# HIGHWAY RESEARCH BOARD

## BULLETIN 105

# Bituminous Paving Mixtures

## FUNDAMENTALS FOR DESIGN

National Academy of Sciences—

National Research Council

publication 355

# HIGHWAY RESEARCH BOARD

## Officers and Members of the Executive Committee
## 1955

# HIGHWAY RESEARCH BOARD
## Bulletin 105

# *Bituminous Paving Mixtures*

## FUNDAMENTALS FOR DESIGN

1955

Washington, D. C.

## *Department of Materials and Construction*

R. R. Litehiser, Engineer of Tests, Testing and Research Laboratories, Ohio Department of Highways

### BITUMINOUS DIVISION

H. L. Lehmann, Chairman, Testing and Research Engineer, Louisiana Department of Highways

### COMMITTEE ON DESIGN OF BITUMINOUS PAVING MIXTURES

Lloyd F. Rader, Chairman, Professor of Civil Engineering, University of Wisconsin

W. K. Boyd, Snow, Ice and Permafrost Research Establishment, Wilmette, Illinois

W. M. Carver, Materials Engineer, Nebraska Department of Roads and Irrigation, Lincoln

A. B. Cornthwaite, Testing Engineer, Virginia Department of Highways, Richmond

Ladis H. Csanyi, Professor of Civil Engineering, Iowa State College, Ames

R. T. Healy, Engineer of Materials, Connecticut State Highway Department, State Highway Laboratory, Portland

F. N. Hveem, Materials and Research Engineer, California Division of Highways, Sacramento

J. T. Pauls, Principal Highway Engineer, Physical Research Branch, Bureau of Public Roads

O. A. Philippi, Assistant Construction Engineer, Texas Highway Department, Austin

W. C. Ricketts, Airfields Branch, Engineering Division, Office of the Chief of Engineers, Department of the Army

J. H. Swanberg, Engineer of Materials and Research, Minnesota Department of Highways

B. A. Vallerga, Managing Engineer, Pacific Coast Division, The Asphalt Institute, San Francisco, California

# Contents

Properties Required of Bituminous Paving Mixtures - - - - - - - - - - - - - - - - - - - - - 1

Uses of Bituminous Paving Mixtures - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 10

Types of Bituminous Paving Mixtures - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 10

Voids - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 14

Methods of Mixture Design - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 18

Effects of Variations in Characteristics and Gradations of Aggregates on Physical Properties of Mixtures - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 19

Effects of Variations in Bitumen Content and Characteristics of Bitumen on Physical Properties of Mixtures - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 21

Practice in Designing Bituminous Paving Mixtures - - - - - - - - - - - - - - - - - - - - 22

References - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 23

Appendix A: Proposed Tentative Method of Test For Stability and Flow Value of Bituminous Mixtures - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 25

Appendix B: Proposed Tentative Methods of Test for Resistance to Deformation and Cohesion of Bituminous Mixtures - - - - - - - - - - - - - - - - - - 32

Resistance to Deformation - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 32

Cohesion - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 36

Appendix C: Kneading Compaction Method for Bituminous Mixtures to be Tested in the Hveem Stabilometer - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 37

Appendix D: Method of Test for Determination of Bulk-Impregnated Specific Gravity of Aggregate for Use in Bituminous Paving Mixtures - - - - - - 39

Appendix E: Method of Test for Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture by Solvent Immersion - - - - - - - - - - 40

Appendix F: Method of Test for Maximum Specific Gravity of Bituminous Paving Mixtures by Vacuum-Saturation Technique Using Uncompacted Samples - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 41

Special Instructions for Mixtures Containing Porous Aggregate Not Completely Coated - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 42

Appendix G: Determination of Specific Gravity of Bituminous Concrete Mix for Field Density Control - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 43

Appendix H: Skid Resistance of Bituminous Pavements - - - - - - - - - - - - - - - - - - 44

# Bituminous Paving Mixtures: Fundamentals for Design

● THIS bulletin discusses fundamentals governing the design of bituminous paving mixtures. It was deemed desirable to assemble information concerning bituminous-paving-mixture design in one publication for the benefit of those engineers who need to have comprehensive, up-to-date material readily available. Many of the problems in this field are only partly solved, but the engineer engaged in designing and constructing bituminous-paving mixtures is nevertheless called upon to give answers to such problems. It is hoped that by means of this bulletin authoritative information based on current knowledge can be disseminated to practicing engineers.

In order to select suitable bituminous materials and aggregates and design properly the proportions of bitumen and aggregates for a paving project involving given conditions of traffic and climate, the engineer should have an understanding of the fundamentals governing the design of bituminous paving mixtures.

—Lloyd F. Rader, Chairman, Committee on Design of Bituminous Paving Mixtures

## *Properties Required of Bituminous Paving Mixtures*

The essential properties required of bituminous paving mixtures comprise stability, durability, flexibility, resistance to skidding, and workability during construction operations.

### STABILITY

Stability may be defined as resistance to displacement. The term implies resistance to shoving and rutting by the action of vehicular traffic and involves resistance to shearing stress. Owing to the plastic nature of bituminous paving mixtures, stability becomes more critical at the higher temperatures encountered in the field; hence stability values are usually determined at an elevated temperature such as 60 C. (140 F.) or, for some mixtures, at a normal temperature of approximately 25 C. (77 F.) but generally not at a lower temperature than 70 F. Stability is considered to be one of the most-important properties required of bituminous mixtures and must always be adequate for the type and intensity of traffic to be carried in order for the pavement to render satisfactory service. The importance of stability for bituminous pavements carrying large volumes of heavy truck traffic should be emphasized. Adequate stability is important also for bituminous pavements subjected to stresses induced by parking of vehicles and by acceleration and deceleration of traffic at stop signs and signals.

However, in designing these mixtures, attention should be given to the other essential properties listed above as well as to stability. For example, in the selection of the proper bitumen content for a given aggregate mixture and for the anticipated conditions of traffic and climate, all of the essential properties should be considered. In dense-graded mixtures, as much bitumen as possible should be placed in the mixture to provide durability and flexibility, but the bitumen content should be kept below the amount which may eventually produce rutting and shoving when the pavement is densified to its ultimate state of equilibrium under traffic.

### PROCEDURE IN DESIGNING FOR STABILITY

Stability is influenced by the grading of the aggregate, the shape and surface texture of the aggregate particles, the relative coarseness or maximum size of the aggregate, the proportions of aggregate to bituminous binder, the consistency of the bituminous binder and the degree of compaction.

The first step in design for desired stability is to select an aggregate that either has or can be processed to have sufficient particle angularity. The degree to which this requirement should be met depends on the severity of the traffic requirements and, to a degree, on the availability and relative cost of various types of aggregate. It should be noted that the surface texture (roughness or smoothness) of the aggregate particles as well as shape of particles is important in developing stability.

Decision as to the maximum size of aggregate, i. e. ½ inch, ¾ inch or 1 inch for surfacing mixtures, should depend upon the relative importance of workability and surface finish versus high stability. Along with the increasing stability that accompanies the use of coarser aggregates goes a tendency toward increasing harshness and segregation which results in less-attractive surface texture and appearance. Unattractive surface appearance resulting from the use of coarse surfacing aggregate can be overcome by requiring a seal and chip or coarse sand cover treatment soon after construction. This has other advantages in that it reduces vehicle tire noise and improves the water-shedding or roofing effect of the pavement, preventing moisture from entering the bituminous concrete until the pavement has become compacted by traffic. Both asphaltic and tar materials may be utilized as sealers.

Although it only affects stability under adverse moisture conditions, the relative preference of the aggregate for coatings of bituminous binder versus water should be investigated when selecting the coarse aggregate, the fine aggregate or sand, and the mineral dust or filler.

The grading of the aggregate has a significant effect on the stability of the bituminous mixture. In general, and within limits that will be discussed, any change in the grading of a particular aggregate that will permit it to be compacted to a greater density or more-intimate packing of the aggregate particles will result in higher stability.

In sand mixtures high density and stability are usually associated with fairly uniform distribution of particle sizes from maximum to minimum and a fairly high percentage of mineral dust or filler passing the No. 200 sieve.

Studies of the density and stability of sand mixtures have shown that skip-graded sands completely lacking in the No. 40 to No. 80 size can produce very dense, stable mixtures. Generally, however, it is not practical to produce this type of sand grading.

There is, however, a practical limit on the amount of dust that can be used which, in general, is below the amount that would result in maximum density and maximum stability. This limit is fixed by the volumetric capacity of the compacted sand for a sufficient amount of bitumen to coat fully, all particles, including those of the mineral filler, and for, additionally, a residual allowance of unfilled air voids. The purpose of unfilled air voids is to provide space for thermal expansion of the bituminous binder in hot weather and for progressive consolidation of the surfacing under traffic.

Determination of the maximum amount of dust that can properly be used in sheet-asphalt mixtures involves some trial-and-error testing, because it is usually necessary to make simultaneous adjustments in both the computed bitumen content and the dust content after the densest blend of sand and dust has been determined. The use of high amounts of mineral filler with low amounts of bitumen make sheet-asphalt mixtures hard and brittle and low in resistance to cracking. It has been suggested that a maximum limit on dust content should be of the order of 1.2 parts of dust by weight to 1 part of bitumen for densely graded mixtures where the bitumen content is also limited by void volume in the compacted aggregate.

In mixtures containing coarse aggregate, material retained on the No. 8 or No. 10 sieve, high density, and correspondingly high stability are promoted by maintaining a high ratio of coarse to fine aggregate. This, like the use of the large maximum-size aggregates, however, tends to produce relatively harsh mixtures that require special care in finishing and compacting. Bituminous-concrete aggregate in which the coarse and fine fractions are proportioned for maximum density and stability generally will have from 35 to 65 percent of the total aggregate retained on the No. 10 sieve. This proportion varies somewhat with the maximum size of the coarse particles, being greater for large than for small maximum sizes.

One of several satisfactory methods of proportioning the coarse, fine, and filler fractions of bituminous-concrete aggregate for high density and stability is described in detail by Pauls and Goode (1).

It involves the use of vibratory compacting equipment and a graphical method of systematic design for maximum density. The same systematic approach to design of the aggregate grading can be used when other methods of compaction are employed, such as dry rodding, direct compression, tamping, or kneading compaction. In the latter three cases, it is necessary to use bituminous mixtures rather than the dry aggregate, using only enough bitumen to permit molding and handling test specimens. The molding process and the quantity of bitumen must be held constant while the effect of changing the grading is being investigated. Changes in density are determined gravimetrically by water immersion.

The proportion of bituminous binder to aggregate is of great importance in developing stability in a bituminous paving mixture.

Determination of the correct bitumen content for a dense-type paving mixture consists of two steps: (a) preliminary estimation of bitumen content by means of surface area formula (2), volumetric computation (3), or some such device as the California centrifuge kerosene equivalent test (4) and (b) final determination of the optimum bitumen content by stability test, which consists of preparing a small number of test mixtures with bitumen contents covering a limited range, compacting test specimens and testing them for stability by one or more of the several test methods available.

## Hubbard-Field Stability Test

Probably the one best known and most widely used is the Hubbard-Field Asphalt Stability Test for sheet asphalt (reference: Asphalt Institute Research Series No. 1). This test has been standardized by the American Society for Testing Materials as Designation D1138-52 Method of Test for Resistance to Plastic Flow of Fine Aggregate Bituminous Mixtures and is published in the ASTM standards. Experience during the past 25 years with this test has yielded a great deal of valuable data useful to the technologist in designing fine-aggregate bituminous mixtures. The Hubbard-Field test is an extrusion type of shear test performed by forcing cylindrical briquets 2 inches in diameter by about an inch high through an orifice 1.75 inches in diameter at a temperature of 60 C. (140 F.).

A 6-inch diameter specimen is employed by Hubbard and Field for determining the stability of asphaltic concrete. This test is also widely used but has not been standardized (reference: Asphalt Institue Manual on Hot Mix Asphaltic Concrete Paving, pp. 29-39).

The Hubbard-Field Asphalt Stability Test is a practical test of the empirical type which has proved to be valuable for bituminous mixture design; this is particularly true of the 2-inch-diameter test for fine-aggregate bituminous mixtures.

## Unconfined-Compression Test

Also well known and rather widely used but of more-recent origin is the unconfined-compression test which has been standardized by the ASTM and designated D1074-52T Tentative Method of Test for Compressive Strength of Bituminous Mixtures. For this test, specimens of bituminous concrete are usually 4 inches in diameter by 4 inches in height. The temperature of test is 25 C. (77 F.).

According to V.A. Endersby (5), the unconfined-compression test measures primarily the cohesion or viscous resistance of the bituminous binder and, to a lesser degree, the internal friction of the aggregate.

The unconfined-compression test has several features that make it especially useful as a research and design tool. The test values, although conservative, are proportionally indicative of the bearing capacity of the paving mixture. It is sufficiently sensitive to measure the effect of the various design factors enumerated above and is simple and convenient to use. The unconfined compression test has been developed and is used by the Physical Research Laboratory of the U.S. Bureau of Public Roads.

## Marshall Test

Another widely employed test for stability is the Marshall test (references: "The Marshall Method for the Design and Control of Bituminous Paving Mixtures", Marshall Consulting and Testing Laboratory, 1127 Fairmont Avenue, Jackson, Mississippi, 3rd. revision, Nov., 1952; also: "Airfield Pavement Design, Flexible Pavements", Chapter 2, Part XII, July, 1951, Engineering Manual for Military Construction, Corps of Engineers, Department of the Army). The test is performed by measuring resistance to application of load on the circumferential surface of a cylindrical specimen. The specimen is mounted vertically and load applied through a collar placed on the curved surface at the top of the specimen. The bottom is held by another collar. In addition to measuring the resistance to displacement, a dial is employed to measure flow of the specimen during test. This test may be described as one where a lateral pressure is exerted on the cylindrical specimen, but zero normal load is applied to the flat surfaces of the specimen. It is, therefore, opposite to the unconfined-compression test where load is applied on the top and bottom of the cylinder with zero lateral pressure on the cylindrical surface of the specimen.

The stability value obtained by the Marshall test measures resistance to displacement of a compressed bituminous mixture. This stability value reflects several properties of a bituminous mixture. According to V. A. Endersby (5), the Marshall stability value is primarily a measure of cohesion and viscosity of the bituminous binder and to some extent a measure also of mechanical stability of the aggregate.

The flow index is obtained by measuring the diametric distortion required to produce fracture of the specimen. N. W. McLeod (6) has pointed out a relationship between the flow index and the angle of internal friction, $\phi$, as determined in the triaxial-compression test (the lower the flow value, the higher the angle of internal friction). Thus, the flow index may provide an indirect measurement of internal friction of the aggregate. This is in accord with the Corps of Engineers' requirements for asphaltic-concrete runways of a maximum flow value of 0.16 inch for high-pressure tires of 200 psi. and of a maximum flow value of 0.20 inch for low-pressure tires of 100 psi. pressure. (Reference: "Airfield Pavement Design, Flexible Pavements", Chapter 2, Part XII, July, 1951, p. 34, Engineering Manual for Military Construction, Corps of Engineers, Department of the Army). This in effect is requiring a greater internal friction for pavements under loads from high-pressure tires.

A factor which affects the flow value is the degree to which the aggregate voids are filled with bitumen. The flow value increases as the bitumen content of the mixture is increased. Flow should be restricted within prescribed limits in order to guard against placing paving mixtures with too great a bitumen content which will cause the pavements to rut and shove (usually 0.20 inch maximum for highways).

The Marshall test has been adopted by the Corps of Engineers of the Department of the Army after extensive research investigations for designing bituminous-paving mixtures for airfields. The test apparatus has been modified so that it is included in a field kit and is suitable for use in designing and controlling bituminous mixtures for military airfield runways in forward areas. The Marshall test is also used by the Bureau of Yards and Docks of the U. S. Navy and by several state highway departments (see Appendix A for Marshall test method).

## Hveem Stabilometer and Cohesiometer

The Hveem procedure for determining stability of bituminous paving mixtures is used by a number of state highway departments in the West. Both the stabilometer and the cohesiometer are used to evaluate the properties of bituminous mixtures (see Appendix B for Hveem test methods).

It is recommended by Hveem that fabrication of the test specimens be performed by the kneading compaction method in order to evaluate properly bituminous mixtures by the Hveem stabilometer and cohesiometer (see Appendix C for Kneading Compaction Method). However, other methods of fabricating are employed as for example the Texas gyratory shear method and the double plunger compression method.

The stabilometer test is performed by placing the compacted test specimen within the stabilometer shell where it is surrounded by a close-fitting rubber tubing and a liquid annulus, subjecting the specimen to a vertical load through a loading follower, and measuring the lateral pressure developed as the vertical load is applied.

The lateral pressure varies inversely with the internal resistance of the mass of the bituminous mixture. The lateral pressure corresponding to a vertical pressure of 400 psi. is used to determine the result of the stabilometer test. This vertical pressure is taken to represent the combined effects of pneumatic-tired traffic loads frequently repeated over a long period of time. (The test is not carried out to reach a yield point.)

Following the idea that plastic materials have properties intermediate between liquids and rigid solids, an arbitrary scale from 0 to 100 has been established in which the value of zero corresponds to a liquid having no measurable internal resistance to slowly applied loads, and at the other extreme, 100 corresponds to a hypothetical solid that will transmit no measurable lateral pressure under a given load. Experimental data indicate that stabilometer results depend almost entirely on internal friction of the aggregate and are influenced to only a slight degree by the cohesion or viscous resistance of the bituminous binder in the pavement. Stabilometer tests are utilized to determine the maximum amount of bituminous binder which can be used without causing instability.

The cohesiometer measures the cohesive strength of the bituminous films. This is accomplished by bending or breaking the same cylindrical test specimen as used in the stabilometer. The cohesiometer test is comparable to a cantilever beam test. The cohesiometer results measure the cohesion or viscous resistance of the bituminous binder and, hence, supplement the stabilometer values (7, 8).

## Triaxial-Compression Test

There is probably more interest in the triaxial-compression test from the standpoint of research in designing mixtures than in any other test method, but it has not been generally adopted as a design test for stability. There are two types of this test: the "open" or applied-pressure type and the "closed" or induced-pressure type. In the open-type, triaxial-compression tests are performed on several different specimens with a different lateral pressure on each (reference, Carpenter, C. A., Goode, J. F., and Peck, R. A.: "An Improved Triaxial Compression Cell for Testing Bituminous Paving Mixtures", Proc. Assoc. Asphalt Paving Technologists, Vol. 20, February, 1951, p. 154). In the closed type of test, only one test specimen is needed (reference, Asphalt Institute Manual on Hot-Mix Asphaltic Concrete Paving, pp. 73-86). By means of the triaxial-compression test, it is possible to determine both the cohesion and angle of internal friction of the bituminous paving mixture. Also by utilizing principles of mechanics, it is possible to design bituminous mixtures for use in pavements on a pounds per square inch bearing capacity basis.

## Test Values

Typical ranges of stability test values for hot-mix bituminous pavements for highways are given in Table 1. Ranges given represent values obtained on various types of aggregates and bituminous materials and do not represent specification values unless so designated. Values given correspond to results obtained on specimens compacted by the method prescribed for each test method. No special curing methods are considered. Values are not correlated between different tests. Certain pavements produced from local aggregates and subjected to special conditions of traffic and climate have rendered satisfactory service even though their stability values were outside of the ranges listed. Specimens formed by reheating and remolding compacted bituminous mixtures give stability values that are much higher than those values obtained from freshly prepared specimens that are molded according to prescribed test methods.

## Summary

Bituminous-paving mixtures can be adequately designed by any of the above methods to have satisfactory stability. Each of the above tests has certain advantages and disadvantages. There is no common agreement at the present time on a single test method as being the best one.

# DURABILITY

A durable bituminous pavement must withstand detrimental effects of traffic, water, air, and temperature change.

## Resistance to Applications of Traffic Loads

To be durable, a bituminous pavement must satisfactorily resist applications of traffic loads during the lifetime of the pavement. In addition to having sufficient stability to resist shoving and rutting, the pavement surface must resist the abrasive action of traffic. A bituminous pavement should also be tough at low temperatures in order to withstand impact from traffic at low temperatures. Toughness is defined as resistance to impact. The Page impact

TABLE 1

TYPICAL RANGES OF STABILITY TEST VALUES FOR HOT-MIX BITUMINOUS PAVEMENTS FOR HIGHWAYS[a]

| Stability Test | Sheet Asphalt | Bituminous Concrete Medium Traffic | Bituminous Concrete Heavy Traffic | No Traffic Differentiation |
|---|---|---|---|---|
| Hubbard-Field 2-in. diam. mold, lbs. (140 F.), tested in water | 1200-4000 (2000 min. for heavy concentrated traffic) | | | |
| 6-in. diam. mold, lbs. (140 F.), tested in water | | 1200-4500[c] | 2000-6000[c] (3500 min. for heavy concentrated traffic.) | |
| Compression 4-in. by 4-in. cylinder, lbs. per sq. in. (77 F.), tested dry | 100-300 | | 350 min. | 200-450 |
| Marshall (Asphaltic Mixtures only)[b] Stability, lbs. (140 F.), tested wet | 300 min. | 500-1200[c] | 1000-2000[c] | 500-1500[c] |
| Flow value, hundredths of inch (140 F.), tested wet | 20 max. | 12-20[c] | 8-20[c] | 10-20[c] |
| Hveem Stabilometer Relative stability, percent (140 F.), tested dry | 15-30 | 35 min. specified. | 35 min. specified. | 35-50[c] |
| Hveem Cohesiometer Cohesiometer value, C, grams per inch of width corrected to 3 inch height (140 F.), tested dry | 75-175 | | | 50 min.[c] (lowest safe cohesion.) |
| Triaxial Compression Cohesion, lbs. per sq. in. (77 F.), tested dry | 8-20 | | | 6-100 |
| Angle of internal friction, $\phi$, degrees (77 F.), tested dry | 25-40 | | | 25-52 |
| Modulus of deformation, lbs. per sq. in. (77 F.), tested dry | | | | 25,000[c] |

[a] Illustrative values are not intended or suggested for use in specifications.
[b] Tar mixtures are frequently tested at 100 F. in the Marshall test.
[c] Limiting test values reported by various State Highway Departments to W. E. Chastain: "Summary of State Practices in the Use of Bituminous Concrete Mixtures"- Sixth Highway Engineering Institute, Bituminous Roads, University of Wisconsin, Feb. 23-26, 1954.

machine has been utilized for performing toughness tests on specimens of sheet asphalt mixtures at low temperatures.

Resistance to Deterioration by Water

Stripping. Bituminous pavements must resist the removal of bituminous material from aggregates when moisture is present. The immersion-compression test has been developed to measure the loss of cohesion resulting from the action of water on compacted bituminous mixtures. This test has been standardized by the American Society for Testing Materials as D1075-49T Effect of Water on Cohesion of Compacted Bituminous mixtures.

A film stripping test devised by Victor Nicholson is also used. A description of this test as conducted by the Highway Research Board Asphalt Committee is described in the Proceedings, Highway Research Board, 17th annual meeting, Dec., 1937, pp. 329-330. The California Division of Highways uses a slight modification of this method as a routine test. A number of static immersion tests are employed to measure resistance to film stripping. The Ohio Department of Highways test is a typical one.

Resistance to moisture vapor. Another test dealing with resistance of bituminous mixtures to water action is the moisture vapor susceptibility test. As conducted by the California Division of Highways a test specimen is compacted in the kneading compactor, subjected to 75 hours of moisture-vapor treatment, and then tested in the Hveem stabilometer. The results are compared to those for a specimen containing no moisture.

Resistance to freezing and thawing. Deterioration in physical properties must be resisted when bituminous pavements are subjected to alternate cycles of freezing and thawing.

Resistance to swell. A durable pavement must also resist swelling action caused by absorption of moisture. Standard swell tests are given in AASHO Designation T101-42, methods A and B. California uses a modification of Method B which permits aggregates up to passing 1-inch size, requires compaction of specimen by the kneading compactor, and reports the swell to the thousandth of an inch as direct gain in height.

Resistance to Deterioration by Air

To resist deterioration by air a bituminous concrete or sheet asphalt pavement should have its voidage restricted below a given maximum to avoid deterioration by air. In other words, oxidation and evaporation causing deterioration and hardening of the bitumen may occur if the compressed mixture is excessively open. For these reasons, dense-graded mixtures should be laid and adequately rolled at temperatures high enough to insure good density of the pavement. Also, wearing courses of open-graded mixtures should be sealed.

Resistance to Temperature Change

At high temperatures, under service conditions, a bituminous pavement should possess sufficient stability to resist the effects of traffic loads. At low temperatures, a bituminous pavement should resist cracking caused by stresses induced by contraction of the pavement due to temperature change. Resistance to cracking will be discussed in detail.

## RESISTANCE TO CRACKING

It is important that bituminous pavements be designed to resist cracking. This is especially true for pavements laid in the northern part of the United States. One of the strong competitive advantages of properly designed and constructed bituminous pavements as compared with rigid pavements is the ability to resist cracking, making it unnecessary to install joints to provide for expansion and contraction.

Cracks in asphalt pavements may be due (1) to the characteristics of the asphalt paving mixtures or (2) to structural defects in the pavement. Cracks of the first class are due primarily to failure of the asphalt pavements to resist stresses caused by contraction produced by temperature reduction. Cracks of the second class may be due to causes such as contraction cracks in portland-cement-concrete base beneath the asphalt surface course, to failure of base or subbase, or to poor foundation support; these cracks caused by structural defects of the pavement structure will not be considered in this bulletin, but attention will be directed to those of the first class.

Bituminous wearing courses which have cracks of the first class are generally nonflexible, and the bitumen in such pavements has usually become hard and brittle. At low temperatures, the bituminous pavement is in an elastic state. The desirability of pliancy and nonbrittleness at low temperatures in a bituminous pavement has been recognized for many years and is considered to be fully as important as stability from the standpoint of a bituminous pavement maintaining desirable physical characteristics and rendering good service.

The flexure test on beams of bituminous paving mixtures has been developed by Rader (9) for determining physical properties at low temperatures when the compressed mixture is in an elastic state. Modulus of rupture and modulus of elasticity values are obtained. The modulus of rupture is a measure of the tensile strength of the paving mixture, and the modulus of elasticity is a measure of stiffness. For well-designed bituminous pavements, it is desirable to have a high value of the modulus of rupture to insure adequate tensile strength to resist stresses set up due to expansion and contraction, but it is desirable to have low values of the modulus of elasticity so the mixture will be pliable and not excessively stiff. Examination of the formula $S = ctE$ indicates that E should be low for given values of c and t in order to produce low stress S in the pavement due to temperature change, where

S = unit stress, in pounds per square inch
c = coefficient of expansion and contraction
t = temperature change
E = modulus of elasticity in pounds per square inch

In recent work by Stauss and by Davidson (10) the sonic modulus of elasticity has been determined at low temperatures on beams of asphaltic concrete.

The sonic method does not require breaking of the specimens, so that the effects of alternate cycles of freezing and thawing, wetting and drying, or other variables can be determined employing the same specimen throughout a series of tests.

Correlation between the flexure test at low temperatures and resistance to cracking of sheet asphalt pavements in service has been established by obtaining modulus of rupture and modulus of elasticity in flexure values at low temperatures on beams sawed from asphalt pavements.

Hardening of asphalt in paving mixtures has been found to reduce resistance to cracking. Investigations by Hubbard, Gollomb, and Rader on the effects of overheating asphalt-paving mixtures and of prolonging the mixing of the asphalt with aggregate at high temperatures showed that such action tends to harden the asphalt in a manner similar to oxidation and that this action reduces the resistance to cracking of the pavement. Proper attention to temperature of asphaltic mixtures at paving plants would contribute to a great extent towards reducing the amount of cracking of asphalt pavements. It may be advisable in certain cases to use asphaltic cements of initially high penetration, so hardening of the asphalt caused by subjecting mixtures to high temperatures at the paving plant and during transportation to the street will not produce asphalt of too low penetration for proper resistance to cracking.

Asphalts differ in their hardening properties depending on the source of crude and the method by which the asphalts are refined. The hardening of asphalts during plant mixing at high temperatures can be controlled somewhat by mixing at the lowest possible temperature to give proper coating to the aggregate and to produce a mixture of the desired workability. It has been proposed that the mixing temperature be based on the viscosity of the asphalt.

Several tests have been devised by which the relative hardening of asphalts can be determined in the laboratory and with proper limits would restrict the use of those asphalts that are highly susceptible to hardening when exposed to high temperatures and air. The thin-film oven test, proposed by Lewis and Welborn (11) could be used for this purpose. Lewis and Halstead (12) proposed the following requirements for the thin-film oven test on asphalts of 50-60 through 120-150 penetration grades: (1) Loss on heating of ⅛-inch thin film for 5 hours at 325 F. shall be less than 1 percent. (2) The residue from thin-film oven test shall have a penetration of at least 50 percent of the penetration of the original asphalt. This would apply to all grades.

A study by Pauls and Welborn (13) further shows the hardening in the thin-film oven test is the same as occurs in mixtures. This report contains the detailed method for making the thin-film test; it also describes results obtained by an abrasion test and by a weathering-strength test.

Pauls and Welborn conclude that the thin-film oven test is the most suitable for use as a specification test.

Another test to determine the relative hardening of asphalts is the shot abrasion test developed by Hveem which is used in conjunction with an accelerated weathering machine (14, 15, 16).

The following conclusions and recommendations have been made by Rader concerning his investigations of the physical properties of sheet asphalt paving mixtures at low temperatures with particular reference to resistance to cracking:

1. An asphalt-paving mixture should not be designed to have unnecessarily high resistance to displacement as measured by stability tests without consideration of the resistance to cracking of the mixture, particularly if the mixture is to be laid in localities which have cold winters.

2. Thorough compaction of a sheet-asphalt mixture is important to develop its maximum tensile strength at low temperatures.

3. Other factors being equal, it would appear that those sheet-asphalt mixtures containing the highest-penetration asphalt and the highest percentage of asphalt consistent with necessary stability should prove the most resistant to cracking at low temperatures.

4. The importance of proper control of plant and street construction operations to insure properly proportioned and well-compacted pavements of uniform density and to prevent great alterations in characteristics of the asphalt cement should be emphasized.

## FLEXIBILITY

Flexibility of a bituminous pavement is understood to mean the ability of the pavement to adjust itself to load settlements of the underlying base without cracking. The property of flexibility is particularly important when the pavement is laid on a flexible or compactible base course, and is of lesser importance where the pavement is laid on a base course having a relatively high degree of rigidity.

The principal factors of a bituminous paving mixture affecting the property of flexibility are: (1) the quantity of the bituminous binder, (2) the viscosity and temperature susceptibility of the binder, and (3) the quantity of mineral filler. These three factors which affect the flexibility of the pavement also influence the stability of the pavement. It is obvious, therefore, that in designing the mixture, a balance should be struck so that flexibility will be obtained without too great a sacrifice of stability.

The sand-silt-ratio method of design takes into account both flexibility and stability. The following is quoted (17):

"Flexibility. This characteristic will be important to the field man only where a road mix or plant mix pavement has been designed for light or medium traffic on poor soil.

"Inflexibility is due to overstable aggregates. Flexibility is improved by decreasing silt or filler to reduce particle contacts; this also reduces surface area of particles and permits greater asphalt film thickness. This item can be overdone; increasing flexibility may result in lowered stability; for example, pavement design for very-heavy truck traffic would be provided with a strong base, thus reducing the need for greater flexibility."

Several laboratory tests have been designed to measure the flexibility of bituminous mixtures. Among them are:

1. Deformation in the compression test (reference: Vokac, Roland: "Compression Testing of Asphalt Paving Mixtures", Proc. Am. Soc. Test Mats., Vol. 36, 1936, pp. 552-567 for "modulus of permanent deformation").

2. Hveem cohesiometer (see description above under Stability).

## RESISTANCE TO SKIDDING

In designing and constructing a bituminous mixture, care should be taken to avoid an excess of bitumen on the surface of the pavement either immediately after construction or after the pavement has been subjected to densification by traffic or affected by climatic conditions. Sufficient voidage should be provided in the compressed bituminous pavement to allow for increased densification by traffic loads and for expansion of the aggregate caused by temperature increase so that exuding of bitumen on the surface of the pavement will be avoided. Resistance to stripping is also of importance, since stripping may cause ascension of bitumen from the bottom of the bituminous pavement to the surface.

Certain types of stone tend to become polished under traffic and may cause a slick surface condition. Some of the nonporous and harder limestones will give such a condition. In this case it is often helpful to use a sharp silica sand as the fine aggregate and to adjust the proportions of the mix to provide sufficient amounts of this fine aggregate to produce a sand-paper surface texture instead of having the stone predominate in the surface. Incorporation of granitic aggregate in the mixture will also help in many cases. Certain serpentine aggregates should be avoided because of their tendency to produce a slippery surface.

A paper on "Skid Resistance of Bituminous Pavements" by Clark and Cornthwaite is given in Appendix H.

Moyer (18) has reported results of extensive tests on skid resistance including both open-graded and dense-graded asphalt pavements. Additional data on skid resistance of bituminous pavements have been reported by Easton (19), Morgan (20), and Normann (21).

### WORKABILITY DURING CONSTRUCTION OPERATIONS

For easy placement in uniform layers with sufficient densification, bituminous paving mixtures must be workable at the temperature desired. The mixture should be easy to spread and roll; it should not be tough to spread and should not be displaced by the roller. This requirement of workability may affect the design of the proportions of a paving mixture; for example, the increasing of percentage of mineral filler in a sheet asphalt wearing course in an effort to improve density and stability may produce a tough mixture which would be difficult to rake or place.

In view of the development of efficient modern spreading and finishing equipment, the workability of mixtures is not of as great importance as it was when hand methods of placement were employed.

With respect to bituminous binder, the following factors affect workability: (1) consistency, (2) temperature of mixture during spreading and compacting, and (3) percentage of bitumen.

With respect to aggregates, the following factors affect workability: (1) the grading of the aggregate, (2) the maximum particle size of aggregate in relation to the compacted thickness of the pavement, (3) the shape and surface texture of the aggregate particles, and (4) the range in size between the largest and smallest aggregate particles.

## *Uses of Bituminous Paving Mixtures*

It is obvious that the design of bituminous paving mixtures is dependent upon their use. The main uses are for highways and streets and for airport runways, taxiways, and aprons. This report is intended primarily to cover the fundamentals governing the design of bituminous paving mixtures for such uses; but such mixtures are extensively used for other purposes: linings of canals and stream beds and for breakwaters, playgrounds, and athletic fields.

## *Types of Bituminous Paving Mixtures*

### TYPES OF BITUMINOUS MATERIALS

#### Asphalts

These include asphalt cements; liquid asphalts; and hard, powdered asphalts with liquid residuals. Asphalt cements require heating for mixing with aggregates and the mixture must be maintained at a relatively high temperature until placed on the road or runway. Upon cooling, the asphalt cement binds the aggregate particles together.

Liquid asphalts are manufactured for cold mixing and cold laying, though warming may be practiced in some instances. After setting or curing, the asphalt cement is left in contact with the aggregate. The liquid asphalts comprise (1) liquid materials containing a mixture of asphalt cement and lighter petroleum products and (2) asphalt emulsions. The former are divided into three classes: slow-curing liquid asphaltic materials (called SC) composed of asphalt cement and slowly volatile and nonvolatile oils; medium-curing (MC) composed of asphalt cement and a light petroleum distillate, such as kerosene; and rapid-curing (RC) composed of asphalt cement and a low-boiling-point petroleum distillate, such as gasoline or naphtha. The latter two are called cutback asphalts and cure much-more rapidly than the SC, since the light, volatile products evaporate more rapidly than the slowly volatile products in the SC. Asphalt emulsions are manufactured in three classes: RS, MS, and SS. For paving mixtures the latter two are utilized. Upon "setting" or "breaking", the water in the emulsion separates, leaving the asphalt cement in contact with the aggregate. (Note: AASHO specifications and grade designations are used in this bulletin.)

Hard, powdered asphalts with liquid residual petroleum oil are utilized primarily for cold-laid plant mix of graded-aggregate type. The aggregate is first mixed with the liquid residual petroleum oil and the powdered asphalt is placed into the mixer subsequently. Such mixtures may be stored for long periods without setting, but when placed on the road and compressed by rollers, the liquid residual petroleum oil fluxes the hard, powdered asphalt to produce asphalt cement that binds the aggregate particles together.

### Tars

Tars include tar binders and cutback tars. There are 12 viscosity grades of tar binders standardized by the road tar industry and 2 grades of cutback tars known as RTCB-5 and 6. (See ASTM Designation D490-47). Road tars are used for road mix and for hot-and cold-laid plant mix.

## TYPES OF AGGREGATES

Coarse aggregates, fine aggregates and mineral fillers are utilized for bituminous paving mixtures.

1. Coarse aggregates include crushed stone, crushed and uncrushed gravel, crushed slag, shells, and special aggregates.
2. Fine aggregates include sand, crushed stone screenings, crushed slag, crushed gravel, and special aggregates, such as chats and volcanic cinders. Typical specifications define fine aggregate as material passing the No. 4 sieve (passing the No. 8, No. 10, or even ⅜-inch sieve size is sometimes substituted for No. 4 sieve). Most specifications permit only a relatively small amount of material to pass the No. 200 sieve.
3. Mineral fillers include limestone dust, portland cement, agricultural lime, traprock dust, silica dust, hydrated lime, flyash, fine-graded sand, and special aggregate dusts.

## DENSE-GRADED BITUMINOUS MIXTURES

Dense-graded mixtures are those mixtures composed of aggregates of such gradation as to give a relatively low percentage of voids in mineral aggregates in the compressed paving mixture. The size of the aggregate particles as well as gradation is a factor. Generally the fine-aggregate-type pavements have higher voids than do the coarser types, although the void spaces are smaller in the fine-aggregate types.

### Sheet Asphalt

Sheet-asphalt paving mixtures, which are utilized almost entirely in surfacing city streets, are composed of carefully designed and controlled combinations of asphalt cement, mineral filler, and fine aggregate. Usually the fine aggregate is a fine-graded natural sand known as "sheet asphalt sand" but sands prepared from stone, air-cooled iron-blast-furnace slag, or gravel may be used. Typical composition ranges are: asphalt cement, 8 to 12 percent; mineral filler, 10 to 20 percent; and fine aggregate, 68 to 82 percent.

Binder courses for sheet asphalt pavements are of the bituminous concrete type.

### Sand Asphalt

Sand-asphalt paving mixtures, which are used for surfacing airport runways and light-to-medium-traffic roads, are composed of sand or fine screenings with or without mineral filler and asphalt cement or cutback asphalt.

### Bituminous Concrete

1. Coarse-graded-aggregate bituminous concrete is composed of bituminous cement (either asphalt or tar), mineral filler, fine aggregate, and coarse aggregate. It is used for base, binder, and surface courses. Typical composition ranges are: bituminous cement, 4 to 9 percent; mineral filler, 3 to 8 percent;

fine aggregate, 15 to 40 percent; and coarse aggregate, 45 to 80 percent. This paving mixture contains a comparatively large amount of coarse aggregate. The maximum size of the coarse aggregate ranges from 2 inches down to ½ inch; the larger sizes of aggregates are used in base courses and in binder courses and the smaller sizes of aggregates in surface courses.

2. Fine-graded-aggregate bituminous concrete (also called stone-filled sheet asphalt when bitumen is asphalt cement) is composed of bituminous cement (usually asphalt cement), mineral filler, fine aggregate, and coarse aggregate. It is used for surface course. Typical composition ranges are: bituminous cement, 6 to 10 percent; mineral filler, 7 to 12 percent; fine aggregate, 30 to 65 percent; and coarse aggregate, 20 to 35 percent. This type of bituminous concrete contains a comparatively small amount of coarse aggregate and the maximum size of coarse aggregate is usually ½ inch.

When coarse aggregate (usually crushed stone or crushed slag) is added to a sheet-asphalt mixture to increase density and stability, the resulting mixture is known as stone-filled sheet asphalt. It is used for wearing course for parking lots and service stations where high density and stability are required as well as for street and highway pavements.

## Plant Mix

Plant mix, using local dense-graded aggregates can be either hot laid or cold laid in type. For hot-laid plant mix, the bituminous material may be asphalt cement (penetration from 85 to 300), liquid asphalt (MC-4, MC-5, RC-4, RC-5, SC-4, SC-5, or SC-6), or tar cement (RT-10, RT-11, or RT-12). For cold-laid plant-mix, the bituminous material may be liquid asphalt or tar. The liquid asphalt may be MC-3, MC-4, MC-5, RC-2, RC-3, SC-3, SC-4, SC-5, or emulsified asphalt MS-2 or SS-1. Tars RT-6 to RT-10 and cutback tars RTCB-5 and RTCB-6 are used for cold-laid plant mixes. The local dense-graded aggregates include both fine aggregate and coarse aggregate. The maximum size of coarse aggregate is 1 inch ordinarily for surface coarse. Mineral filler, such as limestone dust, is frequently added, but some fine material in the fine aggregate passing the 200-mesh sieve may be used; such fine material should not be highly plastic. With respect to emulsified asphalt mixtures, MS-2 is used for plant mixtures of open-graded aggregate with practically no material passing the No. 200 sieve. SS-1 is used for fine aggregate mixtures having a substantial quantity of aggregate passing the ⅛-inch sieve and a portion passing the No. 200 sieve.

## Road Mix

Road mix, using local dense-graded aggregates, is similar to the cold-laid plant mix except that lower-viscosity bituminous materials may be used. Typical liquid asphaltic binders are MC-2, MC-3, MC-4, RC-2, RC-3, SC-2, SC-3, SC-4, SC-5, and emulsified asphalt of SS-1 and MS-2 grades. MC liquid asphalts are preferred by many engineers to RC grades for this type of road mix. Extensive use is made of SC grades. Typical grades of tar are RT-5, RT-6, RT-7 and RT-8. The grading requirements for aggregates are usually less restrictive for road mix than for plant mix. For surface courses, the maximum size of aggregate is 1 inch, but the ¾-inch-maximum size is the most used.

## Sand-Asphalt Road Mix

Another road mix is sand-asphalt mixed-in-place course on natural sand subgrade. It is cold laid. Typical liquid asphaltic materials used are MC-2, MC-3, RC-1, RC-2, RC-3, and emulsified asphalt SS-1 and MS-2. Asphalt cement (penetration 60-70) and SC-6 have been successfully used for cold-laid road mix under proper field temperatures and where travel plant equipment was employed. The sand aggregate is specified to have not more than 25 percent passing the 200-mesh sieve.

## OPEN-GRADED BITUMINOUS MIXTURES

Open-graded mixtures are composed of aggregates containing small amounts of fine material. They are sometimes referred to as "rock-dominant" mixtures. Open-graded mixtures have a comparatively high percentage of voids in mineral aggregates in the compacted bituminous pavement.

Bituminous Concrete, Open-Graded Aggregate Type

This type is either hot laid or cold laid and is not as commonly used as bituminous concrete of the coarse-graded aggregate type (C-1-c-1) above. The open-graded aggregate contains but little fine aggregate. A typical gradation is 0 to 5 percent passing No. 4 sieve. Maximum size of aggregate is 1½ inch for base or binder courses but 1-inch-maximum size is common. Maximum size of ¾ or ½ inch is typical for wearing courses. The bituminous material is either asphalt or tar. Asphalt cement is used for hot-laid and RC-2, RC-3, RC-4, RC-5, MC-3, MC-4, MC-5, and emulsified asphalts MS and SS are liquid asphalts used for cold-laid mixtures. Tars used are RT-10, RT-11, and RT-12 for hot-laid mixtures and RT-8, RT-9 and RT-10 for cold-laid mixtures.

This type of open-graded pavement has a relatively high percentage of voids. It is usually sealed by applying crushed fine aggregate and then applying a bituminous binder. However, sealing is not always required. For example, the California Division of Highways does not seal open-graded bituminous mixtures that are utilized for resurfacing existing pavements or as a thin wearing course over a newly placed dense-graded bituminous mixture; vehicle tires are in contact with the open-textured surface.

Road Mix, Using Open-Graded Aggregate

This type of road mix is used where crushed stone such as macadam aggregate, crushed gravel, or crushed slag is available. For surface course, the maximum size of aggregate is passing the 1½-inch sieve, but 1-inch-maximum aggregate or even ¾-inch maximum is extensively used. It is graded down to 0-5 percent passing No. 4 sieve, and hence contains but little fine material. The bituminous material may be asphalt or tar. Liquid asphalts include RC-2, RC-3, MC-2, MC-3, MC-4, MC-5, and emulsified asphalts of MS and SS grades. Application temperatures range from 100 F. to 275 F. RC liquid asphalts are preferred by many engineers to MC grades for this type of road mix. Emulsified asphalt MS-1 is used for "retread" mixtures containing coarse aggregate. Tars generally used are RT-6, RT-7, RT-8, RT-9 and RT-10 for hot application at temperatures from 150 F. to 250 F. and cutback tars RTCB-5 and RTCB-6 are sometimes employed for cold application at temperatures from 60 F. to 120 F. This type is usually sealed using a crushed fine aggregate and an application of bituminous binder.

## HOT VERSUS COLD PLANT MIXTURES

There are many forms of cold plant mixtures, involving widely differing types of bituminous materials and aggregates. Five general groups of cold plant mixtures employ (1) tars RT-8 to RT-10, (2) cutbacks, (3) emulsions, (4) fluxed products, (5) liquefiers. In spite of the name, many of these mixtures are mixed hot (or at least warm), and some are even laid hot (or warm).

Advantages of Hot Plant Mix

Generally speaking, hot plant mix has the following advantages as compared to cold plant mix: (1) It is a well-established type of construction which has demonstrated good service qualities. (2) It can be constructed to develop a greater density than some types of cold plant mix, since the latter may have to be more open in texture to facilitate curing. (3) Aggregates of a somewhat lower resistance to stripping can be utilized in dense-graded hot plant mix. (4) Hot plant mixes can be adapted to conform to a wide range of aggregate gradings and characteristics. (5) They may be laid when air temperatures are relatively low as compared to certain cold mixes that require fairly high air temperatures for efficient aeration.

Advantages of Cold Plant Mix

In general, cold plant mix has these advantages in comparison with hot plant mix: (1) Results have been obtained in many instances using cold plant-mix construction that are comparable to hot plant mix in quality. (2) Possible damage to the mixtures by overheating is more likely to be avoided. (3) It can be prepared in advance of construction, such as during seasons of bad weather, and stockpiled until needed. This makes possible employment off season and reduces the load on the plant during the height of the construction season. (4) Calls for small tonnages of cold plant mix can be supplied at once from stockpiles without the necessity of starting up the plant, as for hot mix. (5) Cold plant mix is well adapted to maintenance and repair work.

Types of Cold Plant Mix

Classification of cold plant mixes may be made on the basis of types of bituminous and petroleum products employed.

Tars. Tar binders include grades RT-8, RT-9, and RT-10.

Cutback Bituminous Materials. The materials include RC and MC liquid asphalts and cutback tars, RTCB-5 and 6. For open-graded aggregates the following grades are typical: RC-3, RC-4, MC-4, MC-5, and tars RTCB-5 and RTCB-6. For dense-graded aggregates, the following grades are typical: RC-3, and MC-3. (Also SC-3 and SC-4)

Emulsified Asphalts. These include MS and SS. MS-2 is used for cold plant mixes of open-graded aggregate with practically no material passing the No. 200 sieve. SS-1 is used for fine aggregate cold plant mixes having a substantial quantity of aggregate passing the ⅛-inch sieve and a portion passing No. 200 sieve.

Fluxed Products. Typical of fluxed products is hard, powdered asphalt with liquid residual petroleum oil. These products are used in sheet asphalt and in bituminous concrete of dense-graded type including stone-filled sheet asphalt.

Liquefier types. Liquefiers such as kerosene, naphtha, and other petroleum distillates are utilized to coat the surfaces of dry crushed stone or crushed slag aggregate in the production of cold-laid asphaltic concrete. The function of the liquefier is to make the mix workable and to facilitate the coating of the aggregate. A minimum amount of liquefier should be used. For hot plant mixing, asphalt cement of penetration grades 85 to 100, 100 to 120, or 120 to 150 points may be used. For cold plant mix, liquid asphalts of lower viscosity are required. Lime is customarily added to increase the adhesion of the asphalt to the stone particles; however, it is sometimes not used with hydrophobic aggregates, such as blast-furnace slag and certain limestones.

## *Voids*

### REASONS FOR IMPORTANCE OF DENSITY

Mixtures of dense-graded type have improved physical properties when the voidage is restricted below a given maximum. Such physical properties include stability and resistance to deterioration by air and by water.

Adequate and uniform compaction of the mixtures to produce pavements of suitable density is highly important to develop stability and tensile strength.

### TESTS TO DETERMINE PERCENTAGE OF VOIDS IN COMPRESSED BITUMINOUS PAVING MIXTURES

Accuracy in determining the percentage of voids in compressed bituminous mixtures is necessary in order to determine the proper bitumen content when designing by the voids method. A variation of 1 percent in the voids in a compressed mixture corresponds to an adjustment in the bitumen content of approximately 0.5 percent.

The accurate determination of the percentage of voids in compressed bituminous paving mixtures is difficult because different aggregates absorb bitumen to varying degrees. The problem is further complicated by the fact that most aggregates absorb water in different amounts than bitumen. Errors introduced by the conventional methods of determining specific gravities of the aggregates and bituminous material also affect the accuracy of the percentage of voids in compressed bituminous mixtures. The value of the percentage of voids in a compressed bituminous mixture is obtained by comparing the maximum theoretical density of the bituminous mixture and the actual density of the pavement or compacted specimen.

Actual Specific Gravity of Compressed Specimen

The actual specific gravity of a compressed bituminous mixture may be determined by ASTM Designation 1188-53 Method of Test for Specific Gravity of Compressed Bituminous Mixtures. This method involves coating the test specimen on all surfaces with a coat of paraffin. Weighings in air and in water are prescribed. The method determines the bulk specific gravity of the compressed bituminous mixture. Many laboratories in using the method of weighing the compressed specimen in air and in water omit the coating of the specimens with paraffin, but this procedure has not been standardized by the ASTM.

## Conventional Method for Maximum Theoretical Specific Gravity of Mixtures

The conventional method of determining the maximum theoretical specific gravity (density) of bituminous mixtures is by calculation using the percentages by weight and the specific gravities of the aggregates and bitumen. Three different specific gravity values of aggregates (ASTM Designation E12-27) are employed by different laboratories: (1) bulk specific gravity of aggregate; (2) bulk specific gravity of aggregate, saturated surface-dry basis; (3) apparent specific gravity of aggregate.

Each method gives a different value of the maximum theoretical specific gravity (density) and a corresponding different value of the percentage of voids in the compressed bituminous mixture. The use of bulk specific gravity is accurate theoretically when the aggregate absorbs no bitumen. Owing to absorption of bitumen by certain types of aggregates, however, the calculated percentage of voids is less than the actual percentage of voids in the compressed bituminous mixture containing such absorptive aggregates. In extreme cases of highly absorptive aggregates, the calculated value of percentage of voids may be negative where bulk specific gravity is employed.

The use of apparent specific gravity is accurate theoretically when absorbed bitumen equals water absorption. For aggregates that absorb less bitumen than water, where apparent specific gravity of aggregates is used, the calculated percentage of voids in compressed bituminous mixtures is greater than the actual percentage of voids.

The bulk specific gravity of aggregate, saturated surface-dry basis, is inaccurate for aggregates whose bitumen absorption differs from water absorption. The bulk saturated specific gravity of aggregates is intermediate in value between bulk specific gravity and apparent specific gravity.

## Tests Developed for Determining Percentage of Voids in Compressed Mixtures

The following special tests have been developed for determining the percentage of voids in compressed bituminous mixtures.

1. "Effective" specific gravity of aggregates involving calculations based on compressed mixtures containing bitumen in excess of the amount required to fill the aggregate voids (reference: Martin, J.R., and Layman, A.H. Jr.: "Hot-mix Asphalt Design Studies," Oklahoma Engineering Experiment Station Publication No. 75, March, 1950, pp. 5-9).

2. "Bulk-impregnated" specific gravity involving immersion of aggregates in liquid bituminous material. Bulk-impregnated specific gravity is a function of, and is concomitantly proportional to, the ratio of bitumen to water absorption of an aggregate (reference: Appendix D; also Ricketts, W.C., Sprague, J.C., Tabb, D.D., and McRae, J.L.: "An Evaluation of the Specific Gravity of Aggregates for Use in Bituminous Mixtures," Proc. ASTM, June 1954).

3. Measurement of maximum theoretical specific gravity of bituminous mixtures by solvent immersion (reference: Appendix E).

4. Measurement of maximum theoretical specific gravity of bituminous mixtures by vacuum-saturation technique using uncompacted samples (reference: Appendix F).

5. Measurement of maximum theoretical specific gravity of bituminous mixtures by pressure technique using uncompacted samples (reference: Appendix G).

Rice (22) has pointed out that these special methods give significantly different results for the same absorptive aggregate; yet the bitumen absorption of a given aggregate with a given amount and type of bitumen under given mixing conditions should be constant. More research work on this subject is needed.

## FORMULAS TO DETERMINE PERCENTAGE OF VOIDS IN MINERAL AGGREGATE AND COMPRESSED BITUMINOUS PAVING MIXTURES

1. The formula for calculation of percentage of voids in compressed bituminous paving mixtures is:

$$V = \text{Percent voids} = \frac{(D-d) \times 100}{D}$$

where D = maximum theoretical specific gravity (density) of the mixture, and d = bulk specific gravity of specimen of compressed bituminous mixture.

2. The formula for computation of maximum theoretical specific gravity (density) is:

$$D = \frac{100}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} --- \frac{W_n}{G_n}}$$

where $W_1$ = percent by weight of bitumen
$G_1$ = bulk specific gravity of the bitumen, (See ASTM Designation: D70-27)
$W_2$, $W_3$ ---$W_n$ = percents by weight of the different aggregate fractions,[1]
and $G_2$, $G_3$ ---$G_n$ = apparent[1] specific gravities of the respective aggregate fractions. (See ASTM Designation: C127-42, C128-42, D854-52 and C188-44.)

3. The formula for determining d, the bulk specific gravity of the compacted specimen by weighing in air and water is:

$$d = \frac{A}{B-C}$$

where A = weight of the dry specimen in air, in grams,
B = weight of saturated surface-dry specimen in air, in grams,
and C = weight of saturated specimen in water, in grams.

The formula for determining d, the bulk specific gravity by the method of coating the specimen with paraffin and weighing in air and water as standardized by ASTM Designation: D1188-53 is as follows:

$$d = \frac{A}{D-E-\frac{(D-A)}{F}}$$

where A = weight of the dry specimen in air, in grams,
D = weight of the specimen plus paraffin coating in air, in grams,
E = weight of the specimen plus paraffin coating in water, in grams,
and F = bulk specific gravity of the paraffin.

4. The formula for calculation of percentage of voids in mineral aggregate is:

$$V.M.A. = \frac{(D_1 - g)}{D_1} \times 100$$

where $D_1$ = maximum theoretical specific gravity (density) of total mineral aggregate, if free from voids,
and g = specific gravity of the compacted aggregate.

The formula for $D_1$ is as follows:

$$D_1 = \frac{W_2 + W_3 + --W_n}{\frac{W_2}{G_2} + \frac{W_3}{G_3} + --\frac{W_n}{G_n}}$$

The formula for g is as follows:

$$g = d\left(1 - \frac{W_1}{100}\right)$$

5. The formula for calculation of percentage of total voids filled with bitumen is:

$$\text{Bitumen--Void Ratio, in percent} = \frac{100}{\frac{G_1 V}{W_1 d} + 1}$$

## RANGE IN PERCENTAGE OF VOIDS DESIRED

1. Voids in mineral aggregate. In dense-graded mixtures, the grading of mineral aggregates should be designed to give a comparatively low value for V.M.A., but the V.M.A. value should be large enough to make it possible to incorporate adequate films of bitumen around the aggregate particles. Gradation curves of aggregate should aim for comparatively high density, but a theoretical grading curve giving an extremely high density

[1] Further research is needed to determine what specific gravity of aggregate (bulk, apparent, or some intermediate value) to use to determine proper values of D and V; such research is particularly needed for porous aggregate, such as slag, and for aggregates of high absorption.

(low voidage) should be avoided. For bituminous concrete of dense-graded type, this can be achieved by reducing the amount of fines called for in a theoretical maximum density grading curve.

Without exception there are more voids in mineral aggregate in bituminous mixtures prepared with fine aggregate than there are for mixtures of fine and coarse aggregate (assuming comparative tests at optimum asphalt and equal compactive effort to consolidate the mixture). Furthermore, the amount of bitumen required as optimum is very nearly in direct proportion to the amount of voids in mineral aggregate in the compressed paving mixture.

2. Voids in compressed bituminous mixture. In designing bituminous paving mixtures of the dense-graded type, it is desirable to have the voids in compressed specimens above a minimum percentage and below a maximum percentage. The minimum percentage of voids should be such as to allow for increased densification by traffic loads and for expansion of the aggregate caused by temperature increase to avoid exuding of bitumen on the surface and consequent reduction in skid resistance and stability. The maximum percentage of voids should be set at such a point as to insure sufficient density together with other desirable properties, such as stability and tensile strength. The range in air-void values varies within narrow limits, usually not exceeding 3 or 4 percentage points for mixtures with acceptable aggregate gradation. Typical values[2] for minimum and maximum voids in compressed bituminous mixtures are:

| | Design Limits of Voids Total Mix | |
|---|---|---|
| | Sand Asphalt | Bituminous Concrete |
| | Percent | Percent |
| U.S. Corps of Engineers for runways for 100 psi. tire pressure[3] | 5-7 | 3-5 |
| Select optimum at | 6 | 4 |
| U.S. Corps of Engineers for runways for 200 psi. tire pressure[4] | 6-8 | 3-5 |
| Select optimum at | 7 | 4 |

[2]These percentages of voids in compressed mixtures conform to the use of apparent specific gravity values for component aggregates.

3. Percentage of total voids filled with bitumen. The Corps of Engineers determined for runways that for fine aggregate mixtures about 70 percent, and for coarse aggregate mixtures about 80 percent of the voids in mineral aggregate can be filled with bitumen for optimum condition in dense-graded mixtures. Typical values for percent of voids filled with asphalt are:

| | Design Limits of Voids Filled with Bitumen | |
|---|---|---|
| | Sand Asphalt | Bituminous Concrete |
| | Percent | Percent |
| U.S. Corps of Engineers for runways for 100 psi. tire pressure[3] | 65-75 | 75-85 |
| Select optimum at | 70 | 80 |
| U.S. Corps of Engineers for runways for 200 psi. tire pressure[4] | 65-72 | 75-82 |
| Select optimum at | 68 | 78 |

The report of W.J. Emmons (23) on stability of sheet asphalt mixtures tested under highway truck traffic on the circular roadway of the Bureau of Public Roads showed that those mixtures which had a high percentage of aggregate voids filled with bitumen were unstable. Among his conclusions Emmons states:

"No mixture having the voids completely filled with bitumen remained stable under the traffic imposed in these tests. In general, the maximum percentage of bitumen carried by stable mixtures amounted to between 85 percent and 90 percent of the aggregate voids as determined for Hubbard-Field stability specimens."

[3]Marshall test specimens compacted with 50 blows top and bottom of the specimen.

[4]Marshall test specimens compacted with 75 blows top and bottom of the specimen.

# *Methods of Mixture Design*

There are two methods of designing bituminous paving mixtures that are in common use: (1) the void method and (2) the surface-area method. These methods are short-cuts for reaching a suitable combination of aggregates and bituminous material and are only significant insofar as they may indicate features of the essential properties such as stability, durability, flexibility, resistance to skidding, and workability. Neither of these two methods of proportioning are properly classed as basic or fundamental factors.

## VOID METHOD

In general, the void method of proportioning is applicable to all dense-graded bituminous paving mixtures. It is not applicable to open-graded mixtures of high voidage. The following criteria are used:

1. Selection of aggregates of suitable gradation to give a desirable value of percentage of voids in mineral aggregate. A wide range of gradation characteristics are potentially suitable for use in bituminous mixtures. In some instances it may be found necessary to make adjustments to local material as found in nature to achieve a mixture possessing suitable voids in mineral aggregate. For example, the addition of coarse aggregate, or of fine sand, to the mixture may reduce aggregate voids.
2. Selection of a bitumen content to give a desirable value of voids in compressed bituminous mixture, consistent with stability requirements.
3. Checking the value of percentage of total voids filled with bitumen.

## SURFACE-AREA METHOD

The surface-area method of proportioning is applicable to all types of bituminous paving mixtures ranging from very-dense combinations with fine aggregates to very-coarse gradations and may be adjusted to accommodate all grades of bitumen.

Bitumen exists largely as a coating on the aggregate particles. The total amount of superficial surface on the aggregate particles furnishes an index to the amount of bitumen required. This amount to coat all the aggregate surfaces is calculated from the measurement or estimation of the available surface to be coated and the determination of the appropriate thickness of film. The average film thickness, designated as the bitumen index, varies inversely with the amount of aggregate surface. In other words, the finer the aggregate particles and the correspondingly greater available surface, the smaller must be the bitumen index, or film thickness equivalent.

The harder grades of paving asphalt do not perform satisfactorily when the film thickness is reduced to a small value, but the same limitations apply in lesser degree to the more-liquid grades of bituminous materials. Therefore, limitations are imposed by the nature of the bituminous material to the effect that when mixtures contain a great deal of fines, and consequently a high surface area, a point is ultimately reached where the use of hard bitumen becomes impracticable and undesirable. At the other extreme, with very-coarse, open-graded mixtures, low-viscosity liquid asphalts and tars cannot be maintained in the heavy films that are appropriate for such coarse-aggregate gradations representing low surface areas.

The most-rapid and most-widely applicable method of estimating the amount of bitumen that is appropriate for a given combination is by means of the centrifuge-kerosene-equivalent (24) determination, which is a rapid method for evaluating the total available surface of the particles including particle roughness and porosity. This method is applicable to any bituminous binder, but requires minor adjustments to allow for the consistency of the particular bituminous material. The validity of results obtained is dependent to a great extent upon the establishment of suitable constants. The sole purpose of the C.K.E. determination is to arrive at a close approximation of the maximum amount of bitumen which can be tolerated without producing instability. The upper limit to the amount of bitumen used depends upon only two considerations: (1) the question of stability and (2) the need to maintain a nonskid road surface. All other considerations are benefited by increasing the amount of bitumen. Therefore, if the maximum amount of bitumen can be ascertained that can be used without adversely affecting the stability, the best compromise for all the factors involved will be obtained.

Summarizing, the surface-area method is a useful tool and through its use it is possible to estimate a bitumen-aggregate ratio that will give good results.

# *Effects of Variations in Characteristics and Gradations of Aggregates on Physical Properties of Mixtures*

## EFFECTS OF SURFACE CHARACTERISTICS OF AGGREGATES

### Smooth Surfaces of Aggregates

In the case of coarse aggregates having very smooth surfaces, there is a tendency for the bituminous material to run off and segregate into undesirable pockets, causing fatty spots in the finished pavement. This condition may be encountered in cold-mixed, cold-laid asphaltic concrete of the liquefier type where a relatively small amount of fine aggregate and mineral filler are used. This defect can be checked, to a certain extent at least, by increasing the proportion of fine aggregate to produce more bituminous mortar which will adhere to the smooth aggregate surface better than a film of bituminous material. In base and binder courses of bituminous concrete, more fine material is necessary for smooth coarse aggregate than is necessary or perhaps desirable for coarse aggregates having rough surfaces (25).

### Absorption

Mineral aggregates absorb bitumen to varying degrees. Typical values range from practically zero (0.1 percent, for example) to 5 percent or more absorbed bitumen by weight of aggregate. Differences in bitumen absorption are due primarily to characteristics of the aggregates, although type of bitumen (whether asphalt or tar, for example) accounts for some variations.

Mineral aggregates also absorb water in varying amounts. Typical values range from practically zero (0.2 percent, for example) to 12 percent or more absorbed water by weight of aggregate.

The ratio of bitumen absorption to water absorption varies over a wide range from practically zero to over 100 percent. Some unusual relations exist in the amounts of bitumen absorption and water absorption. For example, some aggregates with low bitumen absorption have high water absorption values, whereas others with low bitumen absorption have low water absorption values. On the other hand, some aggregates with high or moderate bitumen absorption values have about the same water absorption. Examples are as follows (26):

| Aggregate | Bitumen Absorption, (Asphalt) | Water Absorption | Ratio |
|---|---|---|---|
| | Percent | Percent | Percent |
| Basalt, spongy | 0.1 | 11 5 | 1 |
| Limestone, dense | 0.1 | 0.2 | 50 |
| Coral, vesicular | 4.9 | 5.2 | 94 |
| Slag, Ashland | 1.7 | 1.8 | 96 |

Variations in bitumen absorption affect the calculation of percentage of voids in compressed bituminous paving mixtures.

### Stripping

Resistance to stripping of bituminous paving mixtures is related to surface characteristics of aggregates. Hydrophilic aggregates have surfaces that possess a greater affinity for water than for bitumen. Hydrophobic aggregates, on the other hand, have a greater affinity for bitumen than for water. Hydrophobic type aggregates tend to have resistance to stripping of bituminous films in the presence of water.

Mineral fillers as well as coarse aggregates and fine aggregates have variable resistance to stripping. Some mineral fillers such as certain (but not all) silica dusts have high stripping tendencies.

## EFFECTS OF SHAPE AND HARDNESS OF AGGREGATE PARTICLES

Angular particles are more effective than rounded particles in the development of stability. If soft, easily crushed aggregate is used, the particles may crush under traffic to an extent that stability may be affected. Many state highway departments have established wear test requirements for coarse aggregates.

## EFFECTS OF GRADATIONS OF AGGREGATES

Stability of the mixture is very closely related to the density of the compacted mineral aggregate, which in turn is related to the gradation or particle size distribution of the aggregate.

Roland Vokac (27) has shown that aggregate gradations which are fairly symmetrical and which range from rather coarse to fairly fine have advantageous properties with respect to easy proportioning and economical dense-graded mixtures. Such gradations are frequently found in straight-run, unwashed quarry products such as screenings and quarry waste. Natural sands when topped at the No. 8 or No. 4 sieve also will result very often in such desirable gradations. Sands which do not meet these requirements may be modified in many cases by the addition of coarse sand to extend their grading.

Most of the state highway departments have specifications for both surface and binder courses of coarse-graded aggregate bituminous concrete (dense-graded type) that require well-graded aggregate materials which can be compacted to high density with a minimum of voids. W. E. Chastain (28) has published representative gradation envelopes in graphical form for both surface course and binder course materials. The controlling top size for the surface course groups are: ⅜-inch to ½-inch maximum size; ½-inch to ¾-inch maximum size; and ¾-inch to 1-inch maximum size. For the binder course aggregate material, the controlling top sizes are: ¾-inch maximum size; ¾-inch to 1-inch maximum size; 1-inch to 1¼-inch maximum size; and 1-inch to 1½-inch maximum size. For surface course materials, the ½-inch to ¾-inch maximum size is most frequently used by state highway departments, and the ¾-inch to 1-inch maximum size is most frequently used for binder course materials. The maximum size of aggregate and the thickness of the lift of the mixture placed and compacted are interdependent. The ¾-inch to 1-inch top size binder course material is usually placed in lifts of 1½-inch compacted thickness. The 1-inch to 1¼-inch top size binder course material is usually placed in lifts of 2-inch compacted thickness. Surface course mixtures of ½-inch to ¾-inch top size are most usually placed in lifts of 1½-inch compacted thickness. Chastain (28) states that a minimum thickness of 1 inch was reported by state highway departments for both surface and binder pavement courses and that a maximum of 3 inches was reported for surface and binder pavement courses where heavy traffic prevails. Base and subbase courses vary greatly in thickness depending on various factors and conditions.

One of the most common means of improving the properties of a bituminous dense-graded mixture is the judicious use of mineral filler. Aside from the fact that a well-graded filler improves the stability of a mixture, it definitely reduces the amount of aggregate voids, and to a lesser extent the voids in compressed bituminous mixture. Since filler and bitumen both are void-filling materials, they supplement each other. Within the range of aggregate gradations and aggregate types associated with dense-graded bituminous mixtures, the addition of a nominal amount of filler will reduce, not increase, the bitumen demand. Also in this concept, the surface area of the mineral filler need not be considered since the filler is encompassed completely by bitumen.

Specifications for mineral fillers usually require a minimum percentage passing the No. 200 sieve to insure that sufficient fine material will be provided. (Example: AASHO Designation: M17-42 requires not less than 65 percent total passing No. 200 sieve.

Specifications may also set the gradation limits to insure well graded mineral fillers; an example is the specifications proposed by the Louisiana Department of Highways:

| U. S. Standard Sieve | Grain Size mm. | Proposed Limits percent finer |
|---|---|---|
| No. 30 | 0.590 | 100 |
| No. 80 | 0.177 | 95-100 |
| No. 200 | 0.074 | 65-100 |
| | 0.050 | 60-100 |
| | 0.020 | 30-60 |
| | 0.005 | 10-25 |
| | 0.001 | 2-15 |

The purpose of the above specifications is to avoid the use of mineral fillers that are not well graded. For example, a fine sand that has 100 percent passing the No. 200 sieve but only 8 percent passing the No. 325 sieve (0.044 mm. opening) has been found to be a mineral filler of poor quality. In general, poorly graded fillers decrease the stability, the density of the compacted bituminous mixture, and the percentage of voids filled with bitumen of dense-graded mixtures as compared to well graded fillers containing some material finer than 0.01 mm. in size.

Difficulties have been experienced, however, with mineral fillers containing a high percentage of very fine particles. This flour-like material may divorce itself from the aggregates, forming a mastic with the bitumen. Such mastic, when present in excessive amounts, may cause flushing of the surface of the pavement.

Skip gradings have been used with success. One type of skip grading consists of coarse aggregate of ¾-inch to ½-inch size, sand of 10-mesh to 200-mesh size and mineral filler passing 200-mesh size. The mixture is prepared by incorporating a sheet asphalt mixture into the coarse aggregate. This type of mixture utilizes the mechanical interlocking of the coarse aggregate to give adequate stability. The bitumen content of the sheet asphalt mixture can be made high in order to provide protection against stripping without impairing stability.

# *Effects of Variations in Bitumen Content and Characteristics of Bitumen on Physical Properties of Mixtures*

## EFFECTS OF VARIATIONS IN BITUMEN CONTENT

The determination of the proper bitumen content for a specific mixture is of utmost importance. Assuming proper quality and grade of bituminous material, most reasonably well-graded aggregates will provide a satisfactory pavement for even a heavy amount of traffic at some specific bitumen content.

Extreme variations in the composition of bituminous pavements should be avoided. This is brought out by Table 2 which shows the effects of composition on characteristics of sheet asphalt paving mixtures as stated by Roland Vokac. The desirability of using normal amounts of asphalt cement and a medium amount of mineral filler is indicated, the exact range in percentages being dependent on the characteristics of the aggregates.

TABLE 2

EFFECTS OF COMPOSITION ON CHARACTERISTICS OF SHEET ASPHALT PAVING MIXTURES (Roland Vokac)

| Amount of Mineral Filler | Low (Amount of Asphalt Cement) | Normal | High |
|---|---|---|---|
| High | Hard and brittle, very strong, low resistance to cracking | Strong. | Gummy and tough, difficult to rake in placing, weak, will shove under traffic |
| Medium | Dry, strong, low resistance to cracking | Stable, has other good properties such as flexibility and resistance to cracking. | Sticky, weak. |
| Low | Weak and friable, may check under roller, may ravel. | Weak. | Soft, weak. |

Amount of Asphalt Cement

Weak means unstable.
Strong means high stability test value.
Third ingredient is sand.

The requirements for quantity of bituminous binder differ for different types of mixtures, but the use of a quantity equal to or greater than the gross volume of spaces between the aggregate particles after compaction is to be avoided in any type of bituminous mixture for roadways. W.E. Chastain (29) states that for coarse-graded aggregate bituminous concrete (dense-graded type) the agreement between state highway departments for asphalt contents was, in general, close. Specified asphaltic content limits for surface course material most generally ranged between 4 and 8 percent, and for binder course material, most generally between 3½ and 7 percent. Even closer agreement was found when considering the asphalt contents reported in job-mix formulas. Asphaltic-content limits reported in job-mix formulas for surface courses by 37 agencies varied between 5.0 and 7.25 percent. For binder course mixtures, the range of asphalt content was between 4.0 and 6.0 percent, based on job-mix formulas.

### EFFECTS OF CHARACTERISTICS OF BITUMEN

In certain types of mixtures, stability is affected by the consistency of the bituminous binder, with the binders of higher consistency producing mixtures of greater stability. In certain types of mixtures, resistance to cracking is affected by the consistency of the bituminous binder, with the less viscous binders producing mixtures of greater resistance to cracking. A proper balance concerning consistency of bitumen should, therefore, be struck in order to obtain a pavement that will be stable under loads and yet be resistant to cracking.

Mixtures composed of bitumens that are highly susceptible to temperature change have less resistance to cracking than those composed of bitumens of normal temperature susceptibility. Mixtures containing bitumens that exhibit rapid rates of age-hardening also have low resistance to cracking.

### USE OF ATOMIZED BINDER

The introduction of atomized binder into a bituminous paving mixture changes the concepts of the design of bituminous paving mixtures as described in this bulletin. Atomizing the bitumen produces thin films upon the aggregates (30).

## *Practice in Designing Bituminous Paving Mixtures*

### DENSE-GRADED TYPES OF MIXTURES

1. Asphalt Institute Method (Hubbard-Field stability test). (Reference: Asphalt Institute Research Series No. 1 - The Rational Design of Asphalt Paving Mixtures.)

2. Method of Vokac. (Method of plotting contours of stability and voids.) (Reference: Vokac, Roland: "A New Method of Design for Bituminous Paving Mixtures", Proc. Assoc. Asphalt Paving Technologists, January, 1936, p. 165.)

3. Method of U.S. Corps of Engineers (Marshall test method). (Reference: "Airfield Pavement Design, Flexible Pavements", Chapter 2, Part XII, July, 1951, Engineering Manual for Military Construction, Corps of Engineers, Department of the Army.)

4. Method based on triaxial-compression test. (Reference: The Asphalt Institute: "Manual on Hot-Mix Asphaltic Concrete Paving".)

5. Method of Hveem. (Stabilometer, cohesiometer, and C.K.E. test methods.) (References: F.N. Hveem: "The Centrifuge Kerosene Equivalent as Used in Establishing the Oil Content for Dense Graded Bituminous Mixtures," California Highways and Public Works, October, 1946. Also: Proc. Assoc. Asphalt Paving Technologists, Vol. 13, January, 1942, pp. 9-40).

6. Formulas for proportioning mixtures. Formulas, where used, mainly apply to road-mix and plant-mix in which liquid bitumens are used. In quite a few instances these formulas have been developed empirically, fitting the average conditions and the materials available in the particular locality or section of the country where they apply. (Reference: Rahn, G.A.: "Design of Bituminous Concrete Mixtures", report prepared for Highway Research Board (unpublished) 1947).

7. Method based on "sand-silt ratio". (Reference: "Manual on Design and Construction of Asphaltic Roads and Streets," The Asphalt Institute, Pacific Coast Division, 2nd. ed., Sept., 1952, pp. 59-79) This design method considers the possibility of improving the aggregate gradation of sand-dominant mixtures by changing the "sand-silt ratio". The sand-silt ratio is the ratio by weight of sand to silt in any aggregate. Sand is defined as aggregate material passing the No. 8 sieve and retained on the No. 200 sieve; silt (and filler) is defined as aggregate material passing the No. 200 sieve.

Too low a ratio such as three of sand to one of silt may indicate harmful quantities of clay. It also indicates that the surface area is excessive and that the amount of asphalt necessary to coat the aggregates may overfill the voids in the compacted mixture. If the ratio is controllable, it can be used to regulate flexibility, stability, impermeability, mix density, and other characteristics.

In this method of design, the percentage of asphalt to be added is calculated by the following formula:

$$P = (R4 + S7 + F12)\ C$$

where P = percentage of asphalt by weight of total aggregate to be added to mix
R = decimal percentage of rock in total aggregates
S = decimal percentage of sand in total aggregates
F = decimal percentage of silt in total aggregates
C = circumstantial factor (normally 1)

The value of C is a variable when: (1) local experience indicates more or less asphalt should be used; (2) additional asphalt may be necessary to compensate for absorptive aggregates; and (3) adjustments may be necessary for light weight or unusually heavy aggregates; the formula is based on an average specific gravity of 2.60 to 2.70.

OPEN-GRADED MIXTURES

1. Method of Hveem (same as above).
2. Formulas of various types (similar to above).

DESIGNING AND CHECKING DENSITY OF JOB MIXTURES

The producer is permitted to develop a mix gradation within certain set limits. This gradation and percentage composition (job-mix formula) must then be used within narrow tolerances. In checking the actual density of a compacted pavement, some state highway departments base their requirements on comparisons with the maximum theoretical specific gravity, whereas other departments base their requirements on comparisons with the highest density determined in the laboratory by standard methods of forming and compacting test specimens.

## *References*


1. J. T. Pauls and J. F. Goode, "A New Vibrating Machine for Determining the Compactability of Aggregates", Proc. Assoc. Asphalt Paving Technologists, Vol. 10, January 1939, pp. 125-145.
2. Pacific Constructor, June 1, 1932, pp. 8 and 9.
3. Proc. Assoc. Asphalt Paving Technologists, Vol. 10, January 1939, pp. 139 to 144.
4. California Highways and Public Works, Vol. 20, No. 7, July 1942, pp. 14 to 17.
5. Discussion of paper by John M. Griffith on "Effects of High-Pressure Tires on Bituminous Pavements," Proc. Asphalt Paving Technologists, Vol. 20, 1951, p. 301.
6. Discussion of paper by W. H. Goetz on "Comparison of Triaxial and Marshall Test Results," Proc. Assoc. Asphalt Paving Technologists, Vol. 20, 1951, pp. 240-241.
7. F. N. Hveem and H. E. Davis, "Some Concepts Concerning Triaxial Compression Testing of Asphaltic Paving Mixtures and Subgrade Materials," A. S. T. M. Special Tech. Publication No. 106 on Triaxial Testing of Soils and Bituminous Mixtures, pp. 25-54.
8. F. N. Hveem and R. M. Carmony, "The Factors Underlying the Rational Design of Pavement," Proc. Highway Research Board, Vol. 28, 1948, pp. 101-136.
9. L. F. Rader: "Investigations of the Physical Properties of Asphaltic Mixtures at Low Temperatures," Proc. A. S. T. M., Vol. 35, Part II, 1935, pp. 559-580.
10. Davidson, B. M.: "A Sonic Method of Determining the Modulus of Elasticity in Bituminous Mixtures," Selected Papers, Bituminous Roads Institute, Univ. of Wisconsin, March, 1951.
11. Lewis, R. H. and Welborn, J. Y.: "The Properties of the Residues of 50-60 and 85-100 Penetration Asphalts from Oven Tests and Exposure," Public Roads, Vol. 22, No. 2, April, 1941, pp. 27-46.
12. Lewis, R. H. and Halstead, W. S.: "Behavior of Asphalts in Thin-Film Oven Test," Public Roads, Vol. 24, No. 8, April-May-June, 1946, pp. 220-226.
13. Pauls, J. T. and Welborn, J. Y.: "Studies of the Hardening Properties of Asphaltic Materials," Public Roads, Vol. 27, No. 9, August, 1953, pp. 187-202.
14. Hveem, F. N.: "Quality Tests for Asphalts - A Progress Report," Proceedings, Association Asphalt Paving Technologists, Vol. 15, Dec., 1943, pp. 111-152, and California Highways and Public Works, Dec., 1946.
15. Hveem, F. N.: "Asphalt Quality Controls," 33rd Annual WASHO Conference, Sun Valley, Idaho, Sept. 16-18, 1954.
16. Stanton, T. E. and Hveem, F. N.: "Test Methods for Performing Acceler-

ated Durability Tests on Asphalts," ASTM Special Technical Publication No. 94, 1949, pp. 84-99.

17. "Manual on Design and Construction of Asphaltic Roads and Streets," The Asphalt Institute, Pacific Coast Division, 2nd. ed., Sept., 1952, pp. 71-72.

18. Moyer, R. A. and Shupe, J. W.: "Roughness and Skid Resistance Measurements of Pavements in California," Bulletin 37, Highway Research Board, 1951.

19. Easton A. H.: "Skid Resistance of Bituminous Pavements and Research on Winter Driving Hazards," Selected Papers, Sixth Highway Engineering Institute, University of Wisconsin, February 23-26, 1954.

20. Morgan, A. D.: "Correlation of Roughometer and Skid Tests with Pavement Type, Design and Mix," Bulletin 37, Highway Research Board, 1951.

21. Normann, O. K.: "Braking Distances of Vehicles from High Speeds," Proceedings, Highway Research Board, 32nd Annual Meeting, January, 1953, pp. 421-436.

22. J. M. Rice: Discussion of paper by P. J. Serafin on "Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture by Solvent Immersion," Proc. Assoc. Asphalt Paving Technologists, Jan., 1954.

23. Emmons, W. J.: "Stability Experiments on Asphalt Paving Mixtures," Public Roads, January, 1934, pp. 197-211 and 218.

24. Hveem, F. N.: "The Centrifuge Kerosene Equivalent as Used in Establishing the Oil Content for Dense Graded Bituminous Mixtures, California Highways and Public Works, October, 1946."

25. National Slag Association: "Composition of Asphaltic Concrete, Hot and Cold Mixed Types, Recommended Design and Quantities," June, 1946 NSA File 103-25-B, p. 23.

26. Ricketts, W. C., Sprague, J. C., Tabb, D. D., and McRae, J. L.: "An Evaluation of the Specific Gravity of Aggregates for Use in Bituminous Mixtures" Proc. A. S. T. M., 1954.

27. Vokac, Roland: "A Type of Aggregate Gradation for Non-Critical Asphaltic Paving Mixtures," Proc. Assoc. Asphalt Paving Technologists, January, 1939, p. 86.

28. W. E. Chastain: "Summary of State Practices in the Use of Bituminous Concrete Mixtures" Proc. Highway Research Board, Vol. 33, Jan., 1954.

29. W. E. Chastain: "Summary of State Practices in the Use of Bituminous Concrete," Selected Papers Sixth Highway Engineering Institute, University of Wisconsin, February 23-26, 1954.

30. Csanyi, Ladis H.: "The Effects of Asphalt Film Thickness on Paving Mixtures," Proc. Assoc. Asphalt Paving Technologists, April 1948.

# Appendix A

## *Proposed Tentative Method of Test For Stability and Flow Value of Bituminous Mixtures*

This method of test is intended for use with hot-mix bituminous paving mixtures containing asphalt or tar and aggregate up to 1 in. maximum size.

### APPARATUS

The apparatus, commonly known as the Marshall test apparatus, shall consist of the following:

Specimen Molds. A minimum of six molds is recommended. Details of a mold are shown on Figure 1.

Base Plate. A minimum of three base plates, as shown on Figure 1 is recommended.

Collar. A minimum of three collars, as shown on Figure 1 is recommended.

Sample Extractor and Extractor Collar. A sample extractor and an extractor collar (Fig. 1) for extruding the compacted specimen from the specimen mold. A suitable means of applying load to the sample extractor to eject the specimen from the specimen mold is required; a hydraulic jack and frame are suitable.

Compaction Hammer. Compaction hammer (Fig. 2), 10 lb. in weight with a striking face 3⅞ in. in diameter. The hammer is designed for a free fall of 18 in. A minimum of two compaction hammers is recommended.

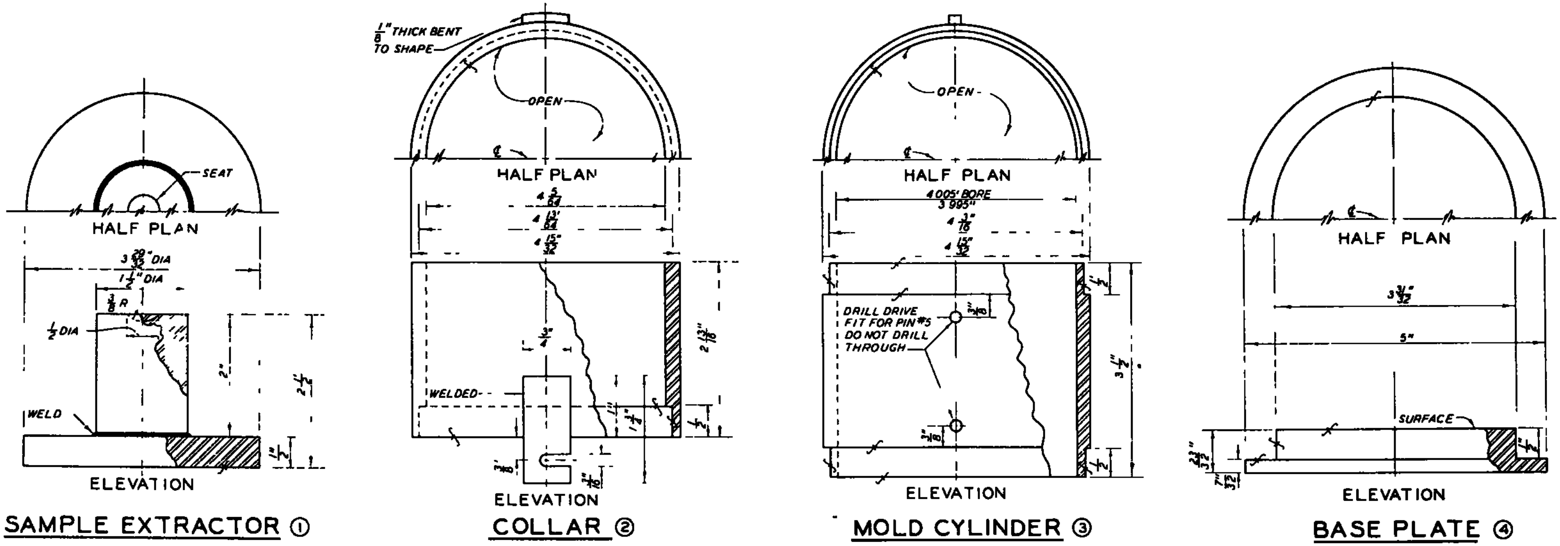
Compaction Pedestal. A compaction pedestal consisting of a wooden post having a minimum cross section of 5½ by 5½ in. (nominal 6 by 6 in.), capped by a 1-in. steel plate. The pedestal cap may consist of a 12- by 12- by 1-in. steel plate, supported by a 12- by 12- by 2-in. wood section over the 6- by 6-in. post, provided arrangements are made for placing the compaction mold directly over the 6- by 6-in. post. The compaction pedestal must be placed on a concrete floor slab or base resting on the ground, or directly over an interior column of a building or similar location. Wooden floors or unsupported areas of concrete floors are unsuitable as a support for the compaction pedestal. The provision of a pedestal in accordance with these requirements is very important, otherwise the compaction obtained will not agree with prototype conditions.

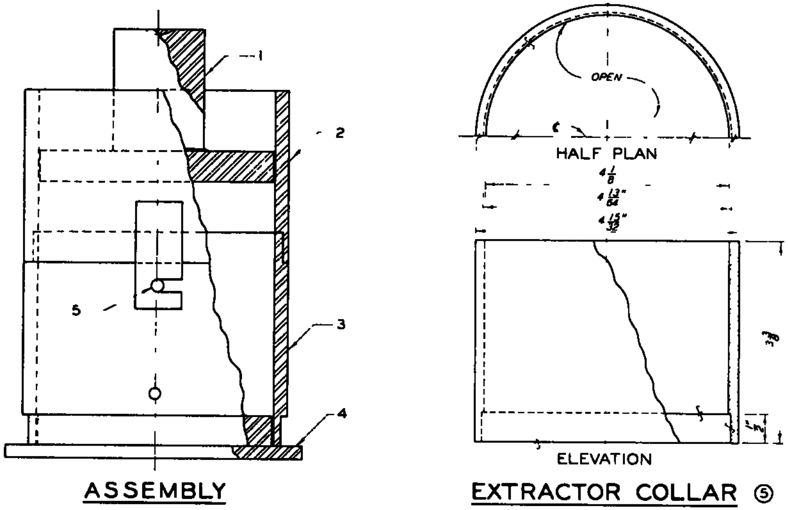
Specimen Mold Holder. A specimen mold holder, consisting of a semicircular base and a circular top, for the purpose of holding the specimen mold in place during compaction of the specimen. Two holes are provided in the base for mounting on the compaction pedestal by means of lag screws. The top section is grooved to fit over the collar of the specimen mold, and is attached to the base by means of a fulcrum on one side of the circle and a tension spring on the other.

Breaking Head. A breaking head (Fig. 3) consisting of upper and lower cylindrical segments or test heads which have an inside radius of curvature of 2 in. accurately machined. The lower segment is mounted on a base having two perpendicular guide rods or posts extending upwards. Guide sleeves in the upper segment are in such position as to direct the terminals of the two segments together without appreciable binding or loose motion on the guide rods. When a 4-in.-diameter specimen is in testing position, the terminals of the two segments are separated by a distance of ¾ in. on each side. In this position the guide rods protrude slightly above the top of the upper arc.

Loading Jack. One screw jack mounted in a testing frame is required for load application to produce a uniform vertical movement of 2 in. per min. An electric motor may be attached to the jacking mechanism for convenience.

Proving Ring Assembly. One proving ring equipped with a dial gage of 5000-lb. capacity and sensitivity of 10 lb. up to a 1000-lb. load and of 25 lb. between 1000-lb. load and 5000-lb. load. The dial gage should be graduated in 0.0001 of an inch to obtain the desired sensitivity. Upper and lower proving-ring attachments are required for attaching the proving ring to the




LIST OF PARTS

| MARK | NO REQ D | DESCRIPTION | MATERIAL | WEIGHT |
|---|---|---|---|---|
| 1 | 1 | SAMPLE EXTRACTOR | STEEL | 2 7 LBS |
| 2 | 1 | COLLAR | " | 2 1 " |
| 3 | 1 | MOLD CYLINDER | " | 2 9 " |
| 4 | 1 | BASE PLATE | " | 2 9 " |
| 5 | 1 | EXTRACTOR COLLAR | " | 2 1 " |
| | PARTS NOT DETAILED | | | |
| 6 | 4 | PIN 5/32"-3/8" LONG | STEEL | 0 02 LBS |
| | | | TOTAL | 12 7 LBS |

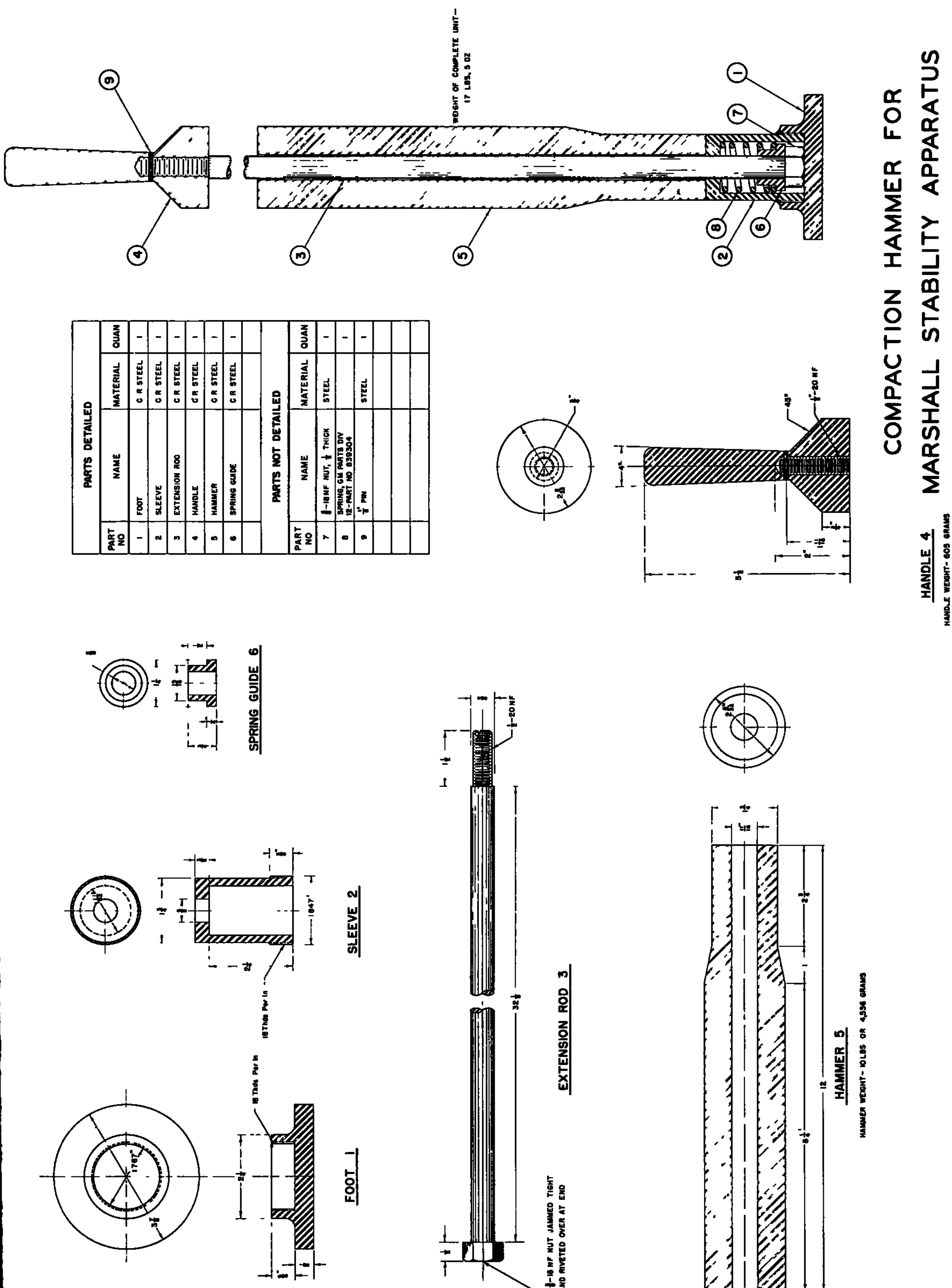
COMPACTION MOLD

FOR MARSHALL STABILITY APPARATUS

SCALE

1 0 1 2 3 INCH

Figure 1. Compaction mold for Marshall stability apparatus.




| PARTS DETAILED | | | |
|---|---|---|---|
| PART NO | NAME | MATERIAL | QUAN |
| 1 | FOOT | C R STEEL | 1 |
| 2 | SLEEVE | C R STEEL | 1 |
| 3 | EXTENSION ROD | C R STEEL | 1 |
| 4 | HANDLE | C R STEEL | 1 |
| 5 | HAMMER | C R STEEL | 1 |
| 6 | SPRING GUIDE | C R STEEL | 1 |
| | | | |
| **PARTS NOT DETAILED** | | | |
| PART NO | NAME | MATERIAL | QUAN |
| 7 | $\frac{5}{8}$-18NF NUT, $\frac{1}{2}$ THICK | STEEL | 1 |
| 8 | SPRING, GM PARTS DIV 12-PART NO 839304 | | 1 |
| 9 | $\frac{1}{8}$" PIN | STEEL | 1 |
| | | | |
| | | | |
| | | | |

Figure 2. Compaction hammer for Marshall stability apparatus.

testing frame and transmitting the load onto the breaking head.

Flow Meter. A flow meter (Fig. 4) consisting of a guide sleeve and a gage. The activating pin of the gage slides with a slight amount of frictional resistance inside the guide sleeve which in turn slides freely over a guide rod of the stability breaking head as indicated on the assembly drawing of Figure 4. The guide rod forces the gage up through the sleeve during the test. The flow meter reads zero when placed in testing position on the breaking head containing a 4-in.-diameter specimen. Graduations of the flow meter gage are in .01-in. divisions.

Ovens or Hot Plates. For the preparation of bituminous mixtures, ovens or hot plates shall be provided for heating aggregates and bituminous materials to a temperature not to exceed 162.8°C. (325°F). (For tar mixtures, aggregates and tar shall be heated to desired temperatures, not exceeding 107.2°C. (225°F.).) When hot plates are employed, a metal shield shall be interposed between the hot plates and the material and mixing pans and the specimen molds containing the mixture. A convenient shield can be made by crimping the edges of a sheet of metal so as to provide an air space beneath its surface. At least 12 sq. ft. of heating surface area is required.

Mixing Apparatus. Suitable equipment is required for thoroughly mixing the aggregates and asphalt cement. Hand mixing is permissible but mechanical mixing is recommended. A commercial dough mixer of 10-qt. capacity has been found satisfactory. Two 10-qt. mixing bowls and two wire stirrers are desirable.

Water Bath. A metal hot-water bath with mechanical water agitator, heating element, and thermostatic controls capable of maintaining the temperature of the water in the bath at 60 ± 1.0°C. (140 ± 1.8°F.). A minimum tank size of 18 by 30 in. is recommended; also, the tank should have a perforated false bottom. The depth shall be sufficient for immersion of the test specimens.

Appurtenant Equipment. The following appurtenant equipment is required:

12 metal pans, 12 in. by 18 in. by 4 in., for heating aggregates.

3 pouring cans with handle, for heating asphalt cement, 1-gal. size.

1 scoop for handling hot aggregates, approximately 2-qt. size.

2 spatulas, 1- by 6-in. blade.

6 thermometers for determining temperatures of aggregates, bitumen, and bituminous mixtures. Armored glass thermometers or dial-type with metal stem are satisfactory. Range of 50-400°F., with sensitivity to 5°F. required:

2 thermometers, glass, mercury, for hot-water bath, with range of 134-148°F. sensitive to 0.2°F.

2 trowels, rectangular blade, approximately 2 in. by 4 in.

1 balance, 20-kg. capacity, sensitive to 1 g., for preparing bitumen and aggregate mixtures.

1 balance, 2-kg. capacity, sensitive to 0.1 g., for weighing compacted specimens.

1 wire basket and water bucket suitable for weighing compacted specimens in water.

6 pair gloves, leather palm or welders, for handling hot equipment.

1 clipboard for data sheets.

1 pair gloves, rubber, gauntlet-type, for lifting specimens from hot-water bath.

1 scoop, flat bottom, of adequate size for use in placing bituminous mixture in molds prior to compaction.

1 trowel, 6 in., garden type, for use in preparation of mixes.

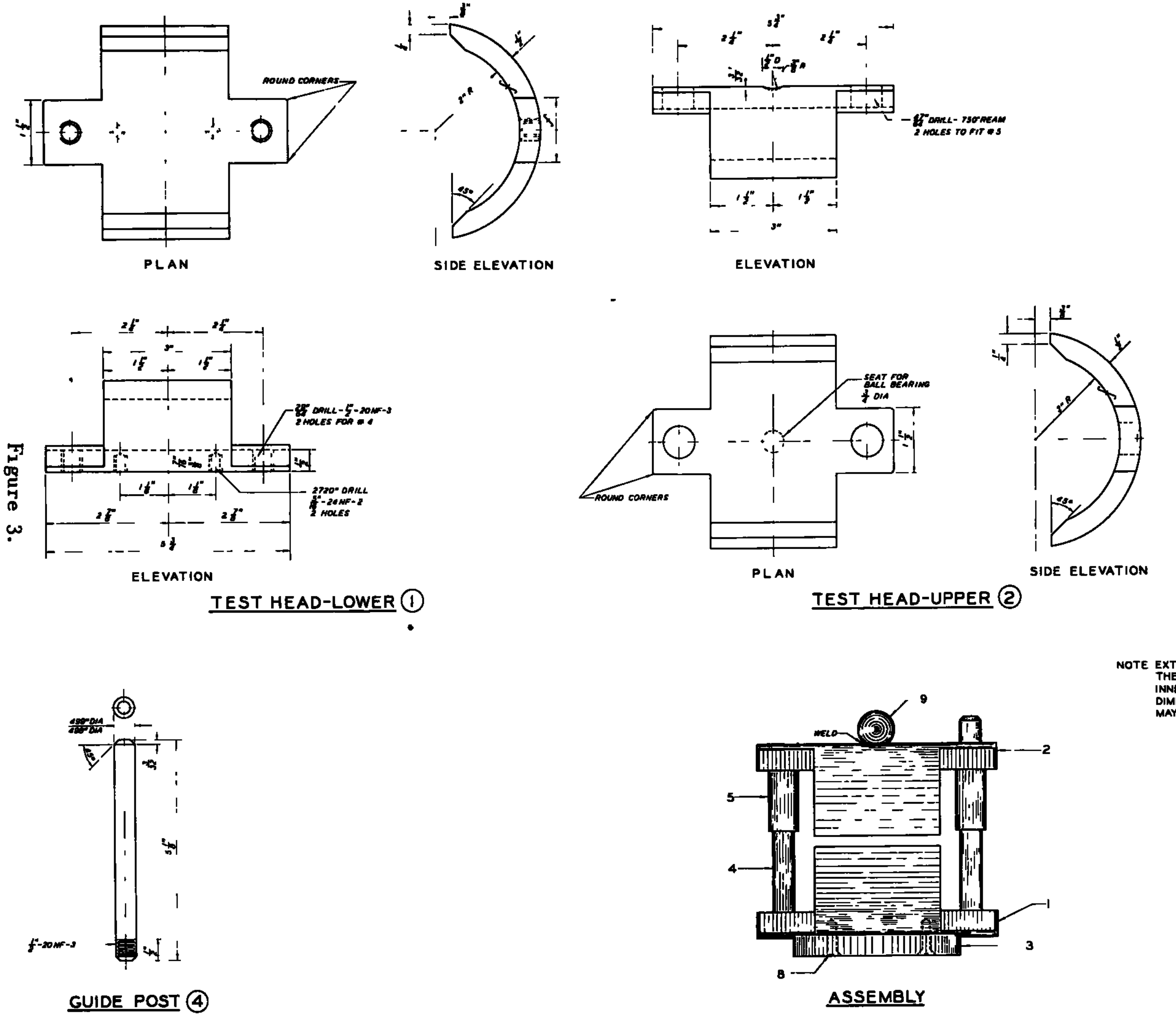
## TEST SPECIMENS

Selection of Bitumen Contents for Specimens. The optimum amount of bitumen for the aggregate to be tested must be estimated in order to start the laboratory tests. Laboratory tests shall be conducted for a minimum of five bitumen contents: two above, two below, and one at the estimated optimum content. Sufficient specimens shall be prepared at each bitumen content to assure definite position of the point. One percent incremental changes of bitumen may be used for preliminary work; however, increments of one-half of one percent shall be used for final tests. The percent of bitumen shall be expressed as percent of the total weight of the batch of paving mixture.

Preparation of Aggregates. A quantity of aggregate of the selected blend sufficient to make the required number of test specimens shall be dried substantially to constant weight at 230°F. (110°C.). The dry aggregate then shall be separated into several size ranges by sieving. Preparation of test specimens by recombining separated size fractions prevents nonuniformity of test specimens resulting from aggregate segregation during handling and heating. Separations may vary depending on the grading of the aggregate. Incomplete sieving of the different sizes is not detrimental if not carried to excess, and providing it is recognized, and appropriate adjustments are made in recombining the aggregates for preparing the test mixtures. A sieve analysis of each of the separated fractions shall be made to determine the adequacy of the separation and to furnish the necessary data for calculating the percentage of each size range to use in preparing the required mix.

Preparation of Mixture and Compaction of Specimens. The weighed aggregate fractions for each batch (allow 1500 g. total weight of batch for one specimen) shall be heated to the desired temperature and thoroughly mixed dry. The mixing bowl shall be charged with the desired weight of heated aggregate and a crater formed in the dry blended mixture; the required amount of bitumen at the proper temperature is then weighed into the mixture. For asphalt mixes, the temperature of the aggregate and asphalt at the time of mixing shall be 300 ± 5°F. and 270 ± 5°F., respectively. For hot-tar mixes (RT-10 to RT-12), the temperature of the aggregate and tar at the time of mixing shall be 225 ± 5°F. and 200 ± 5°F., respectively. Mixing of the aggregate and bitumen shall be as thorough and as rapid as possible; mechanical mixing is recommended. For asphalt mixes, compaction shall be accomplished with the mix at a temperature of 250 ± 5°F. For tar mixes, compaction shall be accomplished with the mix at a temperature of 180 ± 5°F. The striking face of the compaction hammers and the compaction molds shall be thoroughly clean and heated to approximately 200-300°F. A piece of filter paper or paper toweling, cut to size and placed in the bottom of the mold before the mixture is introduced, facilitates removal of the base plate after compaction. The mixture shall be placed in the mold, after which the collar shall be removed, and the surface of the mix smoothed to a slightly rounded shape with a trowel. (The height of the compacted specimen should be 2½ in. within a tolerance of ± one-eighth in.; one or two trials will indicate the quantity of mix required to produce such a specimen.) The collar shall be replaced, the mold assembly placed on the compaction pedestal, and the required number of blows applied with the compaction hammer. The base plate and collar shall be removed, and the mold reversed and reassembled. The required number of blows then shall be applied to the other side of the specimen. The number of blows used for compaction should be that number required to produce the density that will ultimately be attained under the traffic for which the pavement is designed. For example, an airfield paving mix designed to carry 100-psi. tires should be compacted by 50 blows on each end of the specimen; if the pavement is being designed to carry 200-psi. tires, the compactive effort should be 75 blows per side. (The above compactive efforts were established by direct determination of the blows necessary to produce the density shown by cores from actual pavements after traffic.) After compaction, the base plate and collar shall be removed, and the mold containing the specimen placed in cool water for a minimum of two minutes, after which the collar shall be replaced on the mold and the sample extractor placed on the opposite end of the specimen. The assembly is then placed with the extractor collar down in the hydraulic jack and frame, and pressure is applied to the sample extractor forcing the specimen into the extractor collar. The specimen is then removed from the collar and suitably identified. It shall be carefully handled and placed on a smooth, well-leveled surface until ready for testing. The specimens are ready for weighing and testing at any time after they have cooled to room temperature.

Stability and Flow Determination. The test specimens shall be brought to the desired temperature of test by immersing in a water bath for at least 20 minutes. The bath temperature for asphalt samples shall be 140°F. For tar samples (RT-10 to RT-12), the bath temperature shall be 100°F. The inside surfaces of the test heads and the guide rods shall be cleaned thoroughly prior to making the stability test, and the guide rods shall be well lubricated so that the upper test head will slide freely over the guide rods on the lower test head. The specimen shall be removed from the water bath and placed on its side in the lower section of the breaking head. The upper section of the breaking head




LIST OF PARTS

| MARK | NO. REQ'D | DESCRIPTION |
|---|---|---|
| 1 | 1 | TEST HEAD-LOWER |
| 2 | 1 | TEST HEAD-UPPER |
| 3 | 1 | BASE |
| 4 | 2 | GUIDE POST |
| 5 | 2 | SLEEVE |
| | | |
| | | |
| 8 | 2 | MACHINE SCREW F.H 3/16"-24-7/8" LONG |
| 9 | 1 | BALL - 3/4" DIAM |

NOTE EXTREME CARE SHOULD BE EXERCISED IN FABRICATING THE UPPER AND LOWER TEST HEADS TO OBTAIN THE PROPER INNER RADIUS (2 INCHES) FREQUENT CHECKS ON THIS DIMENSION SHOULD BE MADE IN SERVICE, AS HIGH LOADS MAY FORCE THE TEST HEADS OUT OF ROUND

# BREAKING HEAD

FOR MARSHALL STABILITY APPARATUS

SCALE

Figure 3.

shall be positioned on the guide rods and on the specimen, and the complete assembly then placed in position in the testing machine. The flow meter shall be placed over one of the guide rods and an initial reading taken on the flow meter, estimated to 0.01 in. Load shall be then applied to the specimen at a constant rate of 2 in. per minute until failure of the specimen occurs. The load builds up in the typical test as movement occurs, until it reaches a maximum and falls off. The maximum reading of the dial, converted to pounds, is the stability value for the specimen. The flow meter shall be held firmly over the guide rod while loading the specimen, and shall be removed from its position over the guide rod just when the load first begins to decrease as indicated by the dial gage in the proving ring. A second reading shall be taken on the flow meter, and the difference between this reading and the original reading, expressed in hundredths of an inch, is the flow value of the specimen. In order to prevent excessive cooling of this specimen with a resulting increase in stability value, the entire procedure from the time the specimen is removed from the water bath should be performed as quickly as possible; normally the test should be performed in 30 seconds. The stability value varies directly with the thickness of the specimen; therefore, it is necessary to correct the stability values for specimens of a thickness greater, or less than, the standard 2½ in. Figure 5 shows the necessary conversion factors for specimens varying in thickness from 1 to 3¼ in. Figure 5 also contains data whereby the stability conversion factor can be determined on the basis of the volume of the specimen, since the volume is a direct function of height for a constant 4-in.-diameter specimen. Flow values do not vary appreciably with change in thickness of specimen and therefore no corrections are needed for the flow value.

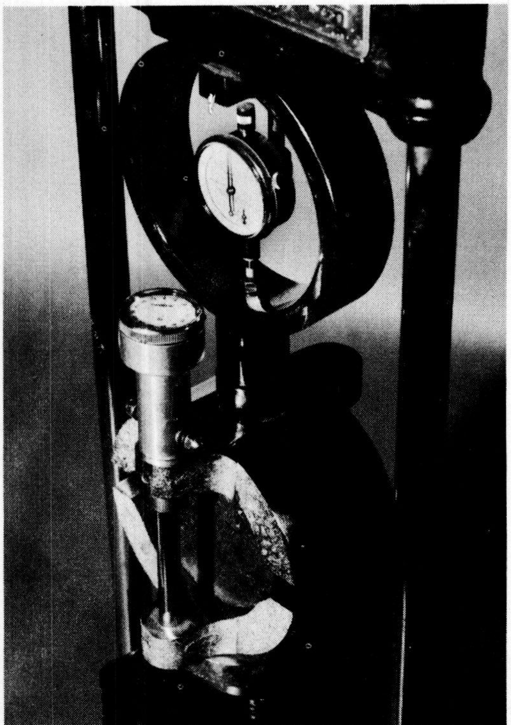


Figure 4. Flow meter for Marshall stability apparatus.

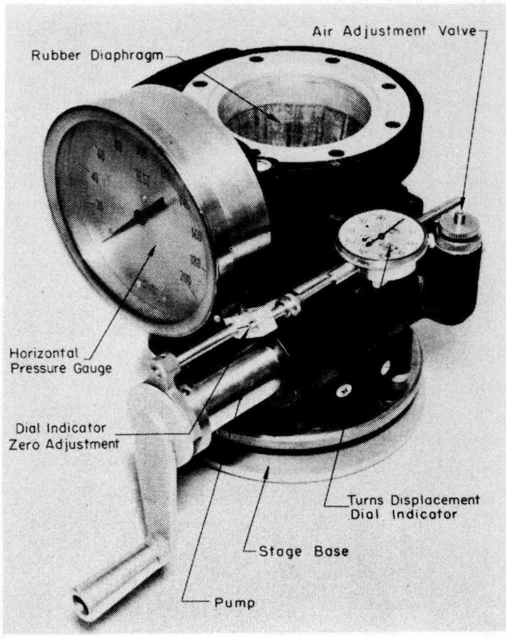



Figure 5. Hveem Stabilometer.

## REPORT

The report shall include the following information for each specimen tested: (1) nominal size of the test specimen, (2) stability value in pounds as corrected, (3) flow value in hundredths of an inch, and (4) test temperature.

# Appendix B

## *Proposed Tentative Methods of Test for Resistance to Deformation and Cohesion of Bituminous Mixtures*

These test methods determine (1) the resistance to deformation of compacted bituminous mixtures by measuring the lateral pressure developed from applying a vertical load and (2) the cohesion of bituminous mixtures by measuring the force required to break or bend the sample as a cantilever beam.

## *Resistance to Deformation*

### APPARATUS

The apparatus shall consist of the following:

Stabilometer - The stabilometer (Fig. 5) is a triaxial testing device consisting essentially of a rubber sleeve within a metal cylinder containing a liquid which registers the horizontal pressure developed by a compacted test specimen as a vertical load is applied. A drawing is given in Fig. 6.

Testing Machine. - Compression testing machine having a minimum capacity of 10,000 lb. Fig. 7 shows assembly of stabilometer in a testing machine.

Oven. - Oven capable of maintaining a temperature of 140 $\pm$ 5$^0$ F.

Calibration Cylinder. - Hollow metal cylinder 4 inches outside diameter by 6 inches high (for calibration purposes).

Measuring Device. - A device for measuring the height of the specimen to the nearest 0.01 inches.

Followers. - One metal follower 3.985 inches in diameter by 3½ inches high, and one 3.985 inches in diameter by 1½ inch high.

Sample Mixing Apparatus. - Suitable equipment is required for mixing the aggregate and the asphalt. Hand mixing is permissible but mechanical mixing is recommended. (California Department of Highways has developed a mechanical mixing apparatus capable of mixing simultaneously from 2 to 5 batches. Working drawings are available.)

Sample Splitter. - (riffle type)

Appurtenant Equipment. - The following appurtenant equipment will be required; balance, 5 Kg capacity, sensitive to 1.0 gram, metal milk pans of various sizes, thermometers, trowels, spatulas, scoops, gloves and beakers.

### ADJUSTMENT OF STABILOMETER

Adjust the stabilometer base so that the distance from the top of the exposed rubber sleeve to the top of the base is 2.4 inches.

Adjust the amount of air in the air cell so that two turns of the pump (0.4 cu. in. displacement) increase the liquid pressure from 5 to 100 psi. with the metal calibration cylinder in the stabilometer chamber.

### TEST SPECIMENS

Selection of Bitumen Content for Specimens. - The theoretical or estimated optimum amount of bitumen for the aggregate shall be determined by the method common to the laboratory (California uses the Centrifuge Kerosene Equivalent Method). On normal materials laboratory tests shall be conducted for a minimum of three bitumen contents, one above, one below, and one at the theoretical or estimated optimum content. The incremental change of bitumen content should be 0.5 percent. For extremely critical mixes the incremental change of bitumen content is lowered to 0.3 percent and the number of tests increased to a minimum of five. Conversely, for highly absorptive aggregates the incremental change of bitumen content is increased to 1.0 percent and the number of tests reduced to three. The percent of bitumen shall be expressed as a percentage of the dry weight of aggregate.

Preparation of Aggregates. - A sieve analysis and specific gravity is obtained on the fine and coarse aggregate (the

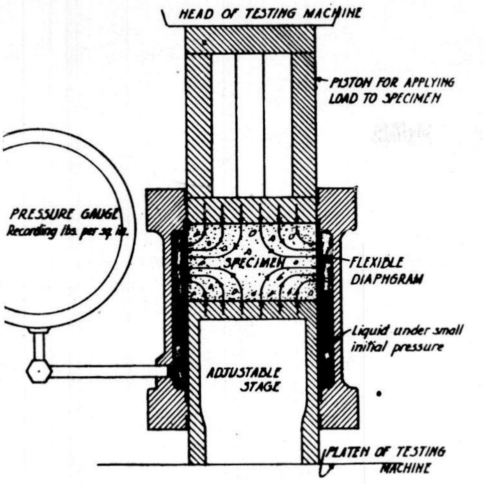



Figure 6. Diagram of Stabilometer.

separation for fine and coarse is made on the No. 4 sieve). The aggregate is then separated into the various size fractions necessary for accurate recombining into test mixtures conforming to specified grading requirements.

Preparation of Mixtures. - Moisture free aggregates are combined into batches weighing 1200 grams. The aggre-

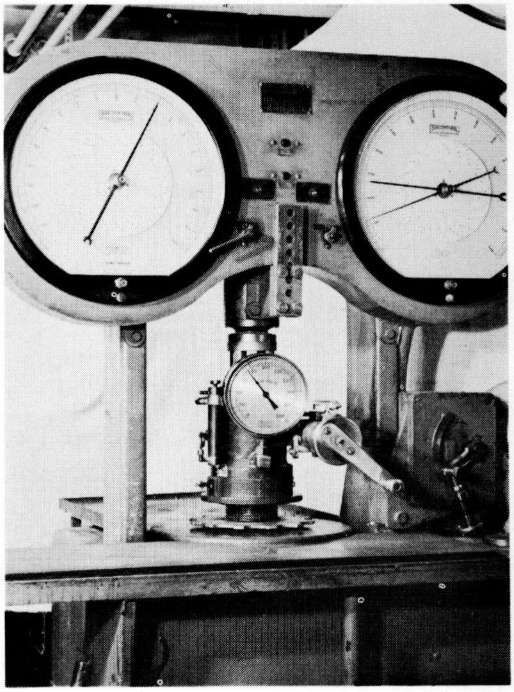


Figure 7. Hveem stabilometer in testing machine during test.

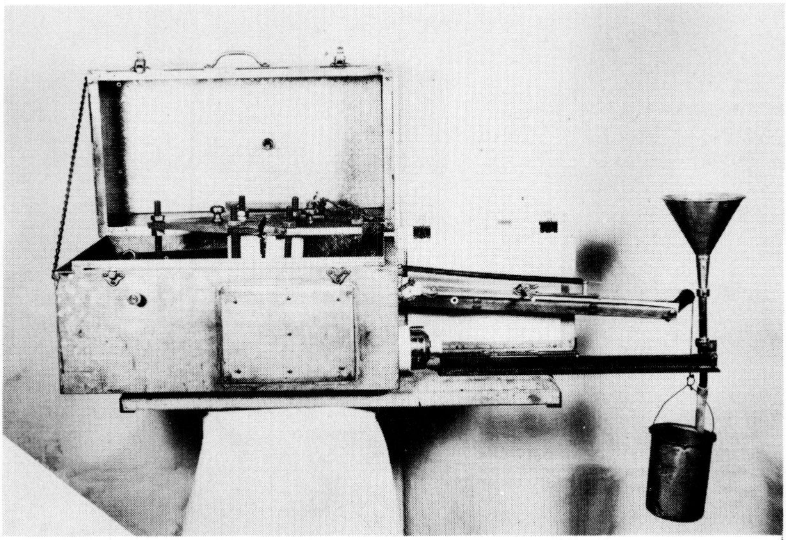
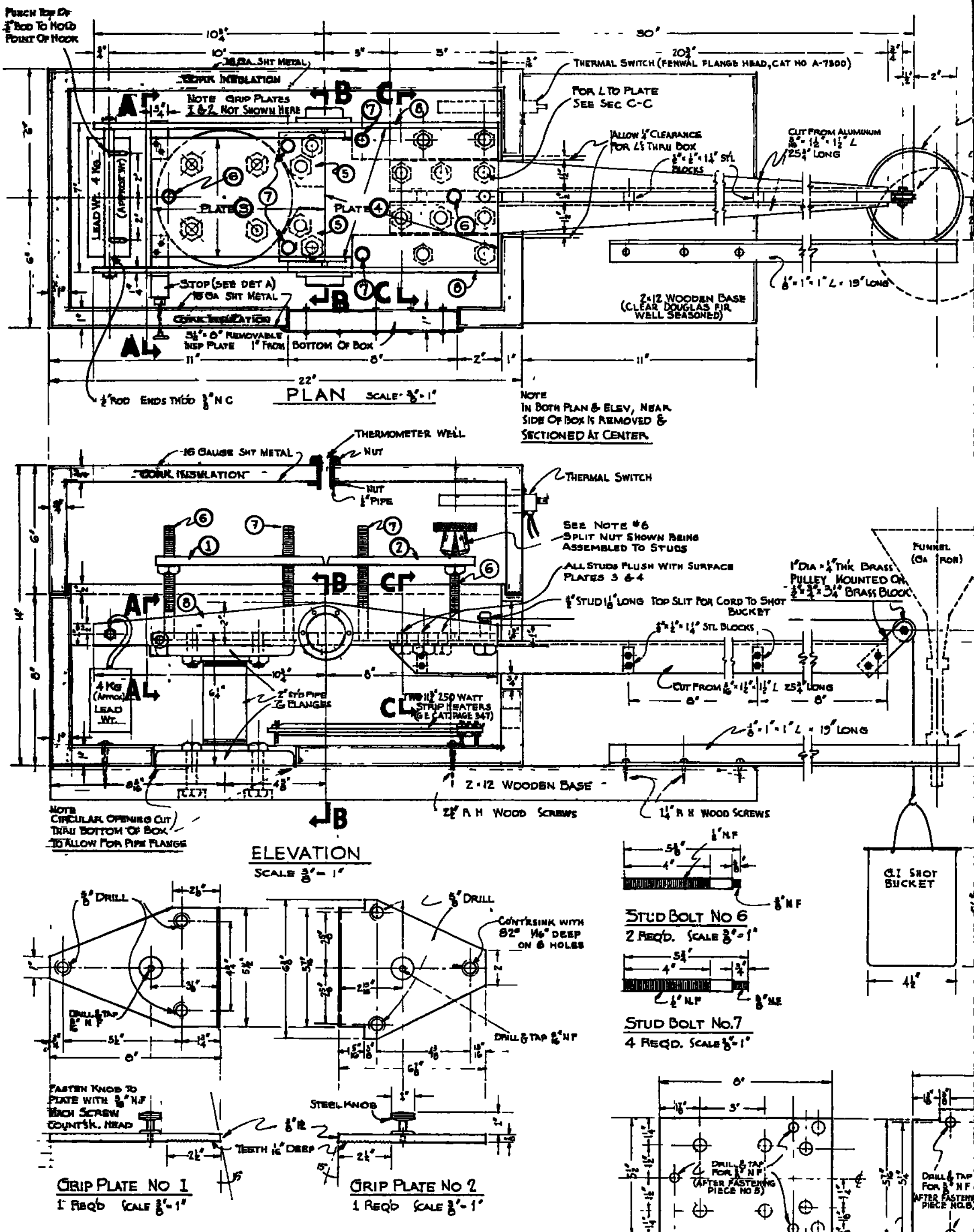


Figure 8. Hveem cohesiometer.

gate is then heated to the proper mixing temperature; the required amount of bitumen at the proper temperature is then weighed into the aggregate mixture. For mixes employing paving grades of asphalt the temperature of the aggregate and asphalt at the time of mixing will vary between 250° F and 300° F depending upon the grade used. Mixtures employing liquid asphalts do not require heat for mixing. Mixing of the aggregate and bitumen shall be as thorough and rapid as possible; mechanical mixing is recommended.

Size of Specimens. - Test speci-




GENERAL NOTES:

1. PIECES 5 AND 8 MAY BE MACHINED FROM ANGLES OF PROPER SIZE
2. THERMAL SWITCH AND HEATERS ARE TO BE SUPPLIED BY BUILDER BUT MOUNTED BY PURCHASER
3. TOP SURFACE OF PLATES 3 AND 4 SHALL BE FINISHED TO A SMOOTH PLANE SURFACE AFTER STUDS WHICH FASTEN FLANGE AND ANGLES HAVE BEEN PLACED
4. ROD FIXED TO PIECE 5 AND BALL BEARING FIXED TO PIECE 8 SHALL BE SO PLACED THAT WHEN STOP IS IN LOCKING POSITION THE TOP SURFACES OF PLATES 3 AND 4 WILL BE IN THE SAME HORIZONTAL PLANE AND WHEN THE STOP IS RELEASED AND ROTATION OF PLATE 4 OCCURS THERE WILL APPEAR NO GAP BETWEEN PLATES 3 AND 4
5. COUNTERSINK ON GRIP PLATES PROVIDE THE SHOULDER TO HOLD HALVES OF SPLIT NUT TO THREADS
6. SPLIT NUT SHOULD BE SPECIFIED WHERE LARGE NUMBERS OF SAMPLES ARE TO BE TESTED FOR OCCASIONAL USE, A STANDARD NUT AND SLEEVE WILL BE SATISFACTORY

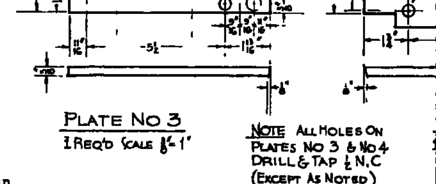
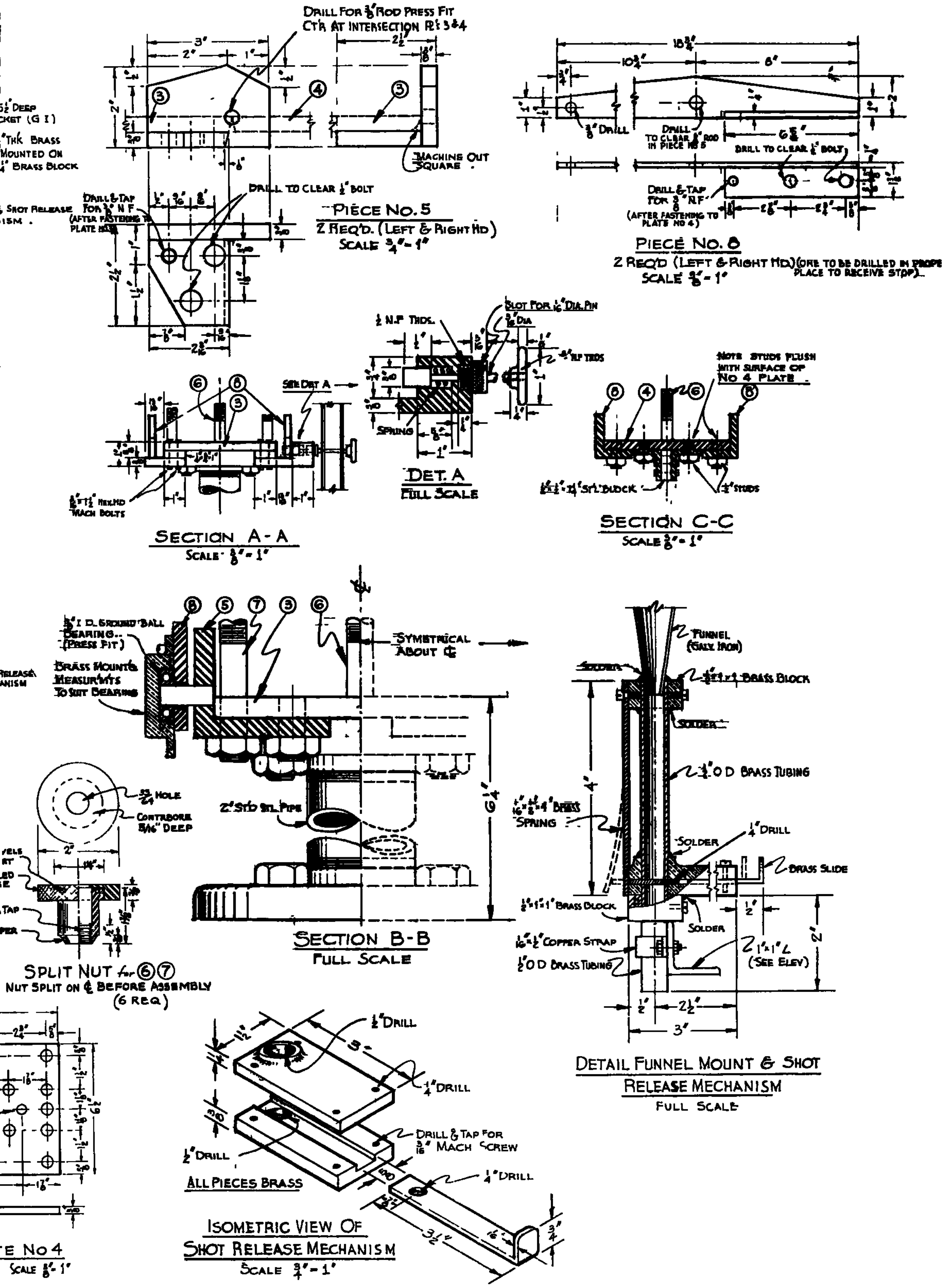


Figure 9.




Cohesiometer.

mens are 4 inches in diameter and 2.5 ± 0.1 inch in height.

Compaction of Specimens. - Test specimens shall be formed and compacted in accordance with the "Kneading Compaction Method" (See Appendix C).

PROCEDURE

Bring the specimen to a temperature of 140 ± 5° F.

Transfer the compacted specimen from the mold to the stabilometer. Place the 3½ inch follower on top of the specimen and adjust pump to give a horizontal pressure of 5 psi. Start vertical movement of press (Speed of 0.05 inch per minute) and record the stabilometer gauge readings when the vertical pressures are 500; 1,000; 2,000; 3,000; 4,000; 5,000; and 6,000 lb. total load. Stop the vertical movement of the press when the total load reaches 6,000 lb. Reduce the vertical load to 1,000 lb. and lock the testing press at this point. Adjust the horizontal pressure to 5 lb. and measure the number of turns of the pump required to raise the horizontal pressure from 5 psi. to 100 psi. with the specimen in place. This is the displacement reading (D) in the following equation.

CALCULATIONS

The stabilometer value of the specimen is determined from the equation:

$$S = \frac{22.2}{(P_h D/P_v - P_h + 0.222)}$$

Where $P_h$ = Horizontal pressure (Stabilometer reading in psi.)

$P_v$ = Vertical pressure (Typically 400 psi.)

D = Displacement on specimen

REPORT

The report shall include the stabilometer value and the test temperature.

## *Cohesion*

APPARATUS

The apparatus shall consist of the following:

Cohesiometer. - The cohesiometer as illustrated in Fig. 8. Detailed dimensions are given in Fig. 9.

Lead Shot. - 2,000 grams of steel or lead shot size No. 6.

Oven. - An oven capable of maintaining a temperature of 140 ± 2° F.

Balance. - A balance having a capacity of 5 Kg and sensitive to 1 g. or less.

TEST SPECIMENS

Preparation of Specimen. - The test specimen will normally be the compacted specimen used after completion of the stabilometer test. If the sample is taken from a compressed pavement slab by means other than coring, it should be cut to size with a suitable saw.

Size of Specimens. - The cohesiometer is designed to test specimens up to 5 inches in width and from 1 to 3 inches high.

PROCEDURE

Place the specimen to be tested in the oven and allow to stand until the temperature is 140 ± 2° F throughout (this will normally require a minimum of 2 hours).

Clamp the test specimen firmly in the cohesiometer being certain that it is well centered, with the top plates parallel with the surface of the specimen. Allow the shot to flow into the receiver at the end of the lever arm using a rate of flow of 1,800 grams per minute. Stop the flow of shot when the specimen breaks or when the lever arm deflects ½ inch from the horizontal if that occurs before the specimen breaks. Weigh and record the amount of shot.

CALCULATIONS

The cohesiometer value is determined from the equation:

$$C = \frac{L}{0.80 + 0.178H^2}$$

Where L = Weight of shot, in grams

H = Height of specimen, in inches

C = Cohesiometer value (grams per inch of width corrected to 3 inch height)

REPORT

The report shall include the cohesiometer value and the test temperature.

# Appendix C

## *Kneading Compaction Method for Bituminous Mixtures to be Tested in the Hveem Stabilometer*

Developed by State of California, Department of Public Works
Division of Highways, Materials and Research Department

This method of compaction is accomplished by means of a mechanical compactor which imparts a kneading action consolidating the test specimens by a series of individual impressions made with a ram having a face shaped as a sector of a 4 inch diameter circle. At each application of the ram a pressure of 500 psi. is applied subjecting the test specimen to a sort of kneading action without impact, over an area of approximately 3.1 square inches, the pressure is maintained for approximately ⅖ second.

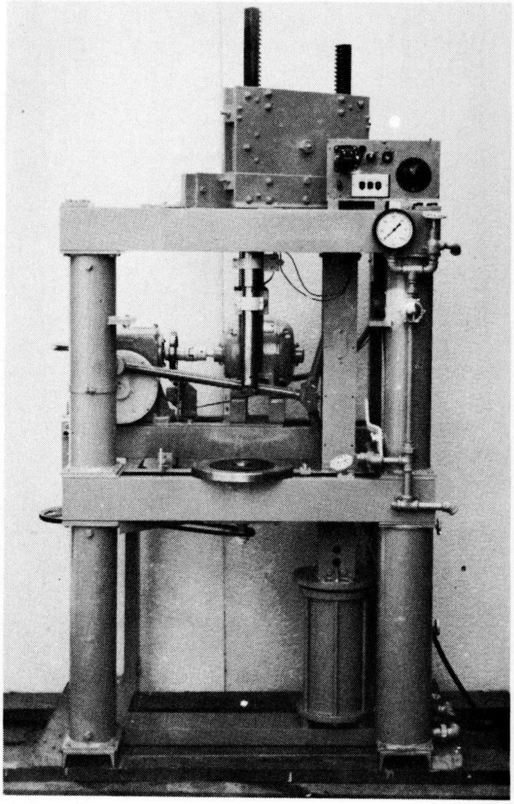


Figure 10. Mechanical kneading compactor.

### APPARATUS

Mechanical kneading compactor. (See Fig. 10.)

Mold holder, funnel, and feeder trough. (See Fig. 12.)

Compression machine having a capacity of at least 40,000 lb.

Ovens capable of maintaining temperatures of 140° F and 230° F.

Molds 4 inches dia. x 5 inches high.

Round nosed steel rod ⅜ inch in dia. by 16 inches long.

Heavy paper disks 4 inches in diameter.

Two metal followers 4 inches in diameter.

### PROCEDURE

The mixture to be tested is compacted at one of the three specified temperatures: (1) 140 F. for mixes using liquid grade asphalts; (2) 230 F. for mixes using paving grade asphalts; or (3) mixtures using liquid grade asphalts are also compacted at room temperature when it is desired to test with whatever moisture may be present in the mix.

Place the compaction mold in position in the mold holder with a 4 inch diameter paper disc inserted to cover the base plate of the mold holder. Also, in order to have the base plate of the mold holder act as a free fitting plunger during the compaction operation a steel shim ¼ inch thick, ¾ inch wide, and 2½ inches long, is placed under the edge of the mold temporarily.

Weigh the mixture to be compacted into the insulated feeder trough. The trough should be preheated to approximately the compaction temperature for the mix.

Spread material uniformly on the feeder trough to insure uniformity when transferring to the mold. With a paddle made to fit the shape of the trough, one-half of the material is pushed into the fabrication mold.

Rod the ½ portion of mix 20 times in

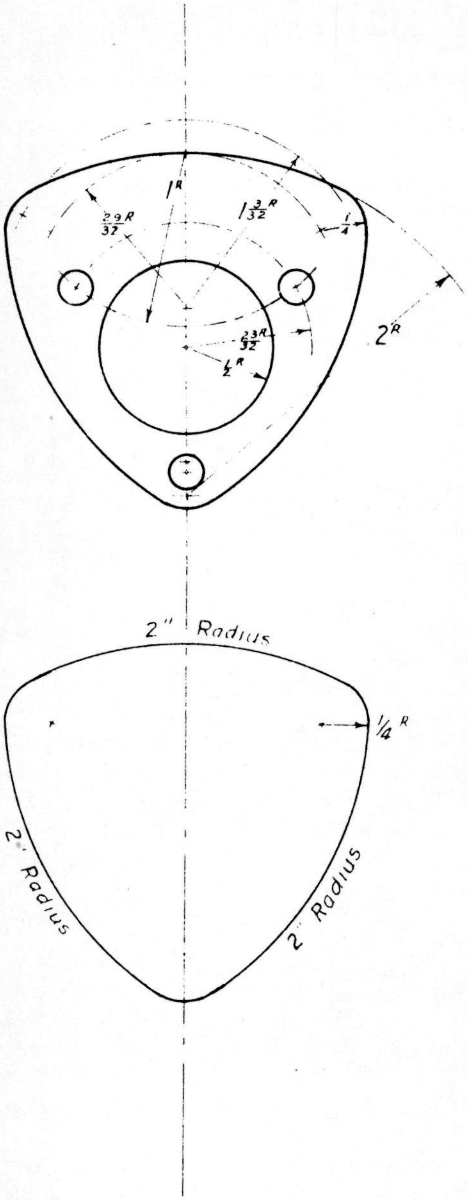



Figure 11. Face of compactor ram.

the center of the mass and 20 times around the edge with a bullet nosed steel rod ⅜ inch diameter 16 inches long. Transfer the remainder of the sample to the mold and repeat the rodding procedure.

Place mold and assembly into position on the mechanical compactor. By means of the variable transformer controlling the heater, the compactor foot should be kept sufficiently hot to prevent the mix from adhering to it. Apply approximately 20 tamping blows at 250 psi. before applying the full compaction load of 500 psi. The number of tamping blows at 250 psi. will vary somewhat with the type of material, the purpose being to form the mix into a semi-compacted condition so it will not be unduly disturbed by the 500 psi. load. After semi-compaction has been accomplished remove shim and release mold tightening screw sufficiently to allow

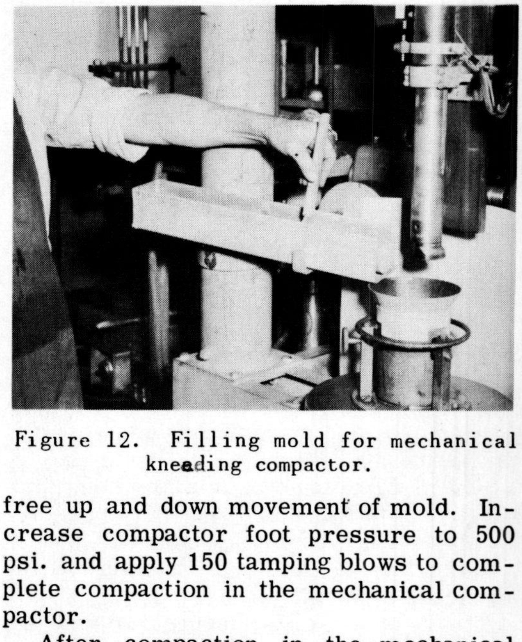


Figure 12. Filling mold for mechanical kneading compactor.

free up and down movement of mold. Increase compactor foot pressure to 500 psi. and apply 150 tamping blows to complete compaction in the mechanical compactor.

After compaction in the mechanical compactor, the mold and specimen is placed in a 140 F. oven for the following periods of time prior to applying the static leveling off load: 1 hour if compacted at 140 F. or 1½ hours if compacted at 230 F.

The leveling-off load consists of applying a static load of 1,000 psi., and is applied by the double plunger method in which a free fitting plunger is used on the top and bottom of the specimen.

After applying the leveling off load, the height of the specimen is measured and recorded.

# Appendix D

## *Method of Test for Determination of Bulk-Impregnated Specific Gravity of Aggregate for Use in Bituminous Paving Mixtures*

Developed by the Corps of Engineers, Department of the Army, December 2, 1953

This method of test is intended for use in making determinations of specific gravity of the coarse, the fine, and the blended aggregate (including filler) for use in bituminous paving mixtures. The method is not applicable to determination of specific gravity of mineral filler except when included in the blended aggregate. Specific gravity of mineral filler alone shall be determined in accordance with standards of American Society for Testing Materials, ASTM Designation D854-52 or ASTM Designation C188-44, whichever is applicable to the type of material to be examined.

### APPARATUS

Equipment used in the test: (1) large oven, thermostatically controlled, sensitive to 5 F. in the approximate range of 225-325 F. (2) balance of approximately 5,000-gm. capacity, sensitive to 0.1 gm. suitably arranged for weighing sample in air and suspended in water; (3) pails of 1-gal. capacity (syrup can with top rim removed to eliminate entrapped air is satisfactory) equipped with wire handle for suspending in water; (4) a suitable large container for immersing the 1-gal. pail and typical assembly for suspending the pail from the center of scale pan or balance; (5) bake pans of size suitable for retaining approximately 1000 gm. of aggregate; and (6) one heavy sheet metal strip about 1 in. wide for stirring contents of each pail.

### SAMPLES

Samples are as follows: (1) Aggregate. Prepare a representative sample of the aggregate (1000 gm. of fine aggregate, 1500 gm. of coarse aggregate, or 1500 gm. of blended aggregate). Care should be taken to insure that the sample represents prototype grading. (2) Bitumen. Obtain a representative sample of about 1 gal. of the bitumen that is to be used for the paving mix.

### PROCEDURE

Specific gravity of aggregate is derived as follows:

Dry sample to constant weight at a temperature not less than 230 F, nor greater than 290 F. and weigh to nearest 0.1 gm.

Heat the bitumen to 280 F. ± 5 F.* using care to assure that the temperature never exceeds 285 F. and add sufficient amount into the 1-gal. pail to fill it to about one-third its depth. Insert the sheet-metal stirrer and allow bitumen to cool to 72 ± 2 F. (A minimum of 8 hours is usually required to accomplish this, and preferably it should be allowed to cool overnight).

Weigh pail plus bitumen and stirrer in air at any temperature and in water at 72 F. ± 2 F.

Place the pail of bitumen with stirrer and the sample of aggregate in the oven at 280 F. ± 5 F.* and leave both until temperatures are equalized. (A minimum of 4 hours is usually required).

Remove aggregate and bitumen from oven and add aggregate to bitumen, stirring thoroughly as aggregate is gradually added to the hot bitumen; continue stirring until entrapped air has been removed. External vibration may be used to remove air when difficulty is encountered in removing air by stirring. During the cooling period, flame surface to remove air bubbles if such are present. Cool to 72 F. ± 2 F. (should cool overnight).

Weigh pail plus stirrer plus aggregate plus bitumen in air at room temperature and in water at 72 F. ± 2 F.

### CALCULATION

Calculate the bulk-impregnated specific

*These temperatures apply when an average penetration asphalt cement is used, when another type bitumen is used the temperature should be the same as that used under normal field conditions gravity as follows:

Bulk-impregnated specific gravity

$$(SG_{bi}) = \frac{A}{(D-E) - (B-C)}$$

where:

A = weight of oven-dry aggregate in grams

B = weight of pail plus stirrer plus bitumen in air

C = weight of pail plus stirrer plus bitumen in water

D = weight of pail plus stirrer plus bitumen plus aggregate in air

E = weight of pail plus stirrer plus bitumen plus aggregate in water

# Appendix E

## *Method of Test for Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture by Solvent Immersion*

(Michigan State Highway Department Method)*

Table A gives a detailed self-explanatory work sheet filled out with example figures. The following is a step by step procedure: (All weights are recorded to the nearest 0.1 gram and all temperatures are measured to the nearest 0.2 C.)

Calibrate the Michigan Specific Gravity Bottle. (1) Weigh the empty flask unit and record its weight under (C). (2) Weigh the flask unit filled to mark with solvent brought to a temperature of 25 C. (3) Subtract from this weight the weight of the empty flask and record results under (E). This is the solvent content of the flask at 25 C.

Determine the specific gravity of the solvent, by hydrometer or weighing in flask, to three decimal places at 25/25 C. and record under (H).

Break up the sample of bituminous mix sufficiently small enough to go through the large neck of the flask. (1) Place 300 to 500 grams of the fragments of bituminous mix in the flask. (2) Weigh flask plus mix and record under (B). (3) The difference (B - C) equals (D) or the weight of the mix in the flask. (4) Add about 250 ml. of solvent to the flask containing the mix. (5) Immerse the flask and contents in a 25 C. water bath, let stand until all bitumen in sample is dissolved. Shake periodically

TABLE A

CALCULATION SHEET FOR DETERMINING MAXIMUM THEORETICAL SPECIFIC GRAVITY OF BITUMINOUS MIXTURE SAMPLE

| | |
|---|---|
| Wt flask + mix + solvent at 25 C | 2223 2 G |
| Wt. flask + mix | 663 4 G |
| Wt flask No B | 355 3 G |
| Wt mix (B-G) | 308 1 G |
| Wt solvent (flask filled with solvent only) at 25 C | 1744 2 G |
| Wt. solvent (above mix) (A-B) at 25 C | 1559 8 G |
| Wt solvent (displaced by mix) (E-F) at 25 C | 184 4 G |
| Specific gravity of solvent at 25/25 C | 1 454 |
| Volume of mix (G/H) at 25 C | 126 8 ML |
| Theoretical max specific gravity (D/J) at 25 C | 2 430 |

Temperature controlled at 25 C.
Note Solvent used is trichlorethylene

to help break up the specimen and to release the air voids. (Length of time varies depending on hardness of bitumen and denseness of mix - ordinarily 1 to 2 hours is sufficient to disperse the average mix. (6) When all bitumen is in solution and no more air bubbles come up, fill the flask to mark with solvent which has been previously brought to a temperature of 25 C. (7) Weigh flask containing the bituminous mix and the solvent at 25 C. and record under (A). (8) The difference (A - B) equals the weight of the solvent in the flask above the mix and is recorded under (F). (9) The difference (E - F) equals the weight of an equal volume of solvent dis-

*Serafin, Paul J. "Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture by Solvent Immersion," Proc. Assoc Asphalt Paving Technologists, Vol. 23, Febr , 1954 placed by the mix and is recorded under (G). (10) The weight of the displaced solvent (G) divided by its specific gravity (H) equals the volume of the displaced solvent or volume of the mix in the flask and is recorded under (J). (11) Weight of the mix (D) divided by its volume (J) equals the specific gravity of a voidless mass of this mix or its maximum theoretical specific gravity measured at 25 C.

# Appendix F

## *Method of Test for Maximum Specific Gravity of Bituminous Paving Mixtures by Vacuum-Saturation Technique Using Uncompacted Samples*

(National Crushed Stone Association Method)*

This method of test is intended for determining the maximum or voidless specific gravity of bituminous paving mixtures using uncompacted samples.

### APPARATUS

The apparatus shall consist of the following:

1. A balance sensitive to 0.05 percent of the weight of the sample to be weighed.
2. The container may be either a glass flask or a glass or metal bowl. (The bottom section of a 1½ quart capacity, Pyrex glass, double boiler unit makes a satisfactory, container.) Containers should be sufficiently strong to withstand partial vacuum. In order to use the flask as a volumetric container the top surface shall be smooth and substantially plane. The size of the container will be governed by the maximum size of the aggregate in the mixture according to the following requirements:

| Size of Largest Particle of Aggregate in Mixture, in. | Capacity ml | Sample Size, g |
|---|---|---|
| 1 | 4000 | 2500 |
| ¾ | 3000 | 2000 |
| ½ | 2000 | 1500 |
| ⅜ | 1500 | 1000 |
| No. 4 | 750 | 500 |

3. For use with the bowl, a container suitable for immersing the bowl in water and suitable apparatus for suspending the bowl from center of scale pan of balance.

*Rice, James M "New Test Method for Direct Measurement of Maximum Density of Bituminous Mixtures," The Crushed Stone Journal, September, 1953, p 10.

### CALIBRATION OF FLASK

The flask shall be calibrated by accurately determining its weight when filled with water at 25 C (77 F). Designate this weight as "D". Accurate filling of the flask may be secured by the use of a glass cover plate.

### TEST SAMPLES

The sample shall be obtained in accordance with the Standard Methods of sampling Bituminous Paving Mixtures (ASTM Designation: D 979-51).

The size of the sample shall conform to requirements of Section 2 (b). Large samples may be tested a portion at a time.

### PROCEDURE

The sample shall be separated, using care not to fracture the mineral particles, so that the particles of the fine aggregate portion are not larger than ¼ in. If the mixture is not sufficiently soft to be separated manually, it shall be placed in a large flat pan and warmed in the oven only until it can be so handled.

The sample shall be cooled to room temperature and shall be placed in the flask or bowl and weighed. Designate the net weight of the sample as "A". Water at approximately 25 C (77 F) shall be added to cover the sample. (A suitable wetting agent added to the water will facilitate the release of entrapped air.)

Entrapped air shall be removed by subjecting the contents to a partial vacuum (air pressure less than 2 cm of mercury) for approximately 10 min. Subjection of contents to reduced air pressure may be done by connecting the flask or bowl directly to an aspirator or vacuum pump, or by use of a bell jar.

The bowl and contents shall be suspended in water at 25 C (77 F) and weighed after approximately 10 min. immersion. Designate the net weight of the sample in water as "C".

TABLE A

Example of Test Calculations

| | |
|---|---|
| **Before Vacuum Saturation** | |
| Weight of bowl plus mixture in air | 1587.7 g |
| Weight of bowl in air | 587.7 g |
| Weight of mixture in air, A | 1000 0 g |
| **After Vacuum Saturation** | |
| Weight of bowl plus mixture in water | 1000.8 g |
| Weight of bowl in water | 400 8 g |
| Weight of mixture in water, C | 600 0 g |
| **Calculation** | |
| Weight of water displaced by mixture, A-C | 400 0 g |
| Specific gravity of mixture, $D_m = \frac{A}{A-C}$ | 2 500 |

The flask shall then be filled with water and the contents brought to a temperature of 25 C (77 F). The weight of the flask and contents shall then be determined. Designate this weight as "E".

In case the specimen contains moisture, it is necessary to correct weight "A" for weight of moisture. After determining weight "C" or "E", determine the percentage moisture by weight in the original sample in accordance with the Standard Method of Test for Water in Petroleum Products and of Bituminous Materials (ASTM Designation: D 95) and apply appropriate correction to weight "A".

CALCULATION

Calculate the specific gravity of the test samples as follows:

(a) Bowl Determination:

$$\text{Specific gravity} = \frac{A}{A-C}$$

where:

A = weight in grams of dry sample in air

C = weight in grams of sample in water

(b) Flask Determination:

$$\text{Specific gravity} = \frac{A}{A+D-E}$$

where:

D = weight in grams of flask filled with water at 25 C (77 F)

E = weight in grams of flask filled with water and sample at 25 C (77 F)

REPRODUCIBILITY

The specific gravity obtained in duplicate tests on portions of the same sample should not vary by more than 0.01.

## *Special Instructions for Mixtures Containing Porous Aggregate Not Completely Coated*

If the pores of the aggregate are not thoroughly sealed by an asphalt film, they will become saturated with water during the vacuum saturation procedure. To determine if this has occurred, proceed as follows after obtaining immersed weight of mix. Drain water from mix (to prevent loss of fine particles, decant water through a dish towel held over top of bowl). Break several large pieces of aggregate and examine broken surfaces for wetness.

If aggregate has absorbed water, spread mix before an electric fan to remove surface moisture. Weigh mix at 15 min. intervals and when the loss in weight is less than ½ g for this interval, the mix may be considered to be surface dry. This procedure requires about two hours and should be accompanied by intermittent stirring of the mix. Conglomerations of mix should be broken by hand. Care must be taken to prevent loss of particles of mix.

To calculate the specific gravity of the mix, the final surface-dry weight is substituted for "A" in the denominator of equation 6 (a) or 6 (b).

# Appendix G

## *Determination of Specific Gravity of Bituminous Concrete Mix for Field Density Control*

H. R. CRAIG, Engineer of Construction, and
F. W. KIMBLE, Flexible Pavements Engineer,
Ohio Department of Highways

This method of test is intended for a field method of determining the specific gravity of bituminous concrete mix within the accuracy necessary for field density control of pavement courses.

### APPARATUS

The apparatus shall consist of the following:

A Torsion Balance of 2 kilogram capacity sensitive to 0.10 gram and a suitable set of weights.

A Volumeter having a sample chamber of 1350 cc capacity and a secondary chamber of 675 cc capacity. (See Fig. A).

Aluminum Inserts 4 inches in diameter; 5 each at 200 cc volume; 1 at 100 cc volume and 1 at 50 cc volume.

A Hand Pump suitable for pressurizing sample chamber of volumeter.

A Mercury Pressure Gauge (open manometer type) calibrated from 0 to 40 inches.

Ointment Cans 4 inches in diameter 3 inches deep perforated every ½ inch with ⅛-inch holes on bottom, side and top.

### PROCEDURE

For each specific gravity determination fill 3 perforated ointment cans with loose mix from a truck or the paver hopper. Place lids on the cans and allow to cool to atmospheric temperature.

After cooling, the cans filled with loose mix are weighed to the nearest ⅒ gram. The weight of the cans, having been previously determined, is subtracted from the weight of the can and mix to give the weight of the mix.

A can filled with mix is then placed in the sample chamber of the volumeter with inserts to fill the chamber. The sample chamber is then closed and pressurized to approximately 41 inches on the mercury pressure gauge. At the end of one minute the pressure in the sample chamber is bled off until the mercury pressure gauge reads exactly 40 inches. The valve to the secondary chamber on the volumeter is then partially opened and the pressure between the sample chamber and the second-

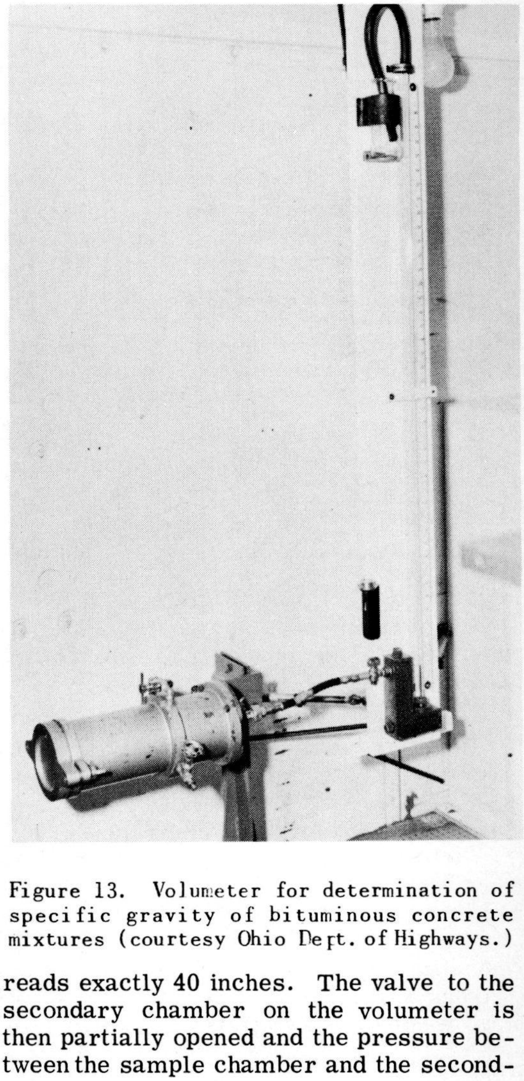


Figure 13. Volumeter for determination of specific gravity of bituminous concrete mixtures (courtesy Ohio Dept. of Highways.)

*The volumeter is calibrated with the use of 4 inch diameter inserts of known volume in sufficiently small increments of volume that a smooth curve results. From the calibration curve a table is prepared for volumes corresponding to gauge readings. In use, a greater degree of accuracy is obtained, if the sample chamber is filled with inserts after sample has been placed in the chamber.

ary chamber allowed to equalize and then the valve is entirely opened.

After one minute the pressure gauge is read and the volume of can and mix is read from the table prepared from a calibration curve *. The volume of the can, which has been previously determined, is subtracted from the volume of the can and mix giving the volume of the mix.

The weight of the mix in grams is divided by the volume of the mix in cc giving the specific gravity of the mix. The average of the 3 specific gravities so determined is the value used.

# Appendix H

## *Skid Resistance of Bituminous Pavements*

SHREVE CLARK and A. B. CORNTHWAITE,
Virginia Department of Highways

The degree of slipperiness of a road surface is a matter of grave concern to everyone as it so often is the cause of collision, upset, and other accidents resulting in death and property damage. To decrease this cause of destruction to the absolute minimum should be the aim of all those engaged in the design, construction, and maintenance of our highways.

One characteristic common to all high types of pavement, either bituminous or cement concrete, lies in some coefficient of friction between the surface and the tires of a moving vehicle. The magnitude of this coefficient is demonstrated in the tendency of a vehicle to slide or skid on deceleration or stopping suddenly, during which period the wheels are locked and unable to turn.

As side slippage and spin are caused by factors other than the condition or character of the surface material, they will not be referred to further.

The degree of slipperiness of a road surface can be most easily and simply determined by the distance it takes a car to stop after suddenly applying the brakes to a point where the wheels cannot turn, or are locked.

By using an indicator to mark the pavement at the point at which the brakes are applied, the distance of the forward movement of the car in a straight line skid can be measured quite accurately. By this simple means, the relative slipperiness of the different types of surface may be determined.

Moyer (A) initially, and by means of rather complicated apparatus, made an exhaustive study of the coefficient of friction between rubber tires and various types of road surfaces.

Shelburne and Sheppe (B), using a standard light car equipped with a chalk gun, connected with the break pedal, determined the relative skid resistance of thirty-two pavement surfaces, involving more than a thousand measurements. Nineteen of these surfaces were Virginia standard bituminous plant mixes consisting of eleven with fine graded and eight with coarse graded aggregates. The distance the car skidded forward was determined, at speeds of ten, twenty, thirty, and forty miles per hour by measuring the distance from the chalk mark on the pavement to the projected location of the gun attached to the running board of the car.

In this work the driver reaction time was not considered, but it is an important factor in the overall stopping distance. For example, at forty miles an hour a vehicle travels 59 feet per second, which when added to the AASHO maximum safe stopping distance of 113 feet at this speed means a total distance of 172 feet will possibly be covered from the point at which the impulse to stop originated and the vehicle's final stopping point.

The overall results of these skidding tests verified Moyer's (A) conclusions and those of other investigators (C).

### TEXTURE

Surface texture is controlled by the grading and maximum size of particles of aggregate in the bituminous mixtures. The shape of the larger particles may also be a contributing factor.

If it had been possible to test fine graded and coarse graded mixes made from the same materials, a better appraisal of the influence of surface texture might have been made. But even then, the shape of the pieces of the large aggregate might have been entirely different from those of the fine aggregate. Although it generally is considered that the fine graded material, which gives a so called "sand paper" finish to the surface, is the most non-skid of all bituminous surfaces, Virginia's experience does not bear this out in every case. Coarser mixes, in many cases, gave equally good results. There are too many modifying factors to consider that the influence of a fine texture is more than a generalization.

## PARTICLE SHAPE

Wholly irregular particles of aggregate give the greatest degree of skid resistance. If the larger particles, especially, have one or more flattened sides which, under rolling, orient themselves parallel to the surface, a lowered resistance to skidding ensues. When the bituminous coating is worn off, the slipperiness of the surface, especially when wet, is increased greatly, and, if the stone is of a type that will polish easily, such as marble, dolomite and many granites, the surface becomes dangerous.

One factor apparently influencing the slipperiness of a bituminous concrete surface is the toughness or abrasion resistance of the stone (B). Analysis of skidding data indicates that slipperiness increases with the Los Angeles abrasion loss. Just why this is so is not evident. As a matter of fact, from past practical experience, many of our harder limestone aggregates have always been considered as making slippery pavements.

## EXCESS ASPHALT

Should an excess of asphalt occur on the pavement surface, it is certain that a low resistance to skidding will result. There are two main causes for such a condition, commonly known as a "fat" surface. One is the ascension of asphalt from the bottom of the bituminous pavement to the surface, due to stripping. The other is either due to the addition of too much asphalt for the void content of the mix or due to a breakdown of the aggregate under heavy traffic loads, which reduces the original percent of voids. Mixes should be made of the hardest and toughest aggregate available and designed for not less than six percent voids, after rolling. There are several lesser causes of slickness, but they are only of importance when their effects are additive.

Although the above mentioned factors are the chief causes of skidding and are due to the design and materials involved in the making of a dense hot mix bituminous surface, there are many contributing causes apart from the surface itself. The presence of varying quantities of water on the surface, the material from which the tire treads are made, the smoothness of the tread, the condition of the car brakes, a high crown of the road, and many other factors contribute to the degree and character of the skid.

As a generalization from the results of many skid tests made on fine and course graded asphaltic concrete, it may be assumed that, in respect to surface condition, the best design for the minimizing of skidding tendency, should include the following factors: (1) A fine-graded aggregate should be used. By fine graded is meant a well graded sand or crushed stone having a maximum size of ¼ inch or ⅜ inch. (2) The use of irregularly shaped particles having a minimum of flat faces, and of a nonpolishing texture or type. When a coarse graded mix is used, this requirement becomes of very great importance. (3) The best available aggregate, having a Los Angeles abrasion loss of preferably less than 40. (4) As high a void content in place as is compatible with water proofness, preferably between 5 and 10 percent. (5) The void content of the finished surface should not be less than one fourth the bitumen content, by volume. (6) Either the use of a combination of aggregate and bitumen which will not separate from each other in the presence of water or water vapor, or the construction of an impermeable surface.

### REFERENCES

A. Moyer, R A. "Skidding Characteristics of Automobile Tires on Roadway Surfaces and Their Relationship to Highway Safety", Bulletin 120, Iowa Experiment Station, Iowa, Aug. 8, 1934

B. Shelburne, T E., and Sheppe, R. L. "Skid Resistance Measurements of Virginia Pavements", Research Report No. 5-B, Highway Research Board, April, 1948

C. Technical Report No. 39-5 "Skid Resistance Characteristics of Oregon Pavement Surfaces", Oregon State Highway Department, December, 1939

## *Some H R B Publications Relating to Bituminous Materials And Flexible Pavements*

BULLETIN 80: FLEXIBLE-PAVEMENT DESIGN (1953) 15 pp. $.30
This Bulletin presents factual information on the main features of design methods currently in use by the various state highway departments for the thickness of flexible pavements.

BULLETIN 105: BITUMINOUS-PAVING MIXTURES: FUNDAMENTALS FOR DESIGN (1955) 45 pp. $.75

BIBLIOGRAPHY 9: RESISTANCE OF BITUMINOUS MATERIALS TO DETERIORATION CAUSED BY PHYSICAL AND CHEMICAL CHANGES (1951) 89 pp. (Mimeo.) $.75
Each reference listed in this publication is annotated and an author index is included. The foremost factors considered in selection of these references on deterioration were: volatilization, oxidation, action of water and light, and internal structure changes occuring with time.

BIBLIOGRAPHY 17: EFFECT OF WATER ON BITUMEN-AGGREGATE MIXTURES (1954) 45 pp. $.60
A comprehensive review and digest of available literature on the subject. An appendix is included on "Adhesion Tests of Bituminous Materials." This bibliography also contains an author index.

SPECIAL REPORT 18: THE WASHO ROAD TEST, PART 1: DESIGN, CONSTRUCTION AND TESTING PROCEDURES (1954) 121 pp. $2.25
This report includes a comprehensive description of the project, methods of test operation and instrumentation procedures. It summarizes all data in construction controls and related operations. This report will be followed by the final report, available in mid-summer 1955.

RESEARCH REPORT 7-B: SYMPOSIUM ON ASPHALT PAVING MIXTURES (1949) 115 pp. $1.80
The papers contained in this symposium are: Selection of Test Equipment; Laboratory Study of Asphalt Paving Mixtures; Asphalt Stability Test Section; Correlations of Laboratory and Field Data; Detailed Test Procedures for Design and Field Control of Asphalt Paving Mixtures; The Practical Application of the Design Method of Asphaltic Mixtures to Pavement; Design of Asphalt Mixes as Related to Other Features of Flexible Pavement Design.

RESEARCH REPORT 8-F: PREVENTION OF MOISTURE LOSS IN SOIL-CEMENT WITH BITUMINOUS MATERIALS (1949) 34 p. $.60
This publication includes the results of four field experiments conducted in Illinois, Kansas, Nebraska and Arkansas to evaluate the efficacy of bituminous cover materials in retaining moisture in soil-cement for seven days following construction.

RESEARCH REPORT 16-B: DESIGN OF FLEXIBLE PAVEMENTS (1954) 77 pp. $1.05
Includes the following papers: Triaxial Tests in Analysis of Flexible Pavements; Flexible Pavement Design as Revised for Heavy Traffic; Flexible-Pavement Design by the Group-Index Method; Modified CBR Flexible-Pavement Design; Designing Flexible-Pavements (Virginia); Flexible-Pavement Design Correlated with Road Performance. Five Discussions are also included.

CURRENT ROAD PROBLEMS 8-R (REVISED): THICKNESS OF FLEXIBLE PAVEMENTS (1949) 49 pp. $.45
This publication is devoted largely to empirical methods of design which are considered the most reliable for present practice.

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government designated by the President of the United States, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY-COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.