN THE PRELIMINARY INVESTIGATION AND CONTROL OF MATERIALS FOR LOW COST BITUMINOUS PAVEMENTS

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SYNOPSIS

In this report, the value of careful laboratory control of materials used in low cost bituminous pavements is demonstrated. The paper outlines the methods which have been adopted in California and discusses the various factors involved in the problem.

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This report outlines procedure for the laboratory control of materials used in the construction of low cost bituminous pavements, and demonstrates that such control is as desirable as in the case of expensive hard surface pavement construction.

Increasing mileage and diminishing funds per mile have combined to increase the importance of the low cost road surfacing problem, and the consequent stress on economical construction leads to the utilization of the cheapest local aggregate obtainable. On the other hand, the probability of excessive maintenance cost due to unsatisfactory quality may rule out the cheapest source of supply. Therefore intelligent consideration requires a balancing of first cost against annual maintenance, with due consideration for available funds and traffic needs.

Many failures and subsequent excessive reconstruction and maintenance costs have been incurred through the use of faulty materials when the original cost would have been but little increased, and the subsequent maintenance problems negligible, had there been more rigid laboratory control.

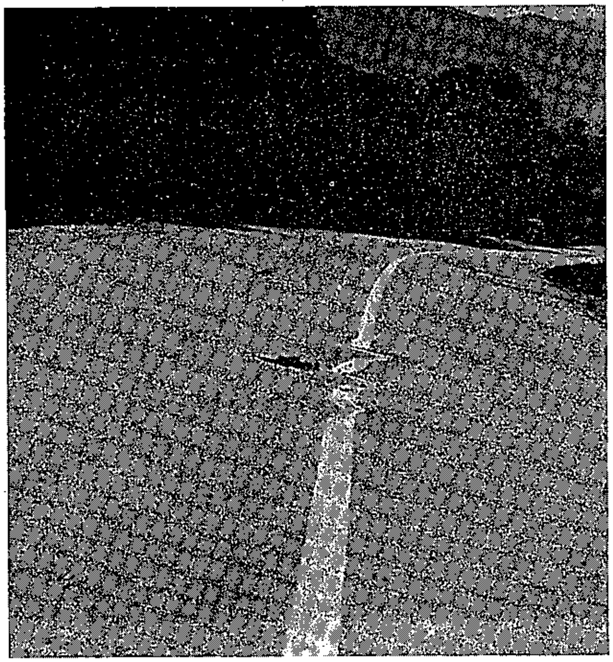

Figure 1. Distortion of Traffic Stripe Due to Small Unstable Area on Center Line.

Up to recent years, most laboratory tests were made solely for the purposes of identification and control, to ensure that the materials complied with specification requirements. There is, however, another important contribution which can be made by the laboratory to ensure quality in the finished product. Through the conduct of preliminary investigations and trial designs of special combinations of materials, a given design or combination can be tested in the laboratory on a small scale without the necessity of risking a large investment in more or less experimental construction.

The grade of materials and requisite tests in Class A pavement construction are fairly well defined. This is not so true of low cost pavement construction, and therefore considerably greater laboratory initiative and advice is frequently required with this type of surface to ensure satisfactory quality of work while maintaining low cost.

Economy in construction is the first essential in designing the cheap pavement, and this factor requires that the most readily obtainable suitable local materials be used. Local sources of supply, while economically desirable, will nevertheless develop considerable variety from one region to another. If uniformly satisfactory pavement surfaces are to be constructed, using aggregates covering a wide range of character, it becomes necessary to vary the construction methods and exercise discretion in the choice of the bituminous binder in order to compensate for variation in aggregates and conditions.

The second requirement, probably of equal importance to low construction cost, is low maintenance cost. It frequently happens that local mineral aggregates are obtainable which represent a wide range in quality, with the more desirable aggregate requiring a greater initial outlay. A choice of the most efficient design can be made only with an accurate prior knowledge of the relative quality and probable service of the materials. In order to utilize all materials which have possibilities for successful combination, laboratory tests and standards of quality must be in close harmony with the requirements of the finished pavement. If the greatest economy is to be attained, no material should be rejected which may give a practicable surface; but on the other hand, no aggregate should be used without accurate knowledge as to its capacity for trouble.

To achieve this desirable end, laboratory tests must be correlated with pavement behavior. It should be possible to predict the extent to which any material, or combination of materials, will resist the destructive action of traffic and the elements. Any pavement which distorts under traffic or which deteriorates due to exposure or the action of water should show the characteristics of such failures in proper laboratory tests.

The various control factors and phases of the work will be discussed under separate headings, with an outline of the manner in which the problem is being approached in California and the methods which have thus far been adopted to meet it.

GRADING OF AGGREGATES

Before discussing the merits or demerits of various gradings of mineral aggregates it will be well to consider the reasons for requiring any particular grading or tolerance limits.

In other words, one should set forth the qualities or benefits to be achieved by a "well graded aggregate" as compared to a poorly graded material.

A casual survey of bituminous pavements already in existence shows that successful results have been obtained at some time in one locality or another with practically every combination of rock particle sizes. In California, for example, existing roads range from penetration macadam without fines and with large spaces between particles, to oiled pavements consisting entirely of material passing a 20-mesh sieve. It is also true that poor results may be found in each type of grading.

It is difficult to find evidence to prove that low void volume is the sole or even an essential measure of quality. This department has long since abandoned voids determination in the design of road oil and cutback mixtures.

It is evident, however, that grading of aggregates does have an effect, either during construction or in the finished product, and it is proposed to set forth at least a few of the factors which are affected by grading, with the premise that "density" is not of itself an essential goal and bears no predictable relation to desirable quality.

Study of the effects of various gradings has led to the belief that there are a number of points or criteria by which gradings should be judged. For instance, engineers engaged in portland cement concrete construction will discuss a grading in terms of "workability" perhaps more often than any other quality.

And, in like manner, the following items are suggested as being the most important in bituminous mixture design: economy, permeability, workability, surface texture of the finished pavement, and, for practical construction, a grading not too critical as to oil demand.

Stability[1] of the mixture, in individual cases, may be affected by the percentage of certain sizes in the combination. For instance, in a given case, an increase in 40-mesh sand may show corresponding and consistent loss in stability. In a second instance, an increase in the amount of sand between the 10 and 30-mesh may be the cause of low stability. In still other cases, however, the same changes in gradation may not produce corresponding loss in stability, or may even result in improvement. While we have by no means investigated all the possibilities, it appears that stability is unpredictably affected, if at all, by changes in grading.

The ideal grading must satisfy all of the various requirements to some degree. From a practical standpoint, the grading to be used represents a compromise. For efficiency of design it is not enough to assume that a "straight line grading," or grading giving maximum density or a certain fineness modulus, will sufficiently meet all these requirements. Each item must be considered separately as the following paragraphs will illustrate.

[1] The term "stability," as used in this paper, is intended to express that property of bituminous pavements which tends to resist plastic deformation. Unstable pavements are considered to be those which corrugate or groove under the action of traffic. A pavement which ravels and disintegrates due to abrasion, or which fails from water action, is not necessarily unstable.

Economy. The most economical grading is usually that which requires neither additions to nor subtractions from the run of plant or pit. Natural gravels, talus deposits, or crusher run usually give a gradation from fine to coarse. Production of single sized aggregate such as is used in the open-graded type of construction, usually means the elimination of a considerable part of the product. Closely sized materials for macadam type construction are frequently more expensive than the uniformly graded aggregate. The matter of greatest economy is again a factor which depends on local conditions, and should be judged by the probable service value of the road as well as by first cost.

Permeability, or *porosity*, like most other considerations, has a varying degree of importance depending on local conditions. In bituminous pavements over a hard, sound subgrade or base unaffected by moisture, or in a dry climate, permeability is a matter of minor importance. Several macadam type pavements in California have given good service for years, even though field tests indicate a high degree of porosity. On the other hand, there have been a number of cases where it is clearly evident that water seeping through a porous surface has completely destroyed the supporting subgrade, and extensive failures have resulted. The importance of permeability is a factor which must be determined for each specific project, but in a majority of cases highly porous pavements are undesirable. In designing a grading, this factor is dependent to a large extent on the percentage of material of the 30, 50 and 100 mesh size. It is apparently a matter of pore size rather than of void volume. It is in all probability the quality that most engineers have in mind when speaking of "density."

Workability is significant only when considered in terms of certain equipment, or under certain conditions. The general practice of placing the material with blade graders, and consolidating under traffic or with rollers, makes the placing conditions fairly constant, and the term "workability" may be taken to apply to existing practice. Workability is most affected by the quantity and grading of the coarse aggregate in the mixture. A restriction limiting the amount of large rock concerns the handling characteristics; it is well known that it is difficult to secure smooth riding, uniform surfaces with an excessive percentage of coarse rock.

Non-skid qualities of pavements are usually obtained by the use of sufficient coarse aggregate to preserve an open texture in the surface, or a mosaic of large particles tightly embedded in a matrix of finer material.

Non-critical or so-called "fool-proof" mixtures are not so easily classified. A study of the failures, however, indicates that troubles of one sort or another are more likely to develop when an excess of fines is present. In other words, mixtures with a high dust content may be classed as critical, and the amount of oil must be precisely correct for satisfactory results. The range of practical variation is narrow, and fine graded mixtures will more often be too dry or too wet than just right. Therefore, on account of the difficulty in mixing as well as maintaining the correct asphalt content within the variations normally attendant upon construction, excess fines are to be avoided if possible.

Stability. In the present state of our research, we have little evidence as yet to show that stability is directly affected by gradation. From a study of field results, there is ample evidence that almost any grading may develop sufficient stability to withstand the thrust of traffic, provided that, due to its surface characteristics, the aggregate itself has a high inherent stability. A brief consideration of existing pavements, including macadam, open-graded types, sheet asphalt, sand clay, etc., will bear this out.

To sum up, a satisfactory grading is one that meets all the various requirements on a particular project to the degree in which they are important. While a variety of combinations may meet any *one* of the above items, only a limited range of gradings will satisfy all.

In approaching the grading problem, it appeared necessary to make some assumptions as a preliminary step, and work was begun on the premise that all gradings, regardless of maximum size, should be comparable on a relative scale and follow similar principles. In other words, considering for instance an aggregate with a maximum size of two inches and graded down to dust, and a second aggregate with a maximum size of one inch, the same percentage of material should be smaller than say one-half the maximum size in each case, and so on with all other fractions. On this basis, a general grading curve can be drawn in which the abscissa values are arranged as fractions or decimals of the maximum size, and the ordinates represent the percentages passing each size. (See Fig. 2.) Grading curves with tolerance limits may be plotted thereon, and have the same shape when applied to a wide range of materials, whether the maximum size is $\frac{1}{2}$ in. or $3\frac{1}{2}$ in. The grading curves shown on Figure 2 can be used for aggregate of any maximum size by substituting the proper sizes of openings for the fractions of the maximum. Figure 3 shows the arrangement for 1 in. maximum size.

With this chart as a basis, studies were made comparing satisfactory gradings from a number of different sources. In addition to work carried on in California, consideration was given to gradings of portland cement concrete, asphaltic concrete and other construction, as reported from various sources throughout the country.

The grading tolerances shown on Figure 2 represent a composite of the grading systems which have been developed under numerous conditions. Notes have been placed in certain areas on these charts as a general guide for recognizing probable characteristics of gradings where the plotted curves transgress these areas. It is believed desirable for the field man, or any one designing gradings, to understand the reasons and their degree of importance for fixing the position of each portion of the curve.

Grading curves within the tolerance limits shown on the charts have proven satisfactory; and while other gradings showing considerable

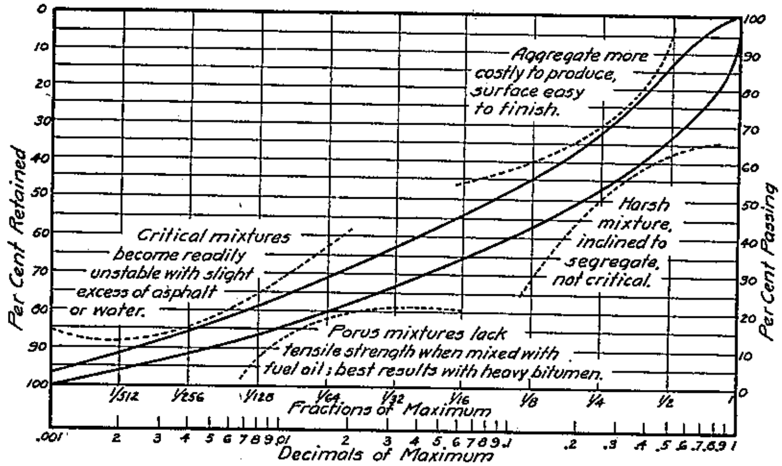

Figure 2. General Chart for Grading According to Relative Sizes. Abscissa position of sieve sizes will vary according to maximum size. Y = Percentage Passing or Retained Linear. X = Log N (relative particle size). Notes on chart apply to gradings that transgress area outside of the dotted lines. The grading curve is designed to avoid all undesirable conditions.

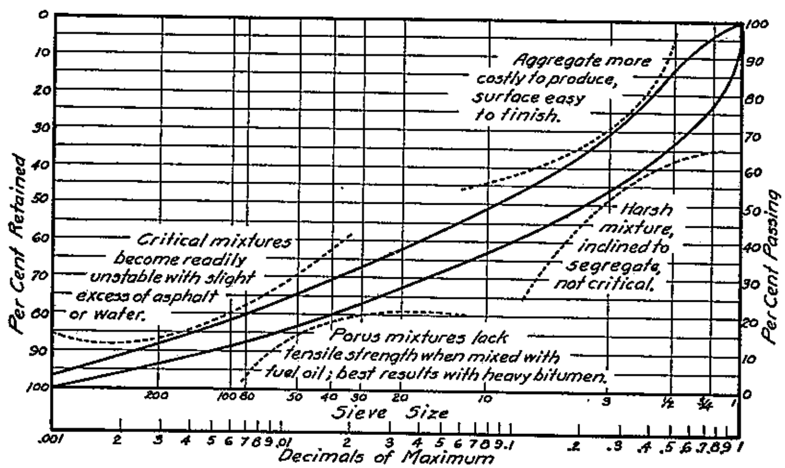

Figure 3. Grading Chart for Bituminous Mixtures, Maximum Size of Aggregate 1 Inch. Notes on chart apply to gradings that transgress the areas outside of the dotted lines. The grading curve is designed to avoid all undesirable conditions.

departure therefrom have been used, they will rarely embrace all of the desirable qualities. It is believed, moreover, that the procedure outlined will permit intelligent selection of gradings with proper allowance for all factors involved. The tolerance limits shown have been established with due consideration for the producer's problem, and are wide enough to be practicable for average plant production. (See Table I.)

Aggregate grading analyses should be corrected when there is appreciable difference in specific gravity between the various sizes.

To summarize, a *standard* grading should meet all requirements, although departures may be made in individual cases when the project renders some phase of greater or less importance. A *specified* grading must have tolerances as narrow as practicable to prevent fluctuation during construction, and should be designed to satisfy all requirements on a given project.

TABLE I

GRADING LIMITS FOR AGGREGATES WITH MAXIMUM SIZES SHOWN

Size or Sieve Number	Maximum Size				
	1½ In. Per Cent Passing	1¼ In. Per Cent Passing	1 In. Per Cent Passing	¾ In. Per Cent Passing	½ In. Per Cent Passing
1½ In.	100				
1¼ In.	80 to 100	100			
1 In.	75 to 95	80 to 100	100		
¾ In.				100	
½ In.	57 to 75	62 to 80	70 to 85	75 to 95	100
No. 3	46 to 60	50 to 65	54 to 66	57 to 75	70 to 90
No. 10	32 to 44	34 to 46	36 to 48	40 to 52	45 to 59
No. 40	16 to 25	18 to 27	20 to 30	22 to 32	27 to 37
No. 200	4 to 9	5 to 10	6 to 11	7 to 13	8 to 17

DETERMINATION OF OIL CONTENT[2]

Formulae for the determination of oil content have been developed and used by a number of State highway departments, particularly in the western states. In all of these the surface area of the aggregate is the major factor governing the oil demand. The formulae best known, such as the McKesson-Frickstad, Stanton, New Mexico, etc., are of the short form type based on the percentage of material retained on the 10-mesh, the percentage between the 10-mesh and the 200-mesh, and the percentage passing the 200-mesh, each percentage being multiplied by a predetermined constant. Each formula represents an average of the conditions with which its author has to contend.

[2] "California Highways and Public Works" for October–November, 1932.

The Stanton or California Formula is as follows:

$$P = 0.02a + 0.045b + 0.18c$$

Where P = percentage of oil in mix by weight
a = percentage of aggregate retained on No. 10 sieve
b = percentage of aggregate passing No. 10 and retained on No. 200 sieve
c = percentage of aggregate passing No. 200 sieve

For coarse mixtures (50 percent or less passing ¼-in. screen) increase coefficient of c to 0.20. For fine mixtures (100 percent passing ¼-in. screen) reduce coefficient of c to 0.15.

This formula is referred to in "Public Roads" for August, 1934, as the "Stanton Formula," and the following note on page 141 is interesting in this respect.

> "It will be noted that the percentages of oil calculated by the Stanton formula are in close agreement with the mean percentages given by the surface area method."

It is not strange that this should be the case, as the Stanton formula was derived from the more elaborate surface area method, and for most uniform gradings the results *should* be comparable.

The multiplicity of the short type of formula devised in efforts to serve the average conditions encountered in each state illustrates the difficulty of developing a single short formula which will fit even the average conditions for the entire country. In addition, we have the situation complicated by the fact that a correct determination of oil demand depends to a great extent on the surface characteristics of the aggregate (hard and glassy, rough and porous, or average) as well as on the correct surface area.

To ensure correct determination, the methods used in the California laboratory include both surface area determination based on a complete sieve analysis, and consideration of the surface characteristics of the aggregate.

Following is a description of the method, together with a table of surface area constants and necessary curves. It is not assumed that these surface area constants are exact; and particularly in the case of material finer than 200-mesh it would be impossible to assign any one constant to fit all aggregates.

In general, the method is based on analyzing the material by sieving, and calculating surface area values from the sieve analysis, with recognition of the following factors:

First, the optimum oil content is directly related to the surface capacity of the aggregate. This surface capacity is affected by three factors, each of which may vary independently of the others.

(a) Most important is variation in surface area due to variation in grading. For the same weight, small particles have a greater surface area than large ones.

(b) Variation in surface area due to shape and character of surface of particles.

(c) Variation in adsorption capacity of different aggregates.

Second, it has been established that the thickness of the oil film, or coverage factor, must be varied according to the *average* size of the particles.

TABLE II

SURFACE AREA CONSTANTS

The equivalent area in square feet of one pound of material of each size

10 Sieves			7 Sieves			7 Sieves			4 or 5 Sieves			3 Sieves		
Sieve No.		Constant	Sieve No.		Constant	Sieve No.		Constant	Sieve No.		Constant	Sieve No.		Constant
Pass	Ret.		Pass	Ret.		Pass	Ret.		Pass	Ret.		Pass	Ret.	
Wash[1]		300												
200	Wash[2]	200	200		250[3]	200		250[3]	200		250[3]	200		250[3]
100	200	120	100	200	120									
80	100	75				80	200	115						
50	80	55	50	100	60									
40	50	36				40	80	50	40	200	80			
30	40	27	30	50	32									
20	30	18				20	40	20						
10	20	11	10	30	15	10	20	11	10	40	18	10	200	45
3	10	5	3	10	5	3	10	5	3	10	5			
									1	10	4			
1	3	3	1	3	3	1	3	3	1	3	3	1	10	4

[1] Silt remaining in suspension over 15 sec. and removed by elutriation.

[2] Sand passing 200 mesh but not removed by elutriation.

[3] This value applies to average dust, and will be in error for some materials.

Application.—Use table according to number of sieves used. Reducing the number of sieves will reduce accuracy. By sieve analysis determine amount of each size of aggregate and express as percentage of the total. Multiply the percentage of each size by the constant for that size and divide by 100. The summation of these items will represent the surface area of the sample in square feet per pound.

PROCEDURE

The surface area equivalents for a sample of aggregate are calculated from the sieve analysis. The grading is first determined, and the amount of each size expressed as a percent of the total. (See Table III for example.) From Table II the constants are selected which represent the surface area in square feet per pound for the size groups. The percentage of each size is multiplied by the appropriate constant for that size, the summation of results giving a surface area equivalent for the grading represented by the entire sample. This method may be used in connection with any number of sieves but more accurate results are obtained with a large number of size divisions, particularly of the finer particles.

TABLE III

Showing Differences in Surface Area Equivalents Calculated from a Small Number of Screen Sizes as Compared to Values Obtained by Using a Full Set

Sieve Number	Per Cent Passing	Constants from Table II					Constants from Table IV				
		Ratio Each Size	×	Surf. Area Constants	=	Surf. Area of Sample	Ratio Each Size	×	Surf. Area Constants	=	Surf. Area of Sample
Grading 'A'											
Wash	4	.04	×	300	=	12.0	.12	×	250	=	30.0
200	12	.08	×	200	=	16.0					
100	13	.01	×	120	=	1.2	.19	×	80	=	15.2
80	15	.02	×	75	=	1.5					
50	20	.05	×	55	=	2.7					
40	31	.11	×	36	=	4.0					
30	32	.01	×	27	=	.3	.14	×	18	=	2.5
20	34	.02	×	18	=	.4					
10	45	.11	×	11	=	1.2					
3	55	.10	×	5	=	.5	.55	×	4	=	2.2
1	100	.45	×	3	=	1.4					
		1.00					1.00				
Surface Area of Sample in Sq. Ft. per Lb.						= 41.2					= 49.9
Calculated Oil Content Using 0.0 Line from Fig. 10.						= 0.37					= .041
Grading 'B'											
Wash	9	.09	×	300	=	27.0	.11	×	250	=	27.5
200	11	.02	×	200	=	4.0					
100	25	.14	×	120	=	16.8	.18	×	80	=	14.4
80	26	.01	×	75	=	.7					
50	28	.02	×	55	=	1.1					
40	29	.01	×	36	=	.4					
30	36	.07	×	27	=	1.9	.10	×	18	=	1.8
20	37	.01	×	18	=	.2					
10	39	.02	×	11	=	.2					
3	65	.26	×	5	=	1.3	.61	×	4	=	2.4
1	100	.35	×	3	=	1.1					
		1.00					1.00				
Surface Area of Sample in Sq. Ft. per Lb.						= 54.7					= 46.1
Calculated Oil Content Using 0.0 Line from Fig. 10						= .043					= .039

TABLE III—*Concluded*

Sieve Number	Per Cent Passing	Constants from Table II					Constants from Table IV				
		Ratio Each Size	×	Surf. Area Constants	=	Surf. Area of Sample	Ratio Each Size	×	Surf. Area Constants	=	Surf. Area of Sample
Grading 'C'											
Wash	6	.06	×	300	=	18.0	.11	×	250	=	27.5
200	11	.05	×	200	=	10.0					
100	18	.07	×	120	=	8.4	.18	×	80	=	14.4
80	20	.02	×	75	=	1.5					
50	25	.05	×	55	=	2.7					
40	29	.04	×	36	=	1.4					
30	32	.03	×	27	=	0.8	.16	×	18	=	2.9
20	36	.04	×	18	=	0.7					
10	45	.09	×	11	=	1.0					
3	60	.15	×	5	=	.07	.55	×	4	=	2.2
1	100	.40	×	3	=	1.2					
		1.00					1.00				
Surface Area of Sample in Sq. Ft. per Lb.						= 46.4					= 47.0
Calculated Oil Content Using 0.0 Line from Fig. 4						= .039					= .039

Procedure. Assuming a sample graded as Grading C having a recommended surface factor No. 5 and with a specific gravity of 2.40.

Referring to Figure 4, it will be found that a surface area of 46.4 on curve number 5 gives a bitumen index of .00102 pounds (of oil per square foot). The product of surface area and bitumen index gives the oil ratio. As the surface area curves are based on a specific gravity of 2.65 and the sample has a specific gravity of 2.40, a correction will have to be made. Hence:

$$\frac{2.65}{2.40} \times 4.64 \times .00102 = .052 = \text{oil ratio; or, 100 lbs. of aggregate will require 5.2 lbs. of oil.}$$

In Table III results are shown for three gradings, with surface areas in each case calculated with 10 sieves, and with four. It will be noted that gradings A and B show a considerable variation in surface area equivalents when computed from 4 measured sizes as compared to a computation using a full set of sieves. Grading C is a uniform grading which gives practically identical results regardless of whether a full set of sieves is used or not. The degree of error depends entirely on the particular grading concerned.

The results thus obtained represent a comparable mathmetical relationship between surface areas of different aggregate gradings. Variation in surface area between different classes of material of the same grading, due to differences in shape and surface characteristics of the particles, must be estimated by inspection of the aggregate or determined by proper laboratory tests. Rough, irregular particles have, of course, greater surface area than smooth, spherical ones. Variation due to adsorption must be determined by trial or laboratory tests. This variation is due to the unequal capacity of different mineral aggregates to attract and hold asphaltic residues on their surfaces.

Having arrived at the surface area equivalent for a particular grading, the amount of oil required is calculated by multiplying the surface area by the bitumen index.[3] The bitumen index is a variable factor indicating the amount of oil in pounds required to cover one square foot of surface area. The bitumen index chart (Figure 4) gives the coverage factor range which may be applied to different surface area equivalents. It will be noted that in fine grading combinations with high surface

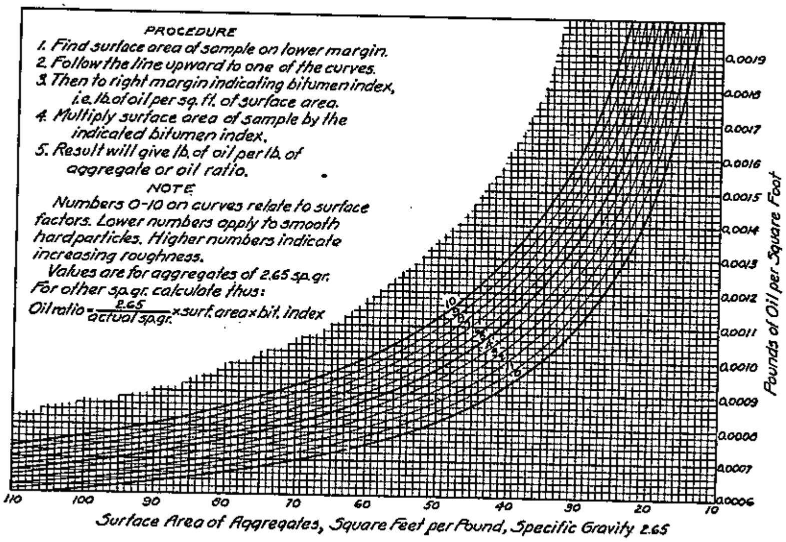

Figure 4. Chart for Determining Oil Content from Surface Area of Combined Aggregate. Developed by F. N. Hveem, California Division of Highways.

area, the coverage factor is smaller and the tolerances more restricted than in coarse combinations.

Corrections must be made for aggregates having a specific gravity above or below 2.65. The fundamental basis being, of course, relative volumes of oil and aggregate, it is obvious that a lighter aggregate will require more oil by weight and a heavier one will require less.

The bitumen index curves are numbered from 0 to 10. These curves represent arbitrary surface factors designed to distinguish between particle surface textures with varying degrees of roughness. The lower curves apply to smooth, glassy particles, the highest curves to rock

[3] This term was used by Mr. A. R. Ebberts. Proceedings, Sixth Annual Conference, "Asphalt Paving Conference," 1927, Circular No. 49.

of the vesicular lava type. In application, the most appropriate curve is selected to represent the surface roughness of a given aggregate. This curve number is then established as a constant, from which oil contents can be calculated for various gradings of the same aggregate. The curve, then, becomes the only constant factor, and is the basis for laboratory recommendations to the field forces.

Material represented by the lower surface factors is usually not highly stable. It is probably true that any aggregate or grading requiring a bitumen index below 0.0007 will be more likely to show distress in wet weather than will be the case where a thicker film is used.

There is reason to believe that this method is applicable to asphaltic concrete as well as to light oil mixes; and, furthermore, brief studies have indicated that required water cement ratios in portland cement concrete may be calculated from surface area analysis, provided that the principle of variable film thickness is recognized.

The form and application of this method rest on the following assumptions. Instability of a bituminous treated pavement and lubrication of the mass are synonomous terms. Then, since all road oils and asphalts are viscous liquids, the principles of lubrication are in operation, and it follows that small particles are more easily lubricated than large ones. There is need for a diminishing oil coverage in order to maintain stability as the particles diminish in average size. (It should be understood that this is a design basis; all particles, large or small, in any given mixture have the same coverage factor or bitumen index.)

In the preliminary investigation of aggregates in the laboratory, surface area equivalents are calculated from grading analysis as described. Trial mixtures are made with several oil contents calculated by means of surface factors arbitrarily selected from inspection of the aggregate. An attempt is made to select curves which will give an oil content both above and below the assumed optimum. Specimens are formed from these mixtures and tested for stability in a special machine (described later). This test, being primarily a measure of internal friction of the mass, indicates the presence of excess oil by measuring the reduction in friction. From these test results, the surface factor or oil line is established and used as a basis for recommendation to the construction forces.

The amount of oil for a given aggregate and grading is fixed on the general assumption that the most desirable oil content is the largest amount the aggregate will tolerate without developing instability. It is believed that all other conditions, such as resistance to moisture, ravelling, impact and oxidation are best met with a relatively high oil content. In the event of re-working, richer mixtures are preferable.

It should be understood, that the term "high" is used only in a relative manner. The highest permissible oil content may be indeed quite low in the percentage scale for some materials.

The point is stressed that the curves shown in Figure 4 are not used merely to indicate a minimum or maximum range. Considerable effort is made to determine the precise surface factor which will provide the optimum oil content for a given aggregate. When once established, this particular surface factor becomes the only constant, and is the basis for laboratory recommendations. The surface factor, or "oil line" furnishes a practical means of comparing the relative degree of oiling between a fine mixture requiring a high oil content and a coarse grading requiring much less.

STABILITY TESTS

As is generally known, paving mixtures using fuel oil as a binder do not show high stability when tested according to methods which force a test specimen through an orifice, or which subject it to direct shear. However, the fact that oil mix pavements have successfully withstood high speed automobile traffic and truck traffic over a period of years demonstrates that such pavements possess the qualities necessary to prevent distortion under traffic.

This situation requires a stability testing device which will measure the stability of fuel oil mixtures, and show that the oil mix which remains hard and smooth under traffic has more stability than asphaltic concrete pavements, constructed of inferior aggregate or poorly designed mixtures which become corrugated and rough under similar treatment.

It is observed that unstable conditions predominate in pavements containing aggregates with a hard, glassy surface texture. On the other hand, when rocks of a rough, irregular surface texture are used, fewer cases of instability are noticed.

Bituminous pavements are most likely to deform during extremely hot weather, and for this reason 140°F. has been generally adopted for the test temperature. Observations in California indicate that black pavements under the direct rays of the sun may reach a temperature at least 35 percent higher than the atmospheric shade temperature. Oil mix pavements must withstand temperatures of at least 140°F., and in the desert regions of California as high as 160°F.

If it is logical to test asphaltic concrete or sheet asphalt at 140°F., as representing its most susceptible condition, all bituminous pavements should be tested at the same temperature for direct comparison.

The first apparatus developed to measure stability consisted of a metal cylinder slit on one side. Opening was restrained by a compression spring. Variations of this type of machine were built and used for routine testing for several months. The metal type was later discarded in favor of the hydraulic type, the latter being found to be more accurate. Tests were first performed on mixtures of sand and gravel without bituminous binder. It was evident that there is a considerable variation in the resistance to displacement of different mineral aggregates under load. This difference is obviously due to the variation in friction between the particles. It may be said here that the development of this idea, together with test results on a great many specimens, lead to the belief that the *surface character of mineral aggregates is their most important single quality affecting stability of bituminous pavements.* It may be further stated that some varieties of stone, even in the form of crushed ledge rock, develop surfaces of a relatively smooth, glassy texture which have shown low resistance to displacement when tested, and have produced relatively unstable pavements. On the other hand, certain stream gravels, even though rounded and waterworn, retain a surface of sandpaper-like texture, which under compression develop high friction and produce stable pavements. It is, of course, usually true that crushed material is superior to uncrushed gravel in this respect. We are here discussing qualities of aggregate, as it is obvious that excess asphalt may render any mixture unstable.

In designing a testing machine, the following assumptions were made. Asphaltic paving mixtures may be classed as plastic solids; hence, a measure of resistance to plastic deformation should be a measure of stability. The degree of roughness or distortion of the pavement is the accumulated result of a large number of quick shoves or pushes, each lasting for a small fraction of time.[4] To produce roughness, the pressure exerted by vehicle tires has first to overcome friction between the particles of mineral aggregate. The residual forces (load minus frictional resistance) cause movement, varying according to the rate at which the particular bituminous binder will flow under the prevailing conditions (temperature, amount and consistency of the asphalt, amount of filler dust, etc.).

In an unstable pavement, if the bituminous binder flows or displaces an amount N under load L during time T, then under traffic (equivalent to the load L) the displacement N will be reached when the sum of the effective duration periods of the individual pushes equals the time T.

$$N = f(LT)$$

This is suggested as tentative form of the equation. The exact relationship is yet to be determined.

It appears that the deformation under load, when a viscous liquid is involved, will vary approximately with time but not directly with the load.

The machine designed in the Materials and Research Department of the California Division of Highways to measure resistance to lateral deformation under load has been termed the "Stabilometer."

[4] This viewpoint is well covered in greater detail in a discussion by G. H. Perkins, Proc. A. S. T. M., Vol. 25 Part II Page 371.

DESCRIPTION AND OPERATION

The Stabilometer is a form of plastometer, and consists essentially of an outer metal shell of cylindrical form within which is secured a rubber tube of smaller diameter. The rubber is clamped to the cylinder at each end in such a manner as to form a water-tight chamber between the outside of the rubber tube and the inner side of the metal cylinder. This water-tight chamber is filled with any suitable liquid, and connected with a pressure gauge to register the pressure to which the liquid is subjected. (See Fig. 5.)

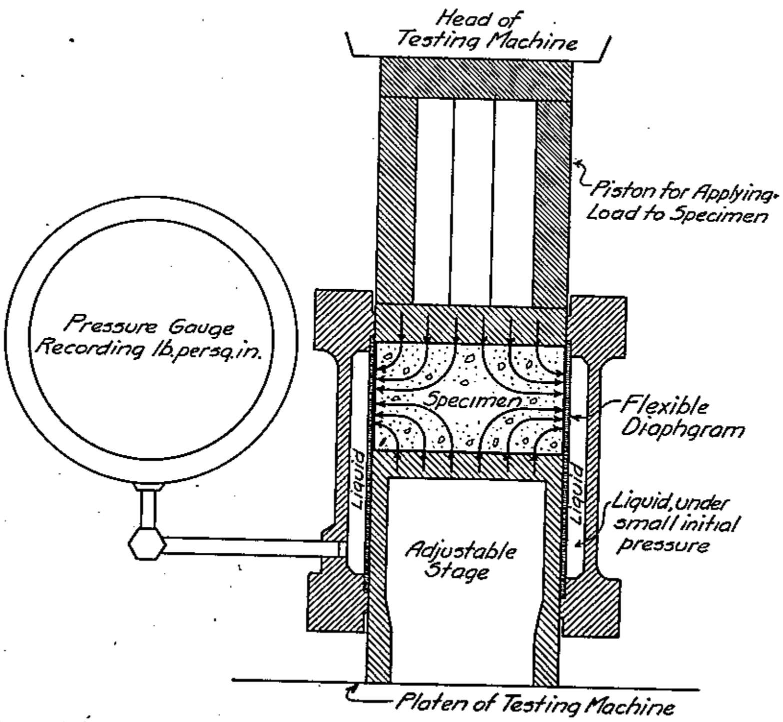

Figure 5. Diagrammatic Sketch of the Hveem Stabilometer. The specimen is given lateral support by the flexible side wall which transmits horizontal pressure to liquid. Magnitude of pressure is read on gauge.

A compacted test specimen is formed to fit snugly within the rubber tube, so that any lateral expansion of the loaded test specimen transmits pressure to the liquid through the flexible rubber walls, the resulting pressure being recorded by the test gauge.

Laboratory test specimens may be prepared by tamping, compression, or any suitable means of compaction designed to give as nearly as possible the same efficiency of consolidation as is obtained from rolling or traffic. We have found that efficiency of consolidation is not always accurately indicated by density.

Specimens cut from the pavement with a core drill should be of proper size to fit the Stabilometer.

With the test specimen in place, the liquid in the surrounding hydraulic cell is brought to a standard initial pressure by means of a hand-operated displacement pump. This initial pressure forces the rubber walls into snug contact with the side of the specimen before the test load is applied. The initial pressure must be maintained uniformly for all specimens if direct comparison is desired.

The Stabilometer is then places on a testing press, and the load applied at any desired speed, preferably a slow head speed of 0.05 in. per minute.[5] The load is applied over the entire top surface of the compacted briquette, and the resultant stress tending to deform the specimen at right

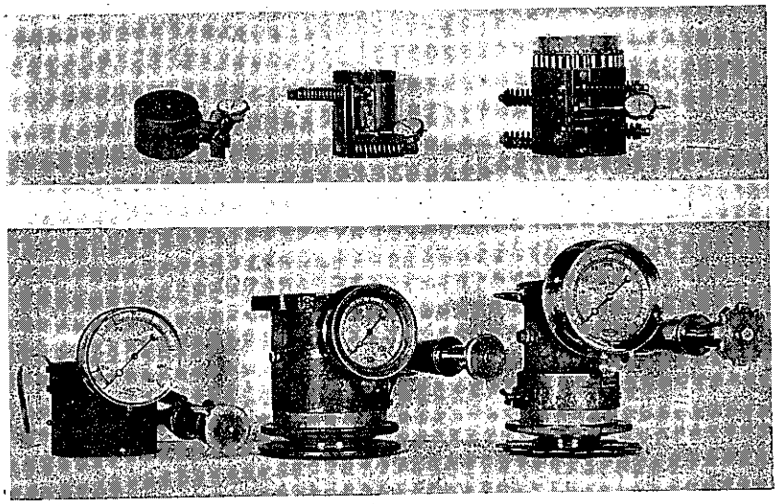

Figure 6. Evolution of Stabilometer from Small Expansible Metal Cylinder To Hydraulic Type With Adjustable Base for Various Specimen Heights.

angles to the direction of the test load is transmitted through the rubber walls and registered by the pressure gauge of the Stabilometer.

Test results may be interpreted in various ways, as for instance by the ratio of transmitted pressure to applied pressure, by comparing the amount of load absorbed in overcoming resistance of the specimen to deformation, or by referring to an arbitrary scale in which zero represents a frictionless liquid condition, and one hundred a rigid solid.

Stability tests may be performed on any sort of stiff plastic material, such as clay, soil (for bearing values), wax, and aggregates with or without bituminous binder. With certain modifications, they may even furnish

[5] American Society for Testing Materials, Standard Method of Making Compression Tests of Concrete, D72–21.

a practicable means of measuring the plasticity or workability of concrete mixtures.

The machine was developed experimentally and has been improved and modified by experience. Its evolution is shown in Figure 6. It has been adopted by the Materials and Research Department of the California Division of Highways as a routine test for bituminous mixtures of the oil mix or cutback type, and in this connection has been applied to more than ten thousand specimens, most of which were compacted in the laboratory.

In applying the Stabilometer test to samples of oil mix pavement, it is necessary to prepare specimens by compaction in the laboratory, as the weak binding medium does not, in most cases, permit the cutting

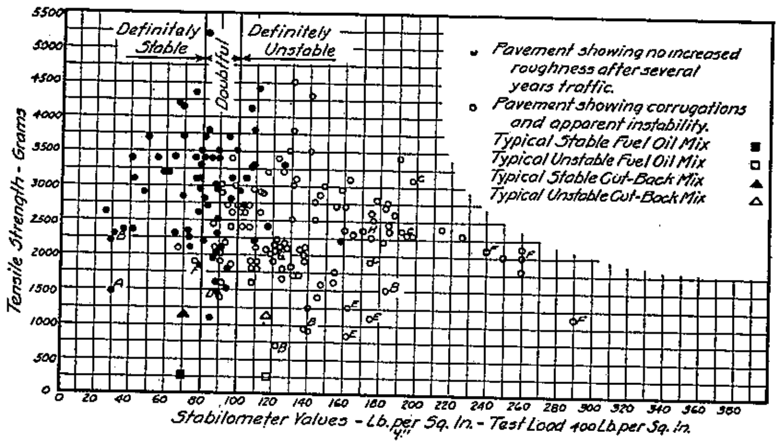

Figure 7. Relative stability and tensile strength of asphaltic concrete cores compared with condition of pavements. A = Sheet asphalt, remained smooth for 20 years. B = Cutback Mix, rutted and grooved. C = Old pavement, had been planed several times. D = Stable A.C. Pavement. E = Unstable A.C. Pavement, badly corrugated. F = Unstable A.C. Pavement, badly corrugated. G = Moderately Rough, remained smooth 5 or 6 years. H = Rough and waved.

of cores from the pavement. Tentative limits were established based on a few observations, and during the application of the test to current work, results have been studied in order to arrive at more correct correlation. For simplicity, stability results are reported in a scale ranging from 0 to 100 per cent, in which 0 equals a liquid condition, and 100 per cent is the equivalent of a solid with no measurable lateral reaction under the test loads employed.

A study of the United States Bureau of Public Roads report on the impact effect of vehicles[6] and the State of Pennsylvania investigations of tire pressures with the sectometer[7] led to the assumption that a test

[6] "Public Roads," November, 1932.

[7] Samuel Eckels, "Distribution of Wheel Loads Through Various Rubber Tires." Proceedings Highway Research Board, Vol. 8, p. 192.

load equivalent to approximately 400 pounds per square inch is reasonably representative of the stresses developed by pneumatic tired truck traffic (recognizing the increase of static load due to so-called impact).

Results are compared by means of the Stabilometer readings under a test load of 400 pounds per square inch. Correlation with pavements under actual traffic indicates that a stability value between 30 and 35

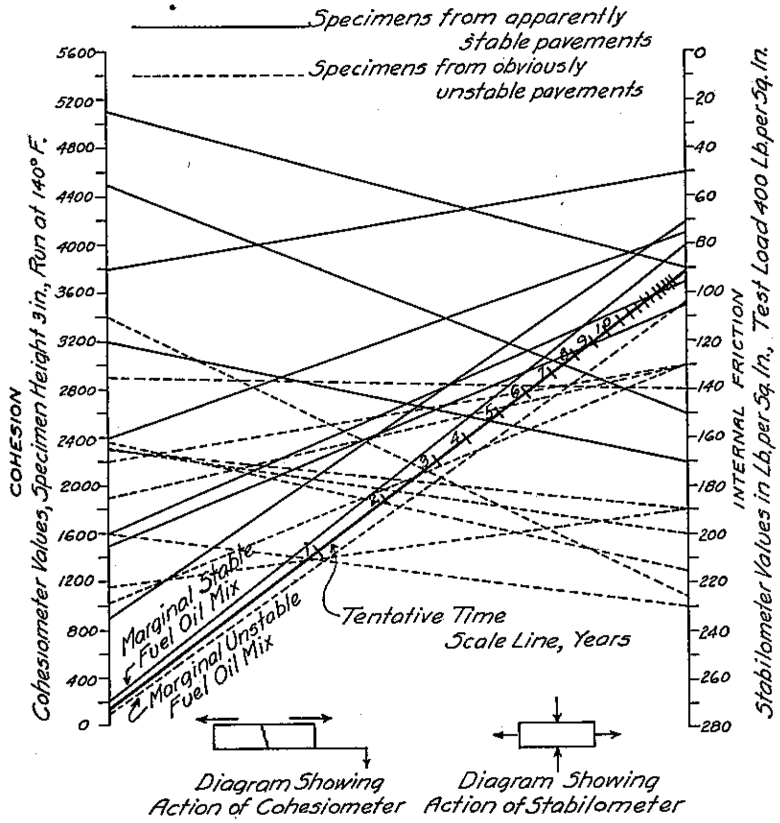

Figure 8. Nomographic Chart Showing Very Probable Relationships of Stabilometer Results and Tensile Strength to Service Rendered by Pavement. The point where specimen lines intersect the time scale indicates proxable time required for pavement distortion to become apparent (assuming 300 cars per day and climate similar to California interior valley region). The time factor will vary with amount of traffic, duration and intensity of warm weather.

per cent represents a borderline condition. In other words, stability values of less than 30 per cent indicate a pavement which will invariably displace under traffic, while pavements having stability values above 35 per cent have so far indicated satisfactory service values. The volume and type of traffic, vary enough between different sections of pavement to make precise agreement difficult.

In order to determine the applicability of the Stabilometer and establish close correlation with field work, a number of cores have been taken from existing asphaltic concrete pavements. The pavements were classified by visual inspection as either stable or unstable, with some cases classed as borderline or slightly unstable. Such visual comparisons are necessarily very inexact. The most that could be expected would be that stability test results would show a preponderance of high values in the stable appearing pavements. Variation in pavements due to segregation of material during placement, and difficulty in selecting a typical area to be sampled, all render it impossible to obtain precise agreement. (See Figure 7.) A very probable relationship of stabilometer and tensile test results to the service rendered by the pavements is shown graphically in Figure 8.

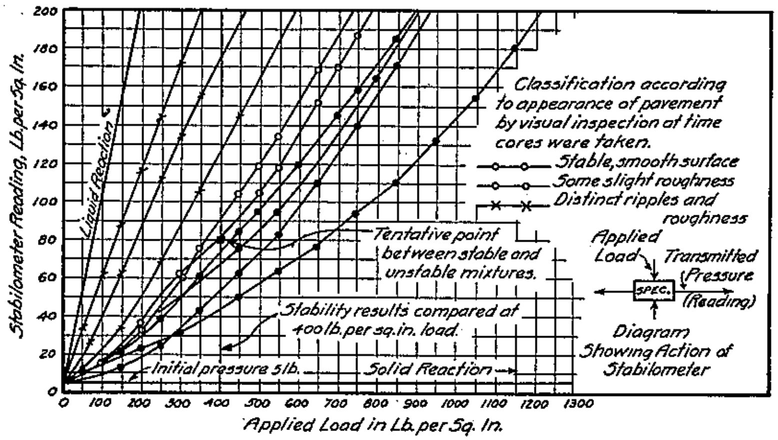

Figure 9. Load Reaction Values as Measured by the Hveem Stabilometer. Results are on 5-in. cores from asphaltic concrete pavements. Height of specimens approximately 2⅜ in.

The first tests with the Stabilometer were made on specimens of oil treated aggregate. As work continued, it became evident that test results were in good correlation with the stability evidenced by pavements under traffic. After a time, specimens of cutback asphalt mixes and asphaltic concrete were tested, and also laboratory mixtures were prepared in which the quality of the aggregate and the grading were maintained constant, the only change being in the consistency of the asphalt.

It was found that the Stabilometer gave practically identical results with a given aggregate, grading and amount of asphalt, regardless of consistency of the asphalt. These test results caused some doubt as to the value of the Stabilometer test, as it was presumably an accepted fact, for instance, that asphaltic concrete was of higher quality and therefore more stable than an oil mix pavement.

Comparisons of good reactive values as measured by Stabilometer tests of cores from asphaltic concrete pavements are shown in Figure 9.

TENSILE STRENGTH

In order to measure and explain the differences which obviously exist between pavements using light oil and those using hard asphalt, a device

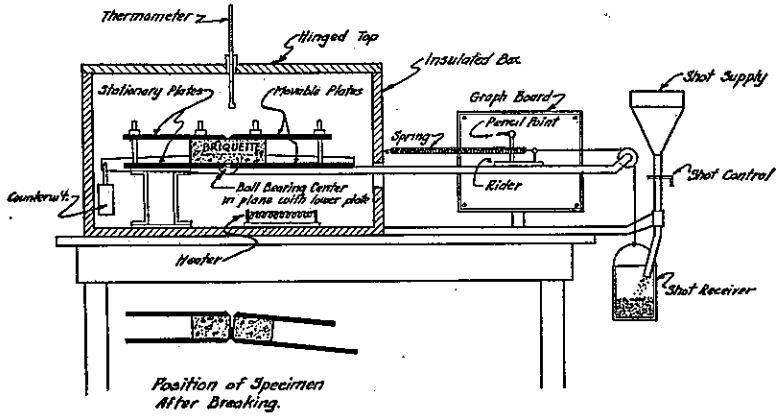

Figure 10. The Hveem Cohesiometer

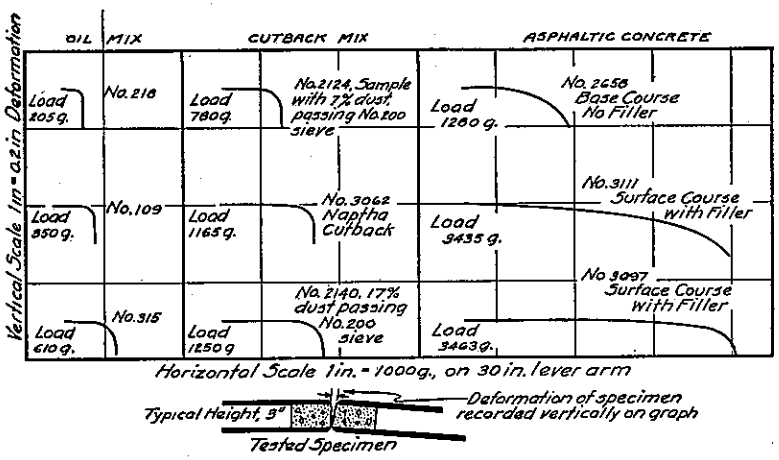

Figure 11. Typical Cohesiometer Graphs Automatically Recorded

was built to measure the tensile strength or cohesion of a specimen. (See Figures 10–11.) The tensile strength of a bituminous pavement is, of course, due chiefly to the adhesion of the asphalt to the aggregate particles, and the cohesive strength of the bituminous film. While the quality is described as tensile strength for the sake of simplicity, it must be recognized that more precisely it is the rate of flow with time, and hence characteristic of the consistency of the bituminous binder, and also the fineness or surface area equivalent of the aggregate.

It was found that definite and consistent differences could be measured in this way between oils and asphalts of varying consistency. A given specimen with "D" grade asphalt may give as much as 50 times the "tensile" strength of a mix using fuel oil.

An attempt to correlate tensile strength values with pavement performance shows very uncertain agreement. The fact that mixtures of very low tensile strength can and do remain smooth under traffic, and also that mixtures of quite high tensile strength have been known to become waved and rutted, is proof that high tensile strength is not essential for resistance to the distorting effects of vehicles.

It is true, however, that if the pavement mixture is lubricated to such a degree that it has a tendency to distort, the time required for roughness to become evident will depend to a great degree on the tensile strength, or more precisely on the rate of flow of the bitumen serving as binder.

SUSCEPTIBILITY TO MOISTURE

There have been several instances of failure of oil road surfaces which cannot be attributed to improper design or faulty construction methods. Several sections in California and others reported from Arizona have softened and disintegrated due to rain or ground water, while other sections subjected to identical climatic conditions have shown no distress. These failures are obviously due to the material being susceptible to moisture.

Before proceeding with the discussion, it may be well to define one of the terms which must be used in connection with this phenomenon. To quote from an article by Mr. A. W. Dow published in the Proceedings of the Sixth Annual Asphalt Paving Conference:

> "*Adsorption* is a term that has generally been accepted to denote the surface attraction or adhesion of one body for another, as for example, when a powder adheres to the surface of a solid, when a liquid wets a solid or spreads out over the surface of another liquid, or when a gas or vapor condenses on the surface of a solid. As stated by H. M. Holmes in his Laboratory Manual on Colloidal Chemistry, 'It seems that every solid surface has an attraction for other substances, greater for some than for others. This holding to a surface we call adsorption, and we differentiate it from chemical reaction or solid solution. It may be due to free valence of the surface atoms but whatever it is we are able to measure it and study it. Some solids have far greater adsorbing power than others and a given adsorbent shows preferential adsorption. Of course the finer a solid is, the greater its surface area and the greater its adsorbing effect per gram.' "[8]

Although Mr. Dow was referring more specifically to variations in adsorption of asphalt from solutions, the question of preferential adsorp-

[8] Proceedings, Sixth Annual Asphalt Paving Conference, "Variation in Adsorption of Asphalt by Different Mineral Aggregates," A. W. Dow, Consulting Engineer, N. Y.

tion also applies to materials of highway construction as regards "affinity" of the mineral aggregate for water and for petroleum oil of the asphaltic type. Any mineral aggregate, whether fine or coarse, which is more readily wetted by water than by asphaltic oil may be expected to give trouble in the presence of water. Affinity for water may be due to the character and composition of the rock particles themselves, or to some surface film or contamination which has been deposited by infiltration of soil water, etc. Water will slowly penetrate such a mass, even though oil treated, and surround the rock particles with a film of water which tends to lubricate or promote instability. In many cases, particularly with oils of low viscosity, the oil may be actually displaced to such an extent that the material will change color and revert to a brownish hue. This phenomenon is not restricted to small size particles such as filler dust, but may appear with any type of grading. The greater surface area per unit weight of fine material is chiefly responsible for the more marked effects on fine mixes as compared to coarse. It has been observed that heating the aggregate to high temperatures before mixing will frequently correct any tendency to adsorb water. This is not effective in all cases, however.

Several test methods have been devised to detect the susceptibility of oil roads to moisture conditions. The methods now in use in the laboratory of the California Division of Highways are modifications of methods originally adopted by the State Highway Laboratory of Arizona under the direction of J. W. Powers, Materials Engineer.[9]

WATER-ASPHALT PREFERENTIAL TEST

This test is usually intended to determine the water-resisting properties of a filler which is to be used in a bituminous mixture, and is made on a sample of dust passing a 200-mesh sieve.

The apparatus consists of:

1. An electric motor stirrer with means for controlling the speed to 1500 revolutions per minute. (Fig. 12.)
2. A water bath that can be maintained at 140°F.
3. An 8-ounce sample bottle with wide mouth and screw cap.

A 50 ml. sample of heavy fuel oil (60–70 per cent asphalt) heated to 140°F. is placed in the sample bottle. To this is added 10 grams of filler dust passing a 200-mesh sieve. The bottle is then placed in the hot water bath and the mixture stirred for five minutes with a mechanical

[9] "A Significant Determination on the 'Fines' Entering into Oiled Road Construction," Arizona Highways, June, 1929; "A Method of Testing to Determine the Suitability of a Material for Oil Treatment," Arizona Highways, June, 1930.

Attention is also called to an article by A. R. Ebberts, "Emulsifying Effects of Asphalt Fillers," Rock Products, Vol. 35, Nov. 22, 1930, pp. 53–55.

Also Victor Nicholson, "Adhesion Tension in Asphalt Pavement," Roads and Streets, 1932, March to June.

mixer revolving at a speed of 1500 r.p.m. After five minutes, 100 ml. of distilled water at 140°F. is added and the mixture stirred for a second five-minute period.

After the sample has had time to settle and the water to become clear, the amount of clean dust in the bottom of the jar is estimated and recorded as the percentage of total dust separated (Fig. 13). If the dust is of satisfactory quality it will remain in the oil and no free particles will be observed in the water at the bottom of the jar. The dust retained in the oil may cause all or a portion of the oil to settle to the

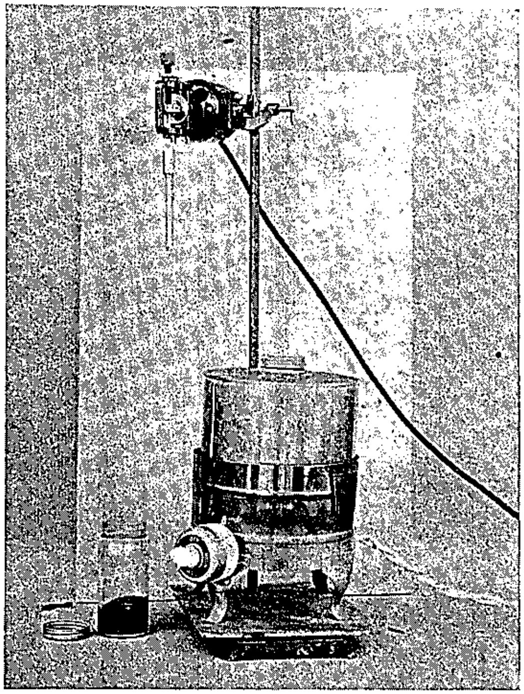

Figure 12. Laboratory Stirrer and Water Bath as Used for Water-Asphalt Preferential Test.

bottom after a certain length of time. If the dust is of poor quality, showing a strong affinity for water, the dust will be concentrated in the bottom of the jar, having separated from the oil. The test is reported by estimating the percentage of dust which separates. Using these terms, 0 per cent separation would be entirely satisfactory; 100 per cent would be entirely unsatisfactory. At the present time, it is considered that separation up to 25 per cent may be tolerated.

This test, however, is not as conclusive as the Swell test, inasmuch as the filler dust may constitute only a small percentage of the total mixture. While it may be shown that the Preferential and the Swell tests are in general agreement, certain cases have been noted where results are difficult to reconcile. The test is considered of value chiefly because of the inexpensive equipment and the relatively short time required for the determination. It is intended to be used principally for distinguishing between various deposits of silt, loam or any fine material proposed for filler. It should be considered as auxiliary to the Swell Test.

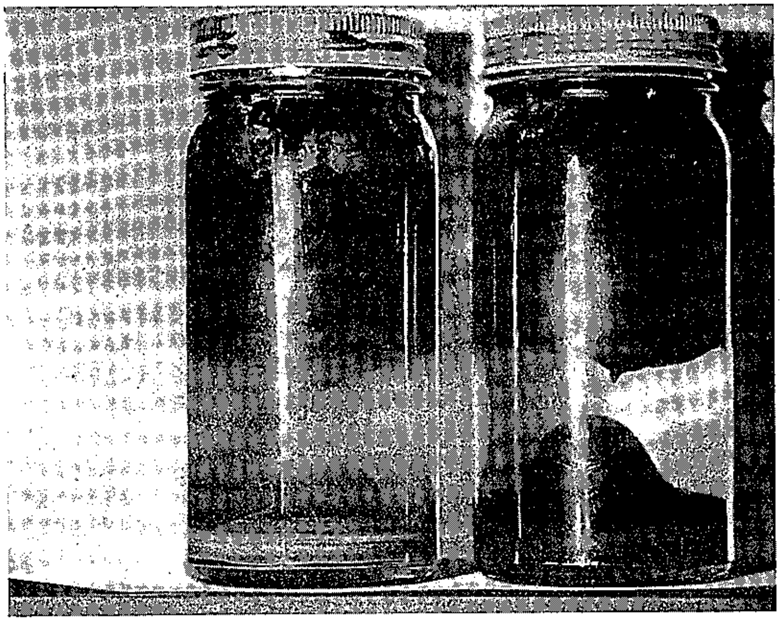

Figure 13. Samples of Water-asphalt Preferential Determination on Filler Dust. Jar on left contains poor material, as evidenced by free dust in bottom. Jar on right shows example of satisfactory test, dust enclosed in mass of oil in bottom of bottle.

SWELL TEST

The Swell test is made on a compacted specimen of oil mixed aggregate representing typical proportions of oil or asphalt as well as grading used in actual construction.

The necessary apparatus (Fig. 14) consists of:

1. A cylindrical metal mold 4 in. inside diameter and 5 in. high.
2. A perforated brass disc $\frac{1}{8}$ in. thick and $3\frac{7}{8}$ in. in diameter, with an upright stem $5\frac{1}{2}$ in. long, fastened to the center.
3. An Ames dial mounted on an arm which may be clamped to an ordinary ring stand.

The bituminous mixture is compacted in one end of a metal cylinder in the form of a briquette approximately two inches thick, using standard methods of compaction. Before applying the final load in the compacting operation, the position of the briquette is reversed in the mold so that the surface exposed to the tamping action becomes the bottom of the specimen. The briquette, without being removed from the mold, is then placed on a ring stand and the perforated plate placed on the upper surface. The Ames dial is brought in contact with the upright stem and the reading noted. Five hundred ml. of water are then poured into the upper part of the mold on the surface of the specimen. After standing for 24 hours, a reading is taken and the swell recorded in thousandths of an inch. The swell thus measured is not a function of the depth of the specimen, but merely results from the

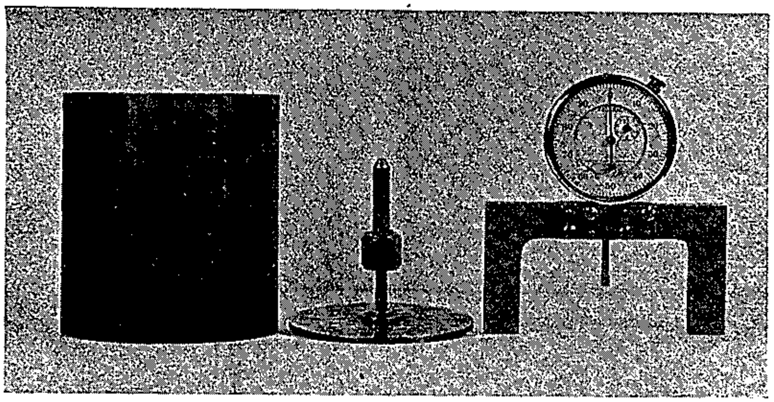

Figure 14. Assembly for Measuring Swell of Compacted Oil Mix Specimen. Master gauge permits large number of tests without expense of separate dials.

water drawn into the surface by attraction between the water and the aggregate, and is the swelling of the wetted surface layer.

It has been observed that fine mixtures having a high surface area may be expected to show greater swell than the same aggregate in a coarse grading. In order to compare results, a tentative scale has been established which permits the allowable swell limit to vary with the degree of fineness of the specimen. This tentative scale is as follows:

Surface Area of Aggregate Sq. Ft.	Tentative Permissible Swell In.
20	.020
30	.025
40	.030
50	.035
60	.040
70	.045
80	.050
90	.055
100	.060

The Swell test is considered to be the most reliable method and will throw more light on the probable effect of moisture on the road surface than any other known test.

It should be understood that the detrimental effects of moisture on a pavement are not confined to those materials which are classified as susceptible under the two tests just described. If moisture is present in the aggregate at the time of mixing, trouble may be expected until it has evaporated. It seems evident that 1¼ per cent moisture is generally about as much as can be tolerated without causing instability. Recent studies in Wyoming as reported in "Public Roads," August,

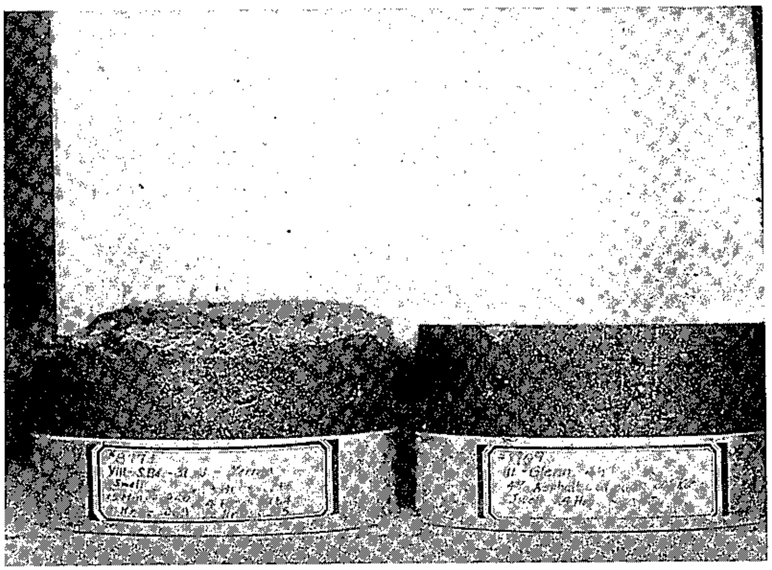

Figure 15. Specimens After Removing from Swell Test. Sample on left gave high swell, from section of highway showing considerable failure. Sample on right gave no swell, and section of highway shows no distress.

1934, are of interest in this respect. Any mixture containing moisture may give trouble if placed on the road. Once having dried out, however, hydrophobic[10] aggregates are not generally subject to further attack; mixtures with hydrophilic[10] aggregate (which show a high swell) may be expected to soften and disintegrate in the presence of moisture, even though placed absolutely dry.

[10] The term "hydrophobic" is generally accepted to designate any material having an "aversion" to water; hydrophilic applies to materials displaying an "affinity" for water.

BITUMENS

The chief function of the bituminous binder, at least in the oil mix type of road, is to furnish adequate resistance against the abrasive action of tires. Ravelling is the inevitable result of too low an oil content. Asphaltic residues furnish a binding medium which also

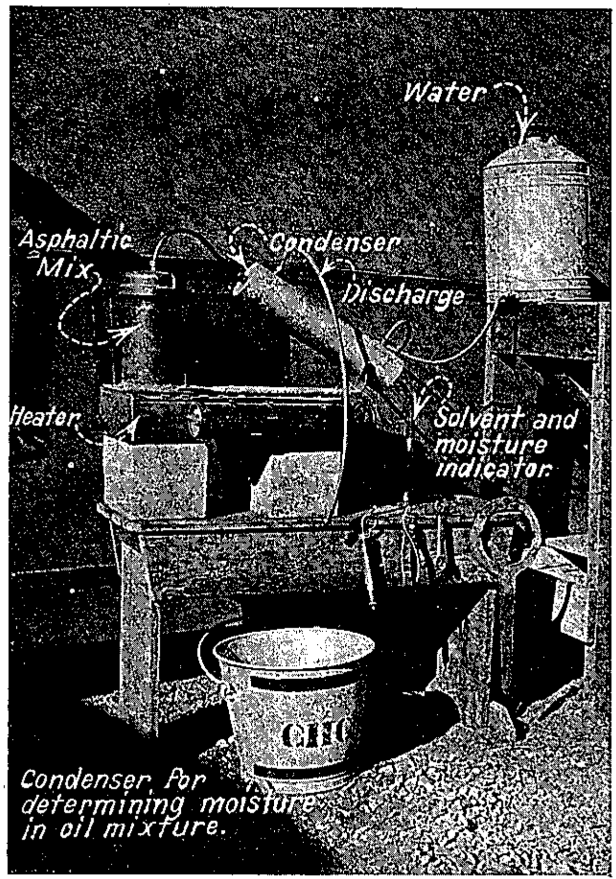

Figure 16. Distillation Apparatus in Resident Engineers Field Laboratory. Used to determine amount of moisture present and avoid error due to loss of volatile oils, etc.

offers a certain amount of resistance to moisture (varying with the amount and type of asphalt and the particular aggregate).

In deciding on the grade or consistency of bitumen for a given project, several factors must be given consideration. Among these are the type of equipment to be used in construction, and the prevailing climate during and after the construction period. The grading and porosity of the aggregate are important factors. The greatest adjustment must be made with the road mix method of construction, because of the difficulty in controlling grading, and the impossibility of controlling climate, even in California.

For the purpose of estimating the grade of oil best suited to a given project, the following tentative equation is suggested as a guide for use in the road mix method:

$$VS = K$$

Where V = viscosity of the oil (Saybolt-Furol) at the test temperature (140°F.)

S = surface area of the aggregate expressed as square feet per pound

When values of K are less than 9,000, mixtures lack tensile strength, and when K is greater than 36,000, road mixing difficulties will be considerable. In other words, the tensile strength will be too great. It is suggested that, so far as possible, the value of K be maintained around 25,000. This formula is tentative only, based on incomplete evidence, and obviously should have a factor for temperature under working conditions. It is felt, however, that with certain modifications an equation of this form will be a satisfactory guide.

In the case of plant mix construction, the upper limits become unimportant, because by means of heat the viscosity can be maintained as desired. The lower limit, however, will apply in any case.

Requirements for rapid, medium and slow curing liquid asphaltic road materials have been written conforming to the specifications recommended by the Asphalt Institute after numerous conferences with representatives of the U. S. Bureau of Public Roads and the various state highway departments. In addition to the materials included in the Asphalt Institute Specifications, we have added an extra series of MC products and an intermediate grade of heavy road oil.

The characteristics of the asphaltic products included in the 1934 Specifications of the California Division of Highways are tabulated in Tables IV and V.

California has had practically no experience with the RC series using grade D asphalt as a base. Several sections have been treated with grade E or 90–95 road oil cut back with naphtha, and the results have been quite satisfactory.

Some of the MC types have been used extensively, although MC-2 has been used very infrequently and MC-1 not at all. MC-3 is specified for road mixing in relatively cool weather, and the evidence so far indicates that several days' curing in the windrow is beneficial before consolidation is effected. MC-4 has been used extensively for road mixing, and is probably the most suitable grade under warm weather conditions. MC-5 is too heavy for road mixing except in extremely

TABLE IV

Characteristics of Liquid Asphaltic Road Materials

Rapid Curing Naphtha Cutback Asphalts

Using Grade D Asphalt of Approximately 70–90° Penetration

Specification Designation	RC-1	RC-2	RC-3	RC-4
Approximate Naphtha—per cent	34	26	20	15
Flash Point, Open Tag—Deg. F.	80 Min.	80 Min.	80 Min.	80 Min.
Viscosity, Saybolt Furol at 122°F.	80–160	200–400		
Viscosity, Saybolt Furol at 140°F.			275–400	700–1400
Distillation, per cent by volume:				
Total Distillate to 374°F.	5 Min.			
Total Distillate to 437°F.	12 Min.	10 Min.	3 Min.	0.5 Min.
Total Distillate to 600°F.	25 Min.	20 Min.	14 Min.	7 Min.
Total Distillate to 680°F.	40 Max.	35 Max.	23 Max.	15 Max.
Test on Residue from Distillation:				
Penetration 77°F., 100 g., 5 sec.	80–120	80–120	80–120	80–120
Ductility at 77°F., cm.	70 Min.	70 Min.	70 Min.	70 Min.
Per cent Soluble in Carbon Disulfide	99.5 Min.	99.5 Min.	99.5 Min.	99.5 Min.
Per cent Soluble in Carbon Tetrachloride	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.

Medium Curing Kerosene Cutback Asphalts

Using Grade E Asphalt Having an Upper Limit of Approximately 120° Penetration

Specification Designation	MC-1	MC-2	MC-3	MC-4	MC-5	MC Extra Heavy[1]
Approximate Kerosene, per cent	46	27	21	17	14	11
Flash Point, Open Tag, Deg. F.		150 Min.	150 Min.	150 Min.	150 Min.	150 Min.
Viscosity, Saybolt Furol at 77°F.	40–150					
Viscosity, Saybolt Furol at 140°F.		150–250	300–500	500–800		
Viscosity, Saybolt Furol at 180°F.					170–280	300–500
Distillation, per cent by volume:						
Total Distillate to 437°F.	10 Max.	2 Max.	2 Max.	1 Max.	1 Max.	1 Max.
Total Distillate to 600°F.	25 Min.	10–20	8–20	16 Max.	14 Max.	11 Max.
Total Distillate to 680°F.	50 Max.	27 Max.	25 Max.	25 Max.	20 Max.	15 Max.
Tests on Residue from Distillation:						
Penetration, 77°F., 100 g., 5 sec.	70–300	100–300	100–300	100–300	100–300	100–300
Ductility at 77°F., cm.	60 Min.	60 Min.	60 Min.	60 Min.	60 Min.	60 Min.
Per cent soluble in Carbon Disulfide	99.5 Min.	99.5 Min.	99.5 Min.	99.5 Min.	99.5 Min.	99.5 Min.
Per cent soluble in Carbon Tetrachloride	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.

TABLE IV—*Concluded*

Medium Curing Kerosene Cutback, 90–95 Road Oil[1]

Specification Designation	ROMC-1	ROMC-2	ROMC-3	ROMC-4	ROMC-5
Approximate Kerosene, per cent	27	21	17	14	11
Flash Point, Open Tag, Deg. F.	150 Min.	150 Min.	150 Min.	150 Min.	150 Min.
Viscosity, Saybolt Furol at 122°F.	150–250				
Viscosity, Saybolt Furol at 140°F.		150–250	300–500	500–800	650–950
Viscosity, Saybolt Furol at 180°F.					170–280
Distillation, per cent by volume:					
Total Distillate to 437°F.	2 Max.	2 Max.	1 Max.	1 Max.	1 Max.
Total Distillate to 600°F.	10–20	8–20	16 Max.	14 Max.	11 Max.
Total Distillate to 680°F.	27 Max.	25 Max.	25 Max.	20 Max.	15 Max.
Tests on Residue from Distillate:					
Float Test at 122°F.	100–250	100–250	100–250	100–250	100–250
Ductility at 77°F., cm.	80 Min.	80 Min.	80 Min.	80 Min.	80 Min.
Per cent Soluble in Carbon Disulfide	99.5 Min.	99.5 Min.	99.5 Min.	99.5 Min.	99.5 Min.
Per cent Soluble in Carbon Tetrachloride	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.

Slow Curing Products—Road Oils

Specification Designation	SC-1	SC-1A	SC-2	SC-3	SC-4	Asphalt Road Material	
						90-95[1]	95+[1]
Asphalt Residue of 80 Penetration, %	30-35	50 Min.	65 Min.	71 Min.	76 Min.	90-95	95 Min.
Water and Sediment, per cent	2 Max.	2 Max.	2 Max.	2 Max.	2 Max.	1.5 Max.	
Water, per cent						0.5 Max.	0.5 Max.
Sediment, per cent						1.0 Max.	1.0 Max.
Flash Point, Cleveland Open Cup, Deg. F.	150 Min.	175 Min.	200 Min.	200 Min.	250 Min.	350 Min.	400 Min.
Viscosity, Saybolt Furol at 77°F	20-40						
Viscosity, Saybolt Furol at 122°F		40-80	200-320				
Viscosity, Saybolt Furol at 140°F				150-300	350-550		
Float Test at 77°F			200 Max.	250 Max.			
Float Test at 122°F						150 Min.	250 Min.
Pen. of residue after loss on heating at 325°F. 5 hours						100 Min.	125 Min.
Distillation, per cent by volume:							
Total Distillate to 437°F		3 Max.	3 Max.	2 Max.	2 Max.		
Total Distillate to 600°F		25 Max.	15 Max.	10 Max.	8 Max.		
Total Distillate to 680°F	50 Max.	30 Max.	25 Max.	20 Max.	18 Max.		
Tests on Residue from Distillation:							
Float Test at 122°F	50 Max.	50 Max.	25 Min.	25 Min.	25 Min.		
Per cent Soluble in Carbon Disulfide	99.0 Min.	99.0 Min.	99.0 Min.	99.0 Min.	99.0 Min.	99.0 Min.	99.0 Min.
Per cent Soluble in Carbon Tetrachloride	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.	99.65 Min.

[1] Not included in the specifications recommended by the Asphalt Institute.

hot weather, but has been used successfully in plant mix with cold aggregate. It is frequently specified when the material is mixed several days prior to placing. The widespread use of driers to reduce moisture has led to the use in plant mix work of an extra-heavy grade containing approximately 11 per cent of kerosene solvent, which would be in the nature of an MC-6 grade. This grade is considered most desirable for all plant mix work when the aggregate is heated, and has proved the most satisfactory,—it can even be handled readily from railroad cars 24 hours after mixing.

Of the slow curing products, SC-1 is used very little, or only in the form of pipeline run oil, without detailed specifications. SC-1A is used for dust oiling and some prime coat work. SC-2 has proved to be

TABLE V
Asphaltic Cements—California Specifications

Grade	Air Blown				
	A	B	C	D	E
Flash Point, Pensky-Martens, Deg. F.	400 Min.	400 Min.	400 Min.	400 Min.	400 Min.
Penetration, Original	0–10	10–20	20–35	40–90[1]	100–250[1]
Loss on heating at 325°F., per cent	1 Max.	1 Max.	1 Max.	2 Max.	3 Max.
Penetration after Loss	70 Min.	70 Min.	70 Min.	60 Min.	50 Min.
Softening Point, Ring and Ball, Deg. F.	185–240	150–185	130–150		
Ductility at 77°F., cm.	1 Min.	1 Min.	1 Min.	30 Min.	75 Min.
Per cent Soluble in Carbon Disulfide	98	98	98	99.5	99.0
Per cent Soluble in Carbon Tetrachloride	97	97	97	98	99.5

No emulsification or solution shall occur when a 30 gram sample is boiled for 2 hours with 250 cc. of distilled water in a 500 cc. Erlenmeyer flask equipped with a reflux condenser.

[1] Penetration of original asphalt at 77°F., 100 g., 5 sec. shall be as provided in the special provisions.

the most satisfactory for prime coat on subgrades, and is used to a considerable extent in both road and plant mix construction. SC-3 and SC-4 grades have been used extensively in penetration surface treatment, and in a few cases in mixing operations. In addition to the asphaltic road material 95+, an additional grade specified as 90–95 has been used for armor coat, sealing and penetration work.

We have also established a series of cutback asphalts using 90–95 road oil cut back with kerosene solvent. This series has been designated as ROMC, and is used much as the MC oils. This grade is more practicable for road mixing, and remains workable for a longer period. It is especially suitable in premix stockpiled material for maintenance patching.

CONSTRUCTION CONDITIONS

The particular methods and equipment employed during construction may have a definite effect on the quality of the finished product, and hence construction methods are of interest to the laboratory, just as laboratory tests and methods are a matter of interest and concern to the field men.

Reduction of moisture content of the aggregate has occupied much attention, as it has been clearly demonstrated that having an aggregate dry at the time of mixing is good insurance against future trouble. In the early days of plant mix construction, moisture was given little consideration, but when the importance of this factor became recognized, steps were taken to require windrowing of the material by blading and scarifying on the roadbed, thus drying the oil treated aggregate prior to consolidation. Such methods are frequently quite successful in hot climates where the relative humidity is low, and it is often possible to reduce the moisture content to less than one percent by working on the road. Moisture can be eliminated by road mixing much more effectively after the material is oiled than before, because the oil coated particles do not take up moisture from the subgrade or night air, as is frequently the case with unoiled aggregate. And since the mixture will absorb more heat due to the dark color of the oil drying is faster.

With an apparently perverse tendency, however, bituminous construction is all too often carried into cold weather; drying on the street becomes difficult or impossible, and artificial drying is the only corrective. This procedure, while at first considered to be too expensive a refinement for a fundamentally cheap type of surfacing, has nevertheless proved to be economical. The increased production with heated aggregate more than offsets the cost of drying. Experienced contractors bidding on plant mix work consider a dryer as part of the regular equipment, whether specified or not.

It may be well to mention in passing the fact that mixtures using fuel oil and cutback asphalt are more difficult to mix in an average pug mill mixer than standard asphaltic concrete. It has been the almost universal experience that plant motors and engines have to be considerably larger in capacity.

The second, and equally important factor in the production of satisfactory plant mix oil surfacing is the control of gradings, particularly in uniformity in the amount of fine aggregate. Mr. T. C. Powers, of the Lewis Institute, has expressed an essential requirement, applying to bituminous work as well as to portland cement concrete. He says, in effect, that a wide variety of gradations may be accomodated, but not wide variation. In the past it has been the practice to add filler dust or fines by dumping them into the pit with the coarse aggregate, or by similar means which do not ensure uniform distribution. It is probably safe to say that in the majority of cases, the preliminary investment and consumption of energy is no greater for adding material uniformly than for adding the same amount of material in a haphazard manner.

It has long been recognized in all types of bituminous construction that fluctuation in the amount of fines is more detrimental than variation in any other part of the mixture. Experience has demonstrated that it is essential that fine material or filler dust be added in a controlled and uniform manner, as it is impossible to maintain a satisfactory oil content when this portion of the mixture is subject to sudden change.

In the early days of oil mix construction it was the practice to make field grading analyses by dry sieving; however, it was soon found that this method does not give the actual amount of fine dust which may be present and the wash method is now the established procedure.

The amount of dust determined by a wash test may range from a negligible increase to as much as 10 times the amount obtained by dry sieving. In the average case the wash test will indicate about double the amount of dry dust passing a 200-mesh.

TABLE VI

Plant Mixing Crushed Gravel Surfacing

	Cost per Ton	
	Contract A	Contract B
Producing Gravel	$0.309	$0.316
Mixing Materials	0.300	0.278
Overhead	0.036	0.045
Bond and Interest	0.036	0.042
Move in, Move out	0.050	0.044
	$0.731	$0.725

Insofar as relative economy is concerned, local conditions must to a large extent be the deciding factor in determining the relative economy of plant and road mix construction. The road mix type is, of course, much the cheaper in first cost when aggregate of suitable quality and quantity is already present on the road, and where the mileage to be handled on the particular project is low, say under four miles. With a larger project, where aggregates must be imported during construction of the finished surface, plant mix construction is usually cheaper, and the results are much more uniform and assured.[11]

In order to compare costs of actual production, the following tabulation has been prepared, based on two plants operating in the desert regions of southern California. The plants produced an average of 666 tons of mix per 8-hour day. Detailed costs are shown in Table VI.

[11] For a more detailed discussion see paper by C. S. Pope, "Factors Determining Choice of Road Mix or Plant Mix Respectively for Low Cost Graded Aggregate Surface," Proceedings Tenth Asphalt Paving Conference, page 29.

MAINTENANCE

An attempt to compare maintenance costs as an index of pavement quality is not always a simple matter. These charges are, of course, affected by the amount and speed of traffic, as well as by local climatic and subgrade conditions.

A few sections have been selected which represent oil mix surfacing constructed of both good and poor aggregate. While climatic conditions and traffic are not uniform, the differences are such as to make the cost data even more significant than would otherwise be the case.

Route 31, on which the selected sections are located, is the main route between Southern California and the Boulder Dam region connecting San Bernardino with Las Vegas via Barstow. The oldest oil mix job in the California State Highway System was built on this route in 1926 between Victorville and Barstow in San Bernardino County.[12] This section is designated as SBd–31–DEF.

Considering the sections in relative order from the city of San Bernardino eastward, the following brief description may be of interest.

The first section (SBd–31–B) surfaced in 1932, is in the mountainous region leading to the Cajon Pass, where the annual rainfall is in excess of 20 inches. Traffic ranges from 1600 cars on week days to as many as 3000 on holidays, with an average of 120 heavy trucks and busses per day. Snow falls several times each year, and there is considerable recreational traffic during the winter. The surface was plant mixed, and laboratory tests indicate that the material is of good quality, although somewhat deficient in fine dust.

The second section (SBd–31–DEF), the pioneer project, is about 30 miles east of the Cajon Pass and in a desert region of comparatively little rainfall. No drainage structures were provided, and water from the occasional cloudbursts is carried over the road surface. The resulting deposits of sand and gravel have to be bladed off after a storm, increasing maintenance costs and wear on the pavement. Heavy trucks and busses average about 75 per day. This pavement is in good condition after eight years, and shows no sign of progressive deterioration.

The third section (SBd–31–H) is east of Yermo and on a new grade provided with drainage structures. Traffic is much lighter, there being about 60 trucks and busses per day. The aggregate used was found to have a considerable affinity for water, as evidenced by a swell in excess of 0.20 in. (0.03 in. is the limit). The mixture was placed with contained moisture, and the section has given considerable trouble, requiring much patching and sealing to preserve the surface. It appears that maintenance costs will continue to be undesirably high.

[12] For additional information on this project, refer to Mr. E. Q. Sullivan's paper in "Proceedings of the American Society of Civil Engineers," August, 1930, page 1260.

The fourth section (SBd–31–L) near Baker is also in the desert, and traffic is even lighter than on the preceding portions. The aggregate gave a high swell and the section has been scarified and reworked several times in order to eliminate unstable conditions due to moisture. There is an average of about 48 heavy trucks and busses per day.

TABLE VII

MAINTENANCE COST PER MILE (REPAIRS TO PAVEMENT ONLY)

On Sections Built With Good Quality Aggregate

County, Route and Section	SBd–31–DEF	SBd–31–B
Length of Project	37.9 mi.	11 mi.
Width of Pavement	18 Ft.	36 Ft.
Year Constructed	1926	1932
Average Traffic, Cars per Day	1000	1800
Year	**Maintenance Charges Per Mile**	
1927–1928	$51.54	
1928–1929	92.46	
1929–1930	171.37	
1930–1931	237.38	
1931–1932	124.86	
1932–1933	164.39	$137.62
1933–1934	286.67	332.24
Total Cost	$1128.67	$469.86
Average cost per mile	$161.24	$234.93

On Sections Where Mixture Showed High Susceptibility To Moisture (Indicated by Excessive Swell)

County, Route and Section	SBd–31–H	SBd–31–L
Length of Project	17.8 mi.	13.1 mi.
Width of Pavement	20 ft.	20 ft.
Year Constructed	1929	1932
Average Traffic, Cars per Day	600	500
Year	**Maintenance Charges Per Mile**	
1929–1930	$231.78	
1930–1931	406.83	
1931–1932	336.81	
1932–1933	335.65	$170.81
1933–1934	335.05	603.84
Total Cost	$1675.12	$774.65
Average cost per mile	$335.02	$387.32

The following tabulation on the four sections is given for comparison, showing length, width, year built and average traffic (all vehicles) for each section, as well as the maintenance costs per mile for each year since completion. (See Table VII.)

These figures indicate that sections using suitable aggregate and proper construction methods can be maintained for at least $150 per mile per year cheaper than sections where poor material is used. The relative saving is probably much greater when reduced to maintenance cost per vehicle or per ton of traffic.

Disregarding the difference in climate and traffic, however, and assuming an average of 1900 tons of surface mixture per mile of road, it appears that an additional cost of 50 cents per ton for good aggregate over the cost of poor material would be balanced by maintenance savings in less than six years. At a nominal cost of $2.00 per ton, this means a justifiable increase of 25 per cent in construction cost.

SUMMARY

Samples of aggregate, either ledge rock, gravel or talus deposits, are submitted to the laboratory by the district engineer, with information as to the type of construction proposed and the amount of material available in each deposit represented.

When received at the laboratory, coarse aggregate is crushed, if necessary, to the size proposed for the work. Grading analyses are made. Hardness or abrasion tests are performed on the coarse aggregate, and a specific gravity determination is made on both fine and coarse material.

Test specimens for oil mix or cutback treated surfacing are prepared corresponding as closely as possible to the proportions which will be used in construction. In other words, if the samples received represent material in place on the road, no change in grading is made, and specimens are prepared using the aggregate as received. If the proposed work involves plant mix, the materials may be recombined and a satisfactory grading determined before preparation of the specimens.

After the grading is fixed, surface area equivalents are calculated in the manner described, and a tentative surface factor is selected from inspection of the aggregate. As a check on the accuracy of the assumption test specimens are prepared using from 1000 to 1500 grams of the complete grading, with three different oil contents, one calculated on the assumed optimum amount, one using a higher oil line, and one using a lower line. Three trial specimens are thus prepared for stability tests, and one extra specimen using the assumed optimum oil content for the swell test.

The accurately proportioned aggregate and oil is mixed in a mechanical mixer, and placed in a constant temperature oven maintained at 140°F. for 24 hours. The specimens are then compacted using a combination method of tamping and compressing which produces density similar to that obtained in the pavement. Compressed briquettes 4 in. in diameter and approximately 2½ in. high are formed, placed in an oven and brought to a temperature of 140°F., and tested immediately for relative stability by the Stabilometer method.

If the original assumption as to the oil requirement is correct, Stabilometer results on the three specimens will show a slightly higher value with the optimum oil content than with the greater or less amounts. It is occasionally necessary to prepare additional specimens, varying the oil content still further, in order to determine the most satisfactory amount. In any event, the Stabilometer results are used as a basis for the laboratory recommendations. This recommendation is made in terms of a surface factor (see Fig. 4), and serves as a guide to the resident engineer, who may actually use a grading differing from the original laboratory samples. The surface factor, or "oil line" is the basis for calculations in the field.

The pat stain test was formerly used as a guide for the field men, but has been abandoned because of the difficulty in classifying a colorimetric test of this nature. Several factors, such as moisture and fineness of the aggregate, have an effect on the stain test, and two individuals rarely interpret the same stain alike.

The test report furnished to the resident engineer and construction department gives details of grading, specific gravity, oil ratio, stability tests, swell of the compacted specimen, and the water-asphalt preferential determination for any filler material provided.

Tensile or cohesion tests have not yet been adopted as a part of routine procedure.

Materials that fail to meet the minimum stability requirements, or which show excessive swell, are not approved, except in cases where entirely suitable aggregate is not available. In such cases, special recommendations for treatment may be made in order to offset the poor qualities as far as possible.

Although the procedure outlined is comparatively simple, considerable work is involved when a number of alternate sources of supply are tested and compared, and also when it is desired to determine the best combination from several available sources of supply.

Adoption of these tests has enabled us to avoid most of the unsuitable aggregate and to make definite recommendations in advance of construction eliminating the necessity for trial and hit-or-miss methods in the field.

There are a number of improvements to be made, and several additional tests and determinations are already visualized which it is hoped will help greatly in achieving the goal of the laboratory, which should be: *ability to obtain accurate and precise prior information concerning qualities of materials, and to predict behavior in service.*