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MIXTURE DESIGN CONCEPTS, LABORATORY TESTS AND CONSTRUCTION GUIDES FOR OPEN GRADED BITUMINOUS OVERLAYS

in cooperation with the
Department of Transportation
Federal Highway Administration

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Field surveys were made in four districts of the Texas Highway Department where open-graded bituminous mixes have been placed as trial sections and/or contract jobs. Data collected include a) freeze-thaw of field cores, b) Mays Ride Meter measurements, c) texture measurements by two methods, d) water outflow measurements, e) frictional performance, f) construction guides and g) types of expected or observed distress with suggestions for remedial action.

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BY

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Research Report 36-1F

Plant Mix Seals--Mix Design and

Pilot Tests

Research Study 2-10-74-36

Sponsored by
Texas Highway Department
in Cooperation with
U. S. Department of Transportation
Federal Highway Administration

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PREFACE

The information contained herein was developed on Research Study 2-10-74-36 titled "Plant Mix Seals - Mix Design and Pilot Tests" in a cooperative study with the Texas Highway Department and the Federal Highway Administration.

The primary purpose of the study was to develop a mixture design procedure for open graded bituminous mixes which would permit adequate drainage of the tire-pavement interface and be essentially non-skid for prolonged periods of time under heavy traffic.

Time and funding allocated to the study allowed only limited developmental work and restricted laboratory tests. Nevertheless a design procedure is recommended together with construction guidelines.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

ACKNOWLEDGEMENTS

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ABSTRACT

A review of the literature together with field experience gained in Texas has resulted in a modification of the Federal Highway Administration design method for open-graded asphalt friction courses. The extension of this procedure involved the development of design curves for synthetic aggregate mixtures over a range of air void contents.

Field surveys were made in four districts of the Texas Highway Department where open-graded bituminous mixes have been placed as trial sections and/or contract jobs. Data collected include a) freeze-thaw of field cores, b) Mays Ride Meter measurements, c) texture measurements by two methods, d) water outflow measurements, e) frictional performance, f) construction guides and g) types of expected or observed distress with suggestions for remedial action.

KEY WORDS

Bituminous mixtures, open-graded, surface course, friction, performance, design, construction.

SUMMARY

The laboratory design of open-graded bituminous mixtures to be used as thin overlays has been the subject of several studies in recent years as this type surfacing offers promise for improved safety on the nations' highways. A review of these studies together with field experience gained in Texas has resulted in a modification of the Federal Highway Administration design method for open-graded asphalt friction courses. Design curves are included in the report which allow for the utilization of aggregates of a wide specific gravity range (synthetic or lightweight aggregates) and air void contents of 15, 20 and 25 percent.

Construction guidelines and performance trends of open-graded bituminous mixtures placed in Texas are reviewed in the report. Construction problems created by water absorption of the aggregates are discussed in considerable detail together with problems associated with crusting, application of tack coat, patching flaws, compaction, laydown and paving intersections.

Performance of this type of surface course in Texas has not been successful in all cases. The infiltration of water into the subgrade accelerated by the presence of these permeable mixtures has resulted in early pavement distress at some locations.

Field surveys were made in five districts of the Texas Highway Department. Data collected included freeze-thaw of field cores, road roughness measurements, surface texture measurements by two methods, permeability as measured by a water outflow method and frictional performance.

IMPLEMENTATION STATEMENT

Material is included in the report which allows the engineer to design an open-graded plant mix seal. Construction guidelines are also included together with observations made during service of plant mix seals placed on Texas highways. These guidelines and observed pavement performance trends serve as background for the engineer to properly select the location for placing plant mix seals and properly construct a smooth riding, high friction, free draining surface course.

A proposed freeze-thaw test for plant mix seal has been developed. It is suggested that a wider range of materials be tested prior to the development of a specification.

An implementation report should be prepared summarizing design, construction and performance information contained in this report together with a copy of Appendix A.

The proper design and construction of open-graded plant mix seals should result in the reduction of accidents while improving aesthetics somewhat. Increase in pavement maintenance costs due to the placement of plant mix seals is a real possibility and should be adequately considered in the overall economics of the use of this type of overlay.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Background

The operation of high-speed rubber-tired vehicles on wet pavements can create a hazardous phenomenon known as hydroplaning. The basic causative factor of hydroplaning is a film of water on the pavement that causes loss of contact between the tire and the pavement surface. The result is loss of directional control and braking capability for the vehicle.

During periods of rain, water tends to stand on the surface of conventional pavements. Because this fact furnishes the "film of water" necessary to cause partial hydroplaning (which, in turn, is a major cause of accidents), some method must be used to remove the water from the surface. One method that has been used with good success is the so-called "Plant-Mix Seal Coat"; variously called "porous friction course", "open- or gap-graded mix", "popcorn mix", and others. This kind of asphalt surfacing is an open-graded, high-void bituminous mixture that can be placed on existing pavement surfaces in thin layers (nominally 3/4 in.). Because of the high void content, water that falls onto the surface drains directly down into the porous surface course, thus allowing the relatively rough surface texture to provide the tire-aggregate contact necessary for control and maneuverability of a vehicle.

This type of asphalt surfacing has been used by several different agencies at various times and under certain conditions since the early 1950's (1,2). Much operational success has been reported, but there have been several different "mix design methods" employed, and no one method has met with complete success or acceptance (2-16).

Besides the anti-hydroplaning and high skid resistance characteristi already mentioned, Eager (8) lists the following advantages of plant-mix seals:

1. No loose stones
2. Smooth, quiet riding surface
3. Pleasing appearance
4. Good durability
5. Reasonable costs
6. Some structural improvement to existing pavement

Additional advantages listed by Smith, et al. (16), of the Federal Highway Administration are:

1. Minimum quantity of aggregate
2. Reduced splash and spray from tires
3. Thin lift for grade control
4. Longer life of pavement striping

The validity of these advantages are discussed in this report based on laboratory and field testing, field performance studies, contractor-author discussions and consultation with Texas Highway Department personn directly involved with design and construction of these open-graded mixtures.

Objectives

The objectives of this Type B study were to develop materials selection, mixture design and construction guidelines for plant-mixed seal (open-graded hot mix) which will provide long lasting, skid resistant surfaces with adequate long lasting drainage.

Scope

A three-element investigation has been performed under this contract. First, a literature survey was conducted to review the available information concerning plant-mix seals. This was done with emphasis placed on the various design methods and specifications. The second element was a laboratory study, the purposes of which were to determine which of the design methods exhibit the most promise as an accepted standard and to determine some of the durability characteristics of several mixes that have been used on Texas highways. In particular, the effects of freezing and thawing of water in the porous surfacing were investigated. Thirdly, field observations were made of several in-place plant-mix seals in Texas Highway Department Districts 2, 11, 17, 19 and 20. The entire program was designed to provide information for material characterization, design procedures, and construction guides.

LITERATURE SURVEY

A number of states (1-8 and 11-16) have designed and constructed open-graded surface courses. The use of bituminous plant-mix seals in the U.S. began in four western states (1). Eager (8) reported on results of tests in Colorado, Wyoming, Utah, and New Mexico. This type of surfacing has also been used rather extensively in Europe (particularly in England and Germany) for airfield pavements (9,17).

A type of plant-mix seal, utilizing asbestos fibers in the mix has been used on highways in Germany (18) and Canada (19). A similar mix has been used in a few states, mostly in the northern part of the U.S. (20, 21). Even though this type of mix is gap- or open-graded, it is designed such that the void content and permeability are low. The voids are mostly filled with asphalt and asbestos fibers. Thus, this mix is not necessarily used to improve friction or to reduce hydroplaning.

Although plant-mix seals possess the advantages listed in the introduction, the literature also reveals that there are some problems in design, construction and performance.

Design

The major design consideration that creates problems (16) appears to be the method used to determine the percentage of asphalt cement to be used. The amount has previously been selected by conducting a series of asphalt "drainage" tests on several trial mixtures at various percentages of asphalt. The aspect that causes this method to be questionab is that the drainage test temperature is made the controlling factor rather than the properties of the material constituents or of the resulting mixture. The temperature specified by various mix design methods varies between placing temperatures as low as 160°F to as high as 280°F.

The selection of the asphalt content by "engineering judgment" based on either drainage tests or mechanical tests is quite risky. It is still very possible that the mix will contain too little asphalt (which could cause ravelling) or too much asphalt (which could result in flushing) (16). The Marshall and Hveem procedures are not applicable because it has been found that stability and flow of these mixes are insensitive to variations in asphalt content (16). Other approaches utilizing dynamic tests are not immediately implementable.

Another critical design factor is aggregate gradation. The gradation influences the amount of internal and surface voids of the mixture, the surface rugosity, resistance to densification, and surface area of the aggregate (which, in turn, influences the asphalt demand, and hence the amount of asphalt cement) (16). Existing design methods attempt to consider these aggregate factors. The definition of the potential polishing susceptibility of the aggregate must also be adequately considered in the design method.

While the actual details of the various mix design procedures have not been discussed as yet, they will be described later in the appropriate places and their impact on or importance to the mix design procedures recommended by this report will be discussed. A limited summary of specifications used by several states and other agencies is given in Table 1 (1,2,4,5,6,7,9,12,15,16,22).

TABLE 1

Survey of State Practices

Item	North Carolina	FHWA Region 9 (Colorado, Wyoming, Utah and New Mexico)	FHWA Region 7 (California, Arizona, Nevada, Hawaii)	Franklin Institute	Louisiana
Mix Designation	Bituminous Seal Coat	Open Graded Plant Mix Seal	Plant Mix Seal Coats	Open Graded Asphalt Concrete	Plant Mix Seal
Aggregate Type	95% of material retained on No. 4 have at least one fractured face. Percent wear 45% or less (AASHO T96)	Hard, durable, resistance to abrasion and stripping, sharp angular and polish resistant. Minimum 75% crushed	Broken stone or crushed gravel with 90% by wt. having at least one fractured face.	Same as California specifications.	Crushed gravel, slag, or expanded clay. Max abrasion loss 45% (by LDH designation TR111) for expanded clay.
Aggregate Gradation	Sieve Size Percent Passing 1/2 100 3/8 90-100 #4 25-45 #10 0-10 #200 0-2	Sieve Size Percent Passing 1/2 100 3/8 95-100 #4 30-50 #8 10-25 #16 0-18 #200 0-5	Sieve Size Percent Passing 1/2 100 3/8 90-100 #4 30-50 #8 15-32 #16 0-15 #200 0-3	Sieve Size Percent Passing 1/2 100 3/8 90-100 #4 35-50 #8 15-32 #16 0-15 #200 0-3	Sieve Size Percent Passing 1/2 100 3/8 95-100 #4 30-55 #10 0-20 #40 0-12 #200 0-6
Approx. Cost per Ton *	$8.00 to $15.00	$7.00 to $10.00	$8.00 to $12.00	None specified	None specified
Asphalt Cement	60-70 penetration	60-70 penetration or 85-100 penetration	85-100 penetration	85-100 penetration	AC-40 (with 0.5% anti-stripping additive)
Asphalt Content (percent)	6 to 10 actual value fixed by engineer	6 to 7	5 to 7	4.0 to 5.5	Crushed gravel 4.0-10.0 Slag 6.0-12.0 Expanded clay 10.0-17.0
Aggregate and Asphalt Temp. (°F) at Mixing	250 maximum 300 maximum	260 to 300 260 to 300	290 290	--- ---	Mixing temp. of mix = 260° max.
Stability, Flow & Voids	None specified	Retained stability 50% min. by AASHO T165	None specified	Exceed criterion for medium traffic uses (10-100 DTN)	None specified
Remarks	Asphalt cement to contain 0.3% of: Nostrip Concentrate 380, Kling XX, Pave-bond 206, Kling HS-BETA-1000-3 or approved equal. No. 10 size aggregate limited to 10% to prevent bleeding.	Asphalt should be 200-300 centistokes at mixing temperature and ductility of 50 cm at 39°F. Stripping to be 95% retained coating (AASHO T182).	Specifications are for California. Arizona and Nevada have similar specifications. No plant mix seal coat placed in Hawaii. Require film stripping test - 95% retained coating.	Mix with 5.5% asphalt most durable. Resistance to stripping by water (ASTM D1664) to be more than 95%. If less, add antistripping agent.	Placement temperature ≥ 180°F min. Hauling in excess of 20 miles may cause separation. A maximum of 260°F most critical for good mix.

*Cost information 1965-1970.

Construction

Details of construction operations and their associated problems are not well documented in the literature. Detailed discussion will be included later in this report.

Performance

Because the aggregate is generally clean, uniformly-graded, and non-polishing, low-friction surfaces may result for the first one to three months of service (1). The cause of this is the heavy film of asphalt on the aggregate surfaces. When the thick film of asphalt exposed to the tire is oxidized or worn away, friction is restored. The high permeability of the mix effectively limits or prevents hydroplaning from the first. Gallaway (1) advocates the use of 8 to 15 percent of sharp sand-sized particles in the mix. This gives the surface good friction characteristics until the top film of asphalt is removed, exposing the coarse aggregate. Structural distress may be a problem wherein open-graded mixtures are placed on pavements with poor surface drainage, that is, pavements with ruts or depressions that do not normally drain freely. Other problems with performance based on experience gained in this study will be discussed in detail later in this report.

HISTORY OF OPEN-GRADED FRICTION COURSES IN TEXAS

The earliest experiments began in THD District 17 on FM 1687 near th west city limits of Bryan, Texas in the fall of 1968. These designs differed from subsequent designs primarily in final void content, binder film thickness and aggregate grading; yet, they would normally be classed as open-graded, since the in-service void contents were in the 15 to 18 percent range. This void range is in contrast with a range of 20 to 25 percent for subsequent designs placed in other districts of THD. Generally, the label used in Texas to identify these higher void content designs is "plant-mixed seals".

The next field experiment with plant mix seals was in District 11, on U.S. 59 north of Lufkin, Texas. Four trial sections of plant mixed se each containing a different aggregate were placed in 1971 on this highway. Subsequent plant mix seals have been placed by District 11 south of Lufkin on U.S. 59.

In 1973, District 2 placed plant mix seals on a trial basis at several locations on urban freeways near Fort Worth, Texas. These surfaces have been subjected to large volumes of traffic during the last year.

District 20 has placed plant mix seals with both a conventional hot mix process and with a "road mixing" process utilizing an emulsion. Thes pavements were constructed in 1974 north of Beaumont, Texas.

District 19 experience with plant mix seals dates from 1973. Blast furnace slag was utilized as the aggregate.

Field cores which have been subjected to a laboratory testing program have been obtained from most of these pavements. Field performance measurements have been made and detailed discussions held with those responsible for the design, construction and testing of these sections.

DESIGN

Based on a review of the literature and discussions with state and federal personnel as well as several consultants, the authors have concluded that the design procedure described by Smith, et al. (16), is probably the most reliable and logical method available at this time.

The method in its originally published form omits a correction for lightweight and/or highly absorptive aggregates. Subsequent to the publication of the design procedure, Smith (16) has developed a table of correction factors which may be used in conjunction with original procedure. Use of the corrections listed in the table yields what appears to be acceptable asphalt contents for aggregates of different apparent specific gravities.

This mixture design procedure is recommended for general use by those interested in successfully placing open-graded mixtures of this type. A copy of the design procedure appears in Appendix A. The recommended corrections for lightweight and absorptive aggregates as developed by Smith (23) are contained in Appendix B. Design charts for aggregates of various specific gravities developed in this study and based on the design procedure from reference 16 are included in Appendix A. A summary of the information contained in Appendix A is included below.

Aggregate Requirements

Those materials requirements detailed in Items 1.1 through 1.3 of Appendix A are recommended with the following exceptions.

It is recommended that a polish value (Test Method Tex-438-A) of not less than 35 be required for traffic volumes $\leq$ 4,000 vehicles per day per lane. For traffic volumes above this value, a polish value of not less than 40 is recommended. For the higher volumes of traffic AC-20 asphalt should be substituted for the AC-10 grade.

If the No. 10 sieve is used as the separation point between the coarse and fine aggregate the recommended grading would become

Sieve Size	Passing Percent
1/2 - inch	100
3/8 - inch	90-100
No. 4	40-60
No. 10	3-12
No. 200	0-5

The coarse and fine aggregates should be tested for specification compliances. And following this the bulk specific gravities of the coarse and fine aggregates are determined.* Measure the dry rodded unit weight of the coarse and fine aggregates using an accepted standard procedure.

Asphalt Requirements

From the gradings, select a combination of coarse and fine aggregates that will meet the grading requirements of the specification and determine the surface capacity of the aggregate by the oil equivalent test. The asphalt content is then determined together with the amount of fine aggregate. Both AC-10 and AC-20 asphalt cement have been successfully used in Texas.

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* If the entire aggregate is of the same type and is supplied pregraded to meet the grading requirements, single determinations will suffice for both the specific gravity and the unit weight.

If it is assumed that construction procedures are properly executed, the resulting mixture will have a performance void content which is related to the amount and type of traffic on the road. This performance void content will be significantly lower than the calculated void content based on the combined solid volumes of the aggregate and asphalt in the mixture but should be in range of 15 to 25 percent.

Observations in the field indicate that the major variables which input to the performance void content are, in addition to traffic, aggregate physical properties such as particle shape, surface texture and resistance to degradation, amount and viscosity of the binder and environmental conditions.

Design Considerations

The field performance characteristics of those mixtures placed thus far on Texas highways together with related literature have illustrated the importance of several items which should adequately be considered in design. These factors include unit weight, film thickness, and temperatu considerations, compaction problems, polish susceptibility, surface texture, particle shape, degradation, densification, mixture problems and binder absorption.

Unit Weight--Since the mating of the tire with the road surface is an are to-area concept with the volume of the friction controlling aggregate a predominate factor, the unit weight of the aggregate per se is not critical and within limits practically unimportant. What is important is difference in unit weights of aggregates if the designer uses weight percent in arriving at the design binder content.

One approach to avoid the design problem of differences in unit weights is to use a volume concept for determining appropriate binder contents, such as that developed in Reference 16. An alternate approach would be to arrive at a design binder content through the use of a film thickness procedure.

Film Thickness and Temperature Considerations--From a theoretical design standpoint, film thickness requirements for plant mix seals should be within a narrow range. Calculations based on existing surface area factors which ignore aggregate surface texture and shape do not confirm this anticipated result. Thus the importance of film thickness can only be discussed on a qualitative rather than quantitative basis.

Film thicknesses determined from laboratory test procedure may be quite different from those existing on the constructed pavement. Mixing, handling and placing temperature are some of the factors responsible for these differences. For a selected original binder viscosity no other factor is of greater importance than temperature control up to the point where the material reaches the road surface and thus the laboratory procedure should adequately consider field temperature control limitations.

Texas' practice in this vital area varies and for different reasons. It would appear that, for a selected binder of known temperature susceptibility, optimum operating temperature would cover a rather narrow range. This, however, has not been the authors' observations on the several jobs constructed in Texas to date.

Several factors input or limit temperature. These factors include environmental conditions, moisture content of the coarse aggregate as the mix falls into the haul unit, aggregate textural characteristics, siz and shape of the haul unit beds and time delay from plant to road surface Even the thickness of the lift being placed may be a factor, except that generally lift thickness is less than one inch and, where this is the case, variation in such thin lifts is relatively unimportant.

Polish Susceptibility--The current practice in Texas is to select aggrega with relatively high polish values for use in plant-mixed seals. Example of such aggregates are shown in Figures 1a to 1d. When such aggregates predominate in the surface of the mat and can freely contact the rubber tire surface, high skid values usually result. If, however, the gritty nature of the aggregate is clouded by a heavy film of binder, much less friction is developed. Whether or not sufficient friction is available depends on service demands. One may, however, ask if the margin of safety provided in the early service life of such surfaces is wide enough Should surfaces of this type be expected to deliver high skid numbers immediately, or can we tolerate the delay in friction build-up?

Generally the answer in Texas has been that the friction immediately available on plant-mixed seals built so far has been adequate, although many have been lower than the designers expected. Possibly these are advantages to this gradual change from low to high friction.

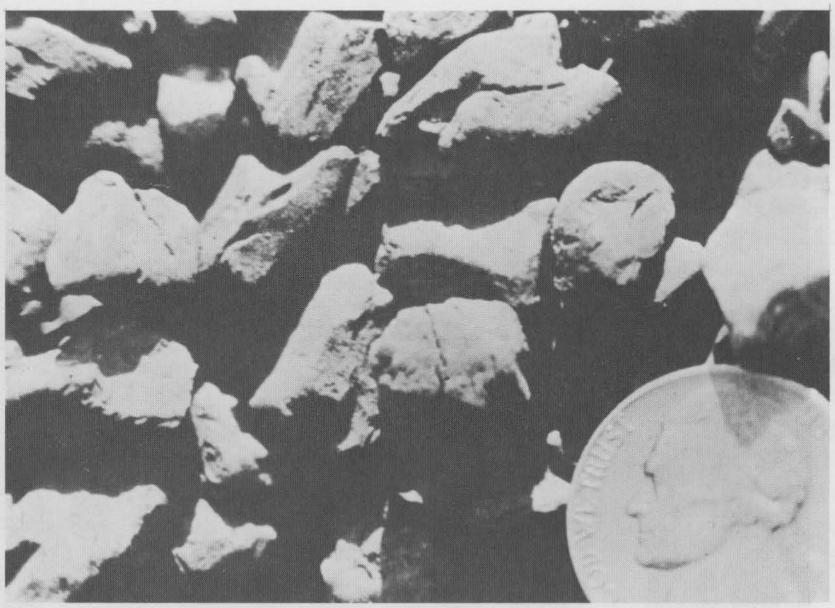
Surface Texture--Surface texture is an important physical parameter inputting strongly to friction development whenever it comes into play. It is also a factor in determining binder content at the design stage.

(a)

(b)

Figure 1. Typical aggregates of high polish value.

(c)



(d)

Figure 1 (continued).

Field observations indicate that particle surface texture affects the operating temperature with the more textured aggregates permitting wider ranges of operating temperatures. Binder run-off is less (for a fixed viscosity) for the more textured materials. Adequate texture is quite desirable but it does present at least one disadvantage.

Under optimum design and construction conditions textured aggregates will retain a heavy film of binder even on those particles at the surface of the pavement and this can contribute to delayed development of the desired level of friction. Indeed, one may build a low friction pavement in this manner, one that persists for weeks to months before the binder film is oxidized and/or worn away by traffic. Field observations and data presented in this report lend credence to this claim.

Particle Shape--Particle shape is a prime factor in determining the ultimate densification of open-graded mixtures under traffic. Crushed aggregates containing flat and elongated particles are offenders of the first order. Blocky, subrounded and rounded particles resist densification under traffic and therefore are more likely to remain open and free draining even under heavy traffic and hot weather.

Degradation--Although proof is lacking in the form of data from Texas' field trials, it is reasonable to believe that aggregate crushing does occur during construction and continues on a diminishing scale during service. The rate at which this crushing takes place and the degree of effect on the void content of the in-place mat can be critical. It can be theorized with reasonable confidence that aggregates of certain physical properties will crush more readily than others. For a given materia and grading subject to median traffic, crushing will be a function of stress at points of contact in the mat. If these points of contact are few, the stress level will be high and conversely, if the points are many, the stress level will be lower. Therefore, an avenue of approach to minimize damage in the form of loss of adequate voids and possible flushing of the surface would be to increase the number of contact point This can be accomplished by a) reducing the top size of the aggregate, b) changing the particle shape, c) keeping the top size fixed and adding some intermediate sized material (a chocking action), d) alter the construction compaction techniques to improve nesting of the aggregates, or increase the design air void content. An increase in binder viscosit might also be helpful.

Densification

Excessive densification in the field has been observed in some trial sections that have been in service for more than three years under medium heavy traffic. In part, at least, this type distress may be attributed to aggregate crushing or degradation. Particle shape is a definite factor in one section. Whether or not sections showing this type distress adequately perform their intended purpose is not clear, because the current survey method of determining a "standard" skid numbe does not take into account pavement performance on surfaces with water depths in excess of about 0.02 inches, nor does the usual test include the effect of speed. Field observations, however, do indicate a change in the water infiltration rate and in some cases the SN_{40} may be considered marginal. The reader is referred to the section of this report which deals with SN data taken on the trial sections.

Shown in Figure 2 are experimental sections of open-graded hot mix placed on FM 1687 in Brazos County. The right lane with approximately 24 percent voids is completely free draining during a rainfall intensity of 1/4-inch per hour. The adjoining lane with about 15 percent voids is only marginally free draining. One might speculate that normal tire contact pressures would eliminate the water film in evidence, at least for nominal speeds.

Although not a planned part of this study, it would seem advisable to consider field tests which might similate the real world problems associated with inundation of the surface macrotexture and loss of voids designed into the mix for water escape at the tire-pavement interface.

The magnitude of the effect of speed on SN may be considered a variable, which in this case, can be related to drainage efficiency at different rainfall intensities. Since this was not a part of the objectives of the study it is not treated here.

Absorption and Moisture Problems--Aggregates used in many of these Texas trial sections are manufactured synthetic materials of low unit weight. Water absorption capacities of these materials range from about 10 to 30 percent and for hot mix operations one might conclude that, since the

Figure 2. Photographed during rain of about ½-inch per hour: Right lane completely free draining, left lane partially flooded.

aggregate is dried before being coated with the hot asphalt cement, the absorption capacity would not enter the performance picture. Moderate reflection on this point will indicate otherwise.

As discussed in detail in another section of this report, aggregates of this type which enter the dryer with considerable water of absorption may leave the dryer and, indeed, reach the road surface with some water remaining in the larger particles. The presence of this moisture may be conducive to early distress of the surface. Such distress may take the form of raveling. Additionally, such aggregates that readily absorb large amounts of water may present freeze-thaw problems. In another section of this report will be found laboratory data and discussions which deal with freeze-thaw tests made on or taken from numerous trial sections that have service records which range from a few months to more than three years. It will be noted from these data that aggregates selected for use in these trial sections present only very minor problems that can be attributed to freeze-thaw damage.

Binder Absorption--So far, water absorption capacity has been discussed without relating this to asphalt or binder absorption. From unpublished studies made by Gandhi (24) on lightweight aggregates from seven sources, there is an indication that asphalt absorption is roughly two percent by dry weight of the aggregate irrespective of the source. These tests were made on materials graded from 3/8-inch to No. 10 size and involved a single source AC-10 asphalt cement. The asphalt-aggregate mixture was held at a constant temperature of 250°F for a period of three hours and the amount of absorbed binder was determined using ASTM Designation D2041 "Standard Method of Tests for Maximum Specific Gravity of

Bituminous Paving Mixtures" (25). Aggregates used in these tests were oven dried to constant weight. Less asphalt absorption would be expected if absorbed water were present. Data are shown in Table 2. A second method of treatment involved holding the mixture at 250°F for one hour then at 140°F for 24 hours, and this resulted in approximately the same amount of absorption. Possibly the three hour treatment at 250°F is more nearly representative of field conditions if the aggregate is assumed to be dry. The 3-day water absorption values for these aggregates are all included and according to these data there is no apparent relationship between asphalt and water absorption values; however, the combined effect of active water release and asphalt absorption is another "ball game." In most operations involving absorptive aggregates moisture is being released continuously from the time the aggregate leaves the dryer until th roller hits it on the road. This moisture release may allow very little asphalt to be absorbed by the aggregate - surely much less than indicated in Table 2.

The absorption capacity of most of these aggregates is greater than that listed for three days soaking but the 3-day value is considered representative of what would occur under average field conditions.

The field problems relatable to water and/or binder absorption are different from laboratory problems and some discussions of these are in order and are dealt with later in the report.

A Texas Highway Department Specification for Plant Mix Seal Coat is included in Appendix C.

TABLE 2

Asphalt Absorption Values for Lightweight Aggregates from Different Sources

(ASTM D2041, Rice's Method)

Source of Lightweight Aggregate in the Mix	Dry Bulk Specific Gravity	Absorption % by Weight of Aggregate in the Mix (Graded 3/8" - No. 10)		3-day Water Absorption percent
		Mix Cured for 3 hrs. @ 250°F	Mix Cured for 1 hr.@ 250°F+20 hrs. @140°F	
A	1.50	3.1	2.4	9.7
B	1.17	1.8	2.2	27.0
C	1.10	2.6	2.2	16.4
D	1.62	0.2	0.1	6.7
E	1.44	2.8	2.6	11.5
F	1.45	2.8	2.0	21.0
G	1.48	2.8	3.2	17.3

CONSTRUCTION

Once an adequate mix design has been achieved through laboratory evaluations and subsequent adjustments for a suitable job mix formula, attention should be directed to those factors which input to the successful application of the material on the road surface. Since the thermal characteristics and absorption of natural aggregates of average unit weight differ from natural or manufactured aggregates classed as lightweight, the two groups of materials will be discussed separately.

Lightweight Aggregates

The physical properties of most manufactured lightweight aggregates are quite similar and are characterized by high water absorption capacities and considerable particle surface texture. In the laboratory one will be concerned with aggregate surface texture, grading and absorption in trials to determine binder content.

Moisture Absorption

Two factors come into play at the hot mix plant. One factor is, of course, the amount of absorbed water present in the aggregate as it enters the dryer. The other is the rate at which the absorbed water leaves the aggregate. Free water contained in the lightweight aggregate stockpile will not differ in evaporation rate from free water contained on natural aggregates (from the viewpoint of ease of removal). Hence, this aspect of the drying problem will not be dealt with any further at this point in the discussion.

The amount of absorbed water that may be contained in lightweight aggregates manufactured in Texas vary but fall in the general range of

10 to 30 percent based on the dry weight of the aggregate sized in the range of 3/8-inch to No. 10 sieve size material (see Table 2). The values quoted are for the 3-day absorption; the amount in question that may not have its absorption capacity fully satisfied. The condition that may exist in the stockpile is a function of the exposure of the material to the environment. Stockpiles in the Gulf Coast area of Texas are more likely to be wet than those in the more arid western part of the state; however, moisture problems have been experienced in all areas of the state.

Under a given set of operating conditions aggregate passing through a hot mix plant is exposed to drying a fixed amount of time; consequently, aggregates with a given amount (number of pounds) of water will be dried to a degree dependent, to a large extent, on the rate at which the absorbed water is released. Aggregates which are slow in taking on absorbed water may be expected to release this water more slowly. Hence, if two aggregates of essentially the same grading contain the same amount of absorbed water but one accepts absorbed water quickly compared to the other, it will likewise release water in the dryer more quickly. The net result of this operational effect will be revealed in the handling and placing properties of the mix.

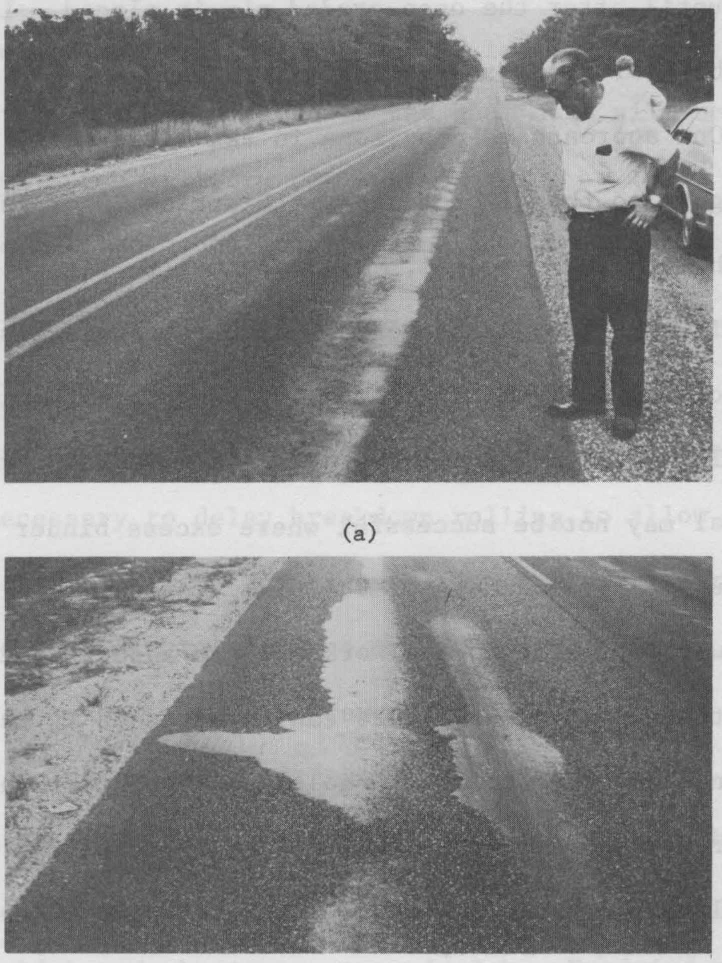
Let us now compare the handling and placing properties of these mixes as affected by differences in water release rates. At this point it is assumed that in the case of the quick water release material drying has been sufficiently effective to produce a mix at the laydown site that has no moisture problems. Such a mix may, in fact, contain more than one percent water as it leaves the laydown machine. The other mix consisting of an aggregate that releases absorbed water more slowly may present handling and placing problems. Aggregates in this mix will quite likely release appreciable moisture after it has been dropped into the haul unit and moisture in significant amounts may continue to be released through the breakdown rolling processes. Evidence of this delayed release of water will be apparent to an experienced observer.

Such a mix when dumped into the haul unit will be almost fluid. That is, instead of the normal angle of repose in the haul unit the dumped material will flow much like high slump portland cement concrete. If the haul unit bed is filled, in-transit problems may result. A sudden stop or change in direction of the haul unit may cause overflowing. Uncontrolled flow from the truck may cause overflow of the hopper of the laydown machine.

If delivery of such a mix to the laydown machine is made without incident, placing may present no more than the usual problems. However, under conditions of continued release of appreciable moisture the breakdown roller should be held back to allow escape of the water; otherwise, an excess of binder may be brought to the surface of the mat. Should excess binder be deposited at the surface of the layer being placed, this will result in a low skid number even to the point of being hazardous. (See Figure 3.) Additionally, in areas where this occurs delamination of the layer placed (from the surface on which it is applied) is much more likely.

Identification of field distress modes creates a useful input to the data bank of successful placement of open-graded mixtures. The photographs presented in Figures 3 and 4 present two types of distress

Figure 3. Evidence of delayed moisture release during construction.



(a)

(b)

Figure 4. Flushed areas caused by fat spots in underlying pavement.

that result in the same damaging end effect, but each of these is caused in a different way. Figure 3 presents the typical effect of moisture in the mix at the time of placing the mat; whereas, Figure 4 shows an entirely different type of distress, one caused by pavement condition before the job began, namely, a flushed area of pavement. The moisture problem can be handled by altering plant operating procedures but the surface associated problem is not so easily managed and may not be evident until after the open-graded mix is placed. Let us now examine possible solutions to the latter problem.

One approach used by some in the field is to apply heated (350°F ±) aggregate to the flushed areas. District 20 of THD has used this approach with some success. One may note in Figure 3 the dull or darker area in the flushed patches. Heated aggregate has been rolled into the surface for improved friction. This approach will usually be successful for flushed areas caused by fat spots in the underlying area but in general may not be successful where excess binder has been brought to the surface by moisture at the time of placement. Immediately one may ask, why does the process work for one aspect of the problem and not for the other. Heated aggregate can be attached if there is sufficient depth of binder at the surface to hold the stone irrespective of how the binder arrived at the surface. Sufficient binder at the surface is a more likely probability where a thin overlay of open-graded mix is applie over a flushed pavement than it is where binder has been brought to the surface by moisture release immediately behind the laydown machine. Also plastic instability will exist for the former and be unlikely for the latter. A surface with plastic instability will accept hot aggregate under the action of a roller with relative ease.

What then is the nature of the moisture problems mentioned above and how may these problems be minimized or avoided? The problem is caused by the conversion of liquid water in the pore structure of the coarse aggregate to water vapor or steam after the aggregate particles are coated with a heavy film of binder. Sufficient pressure is developed to produce literally thousands of bubbles. These bubbles may be so numerous as to completely encapsulate most of the large aggregate particles. In effect, most of the entire load in the haul unit will be simply "floating on air". The batch will, in the extreme case, be quite fluid. Can this condition be tolerated and if not, what are the alternatives?

In many instances the delayed release of moisture - sufficient to cause a fluid condition - will not cause insurmountable problems. The mix can be transported, placed and compacted. As indicated previously, it may be necessary to delay breakdown rolling to allow escape of some of the moisture. Otherwise, normal operating procedures are in order. If trouble persists, other solutions are in order.

An ideal solution to the prevention of the problem is to maintain a supply of relatively dry aggregate in the stockpile. Predrying offers one alternative. Drying rates differ depending on weather conditions. It is more difficult to dry aggregates early in the morning when the humidity is high and the temperature is low. Predried material could be used in the early hours of the day and the plant operation could be phased into the regular stockpile at, say, 10 to 11 a.m. In slack periods aggregate can be predried and stockpiled for use the next day.

The use of silicone [36] in the binder has been found effective in minimizing the effects of moisture release in the time interval between the pug mill and the laying and rolling operations. Silicone is used at the rate of about 1.5 parts per million and serves to prevent the formation of vapor bubbles on the surface of the aggregate particles. Water vapor either condenses and may drain from the haul unit or it may eacape as vapor. High moisture mixtures containing silicone treated binder may be handled in much the same manner as moisture free mixtures.

The above described condition should not be confused with the distress shown in Figure 4 where flushing is in evidence but is caused by fat spots which existed in the pavement before the overlay of open-graded hot mix was placed. Here the total voids are filled with asphalt, whereas in the previous case an excess of binder exists only at the surface of the pavement.

The flushed areas caused by fat spots are subject to plastic instability. Distress traceable to plastic instability is shown in Figure 5. It is apparent that the mix design is not suited to the traffic demand at this location on the roadway. Generally, this surface would not be free draining.

A major problem caused by the delayed release of moisture is the associated cooling of the aggregate between the dryer and the pug mill and of the aggregate-binder mixture during mixing, dumping, transporting and placing.

Selected aggregates with low rates of moisture release may leave the dryer at 350°F, be at 260±°F when dumped into the haul unit and come out of the laydown machine at 200 to 220°F [27].

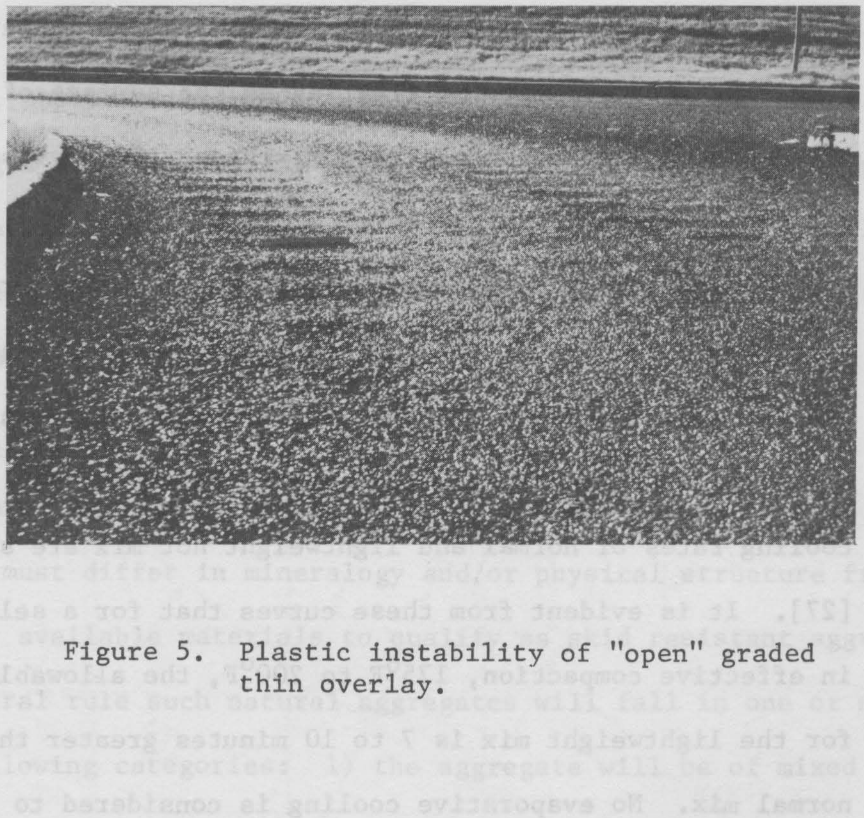


Figure 5. Plastic instability of "open" graded thin overlay.

In normal operations a mixture leaving the plant at 260°F would reach the road surface at about 245°F, the associated cooling being primarily attributable to losses by radiation and conduction. The use of insulated covers over the load will minimize heat losses and their use is advised in all cases where excessive cooling is a problem. In fact, the use of insulated covers is advised in all hot mix paving operations. This is not only an energy conservation measure but it also reduces the probability of crusting on the surface of the load, a problem often encountered in open-graded mixtures. Such crusting results in laydown and compaction problems.

The presence of an excess of water in the mixture may very well present other special problems. Difficulty may be encountered during the placing and compaction of thin lifts of such mixtures. Ease of placing and compaction is strongly temperature related [28]. Curves for the cooling rates of normal and lightweight hot mix are shown in Figure 6 [27]. It is evident from these curves that for a selected cut off point in effective compaction, 175°F to 200°F, the allowable compaction time for the lightweight mix is 7 to 10 minutes greater than that for the normal mix. No evaporative cooling is considered to take place. No correction has been made for unit weight differences in the two materials Such a correction would reduce the stated time extensions given above.

Detailed cessation requirements given in Reference 28 are based on a knowledge of

a) The rate at which the mat cools,

b) Establishment of a reasonable time for applying breakdown rolling and

c) The temperature below which breakdown rolling is not effective in producing compaction.

The data developed and field tested in Reference 28 are based on normal dense-graded hot mix and therefore cannot be used directly for open-graded friction courses. The two primary reasons for this are (a) the compactabilities of the two mixtures are not the same and (b) the heat capacity per unit volume of the open-graded mixture is less. Nevertheless, cessation requirements in Reference 28 can be used as guides. The data developed in Reference 27, part of which is presented in Figure 6, should be helpful to the contractor for construction planning. The lightweight mix curve in Figure 6 is for hot mix containing approximately 50 percent by weight lightweight aggregate. Such mixtures would contain about the same heat content per unit volume as open-graded mixtures made with normal weight aggregate.

Natural Aggregates

Natural aggregates of the type usually specified for high friction surfaces must differ in mineralogy and/or physical structure from generally available materials to qualify as skid resistant aggregates. As a general rule such natural aggregates will fall in one or more of the three following categories: 1) the aggregate will be of mixed mineralogy (composed of a mixture of hard and soft particles that wear at distinctly different rates), 2) the aggregate will granulate under the action of pneumatic tires and thus will not polish, and/or 3) the aggregate will contain discrete voids throughout the individual particle which furnish the required microtexture for friction development. Combinations of these may also exist. With the possible exception of the first mentioned type of aggregates such materials are generally absorptive. Absorption capacities in the two to four percent range are not uncommon.

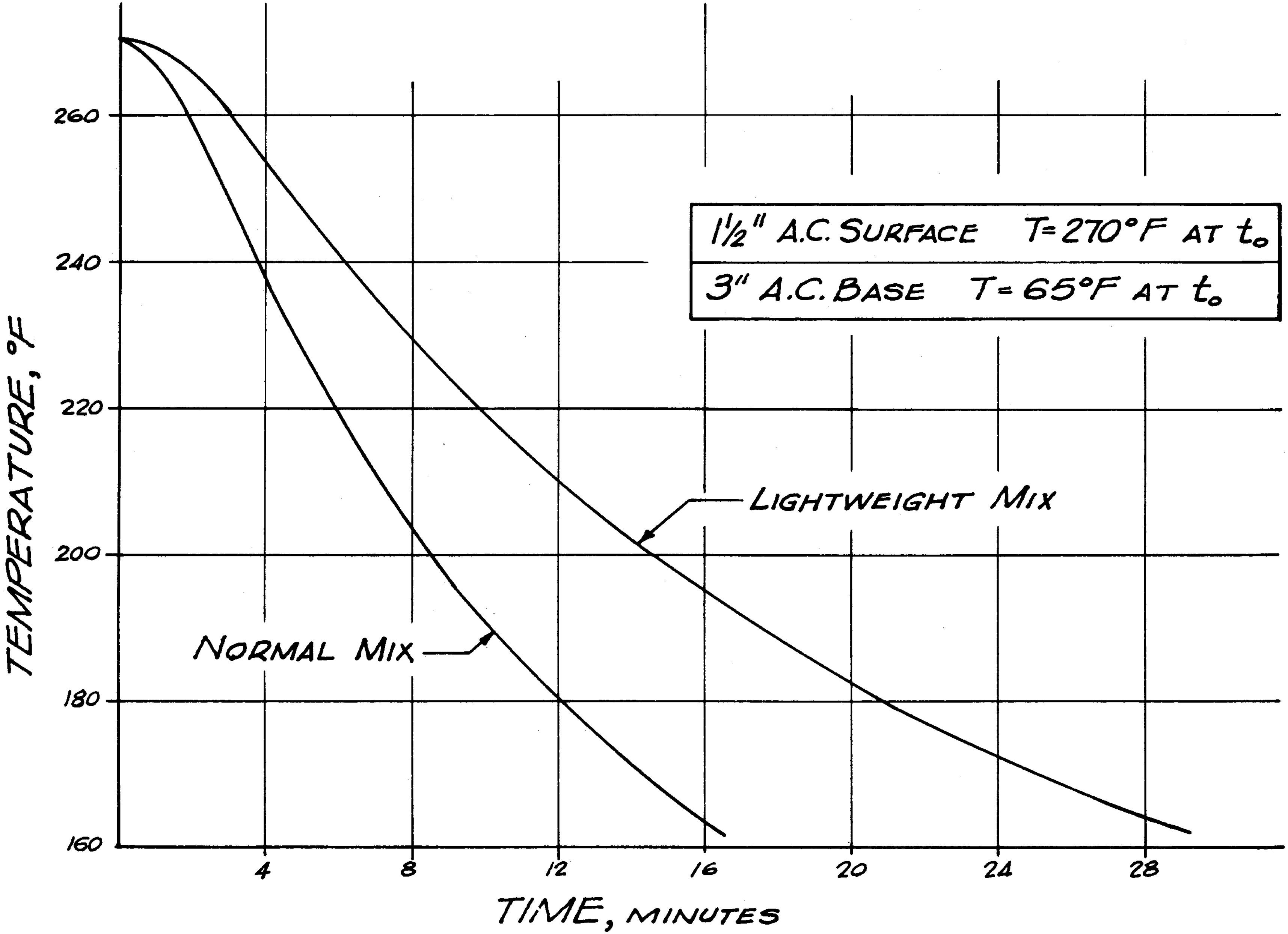


Figure 6. Cooling curves - normal & lightweight mixes (27).

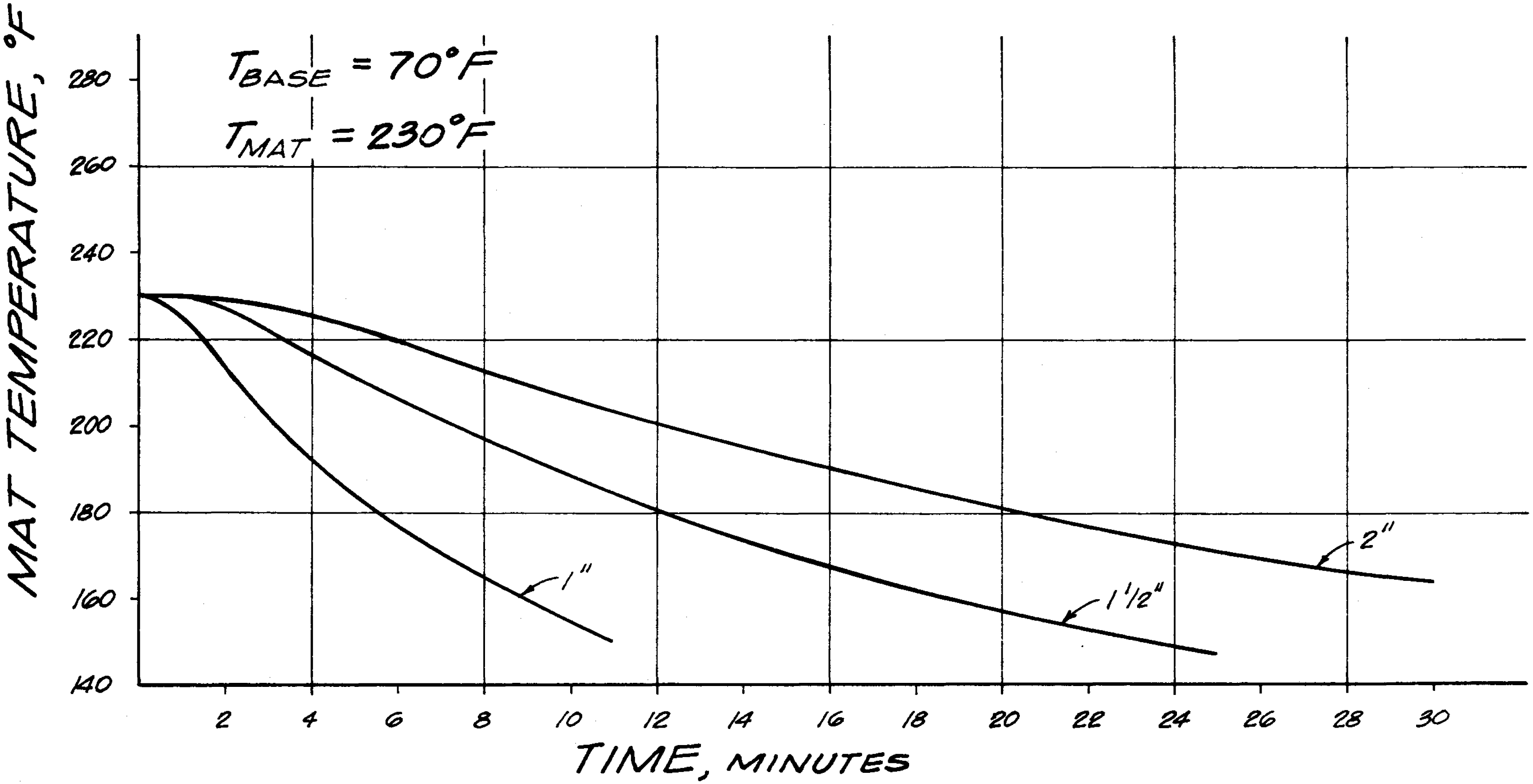


Figure 7. Cooling curves (27).

Again, large amounts of absorbed water can cause problems especially in those cases where the release rate is low. The problems with natural aggregates of the high absorption-low release rate type are no different from those previously discussed for manufactured materials. It may be only a matter of degree.

General Construction Problems

Features associated with the general operation of mixing, handling and placing open-graded bituminous friction courses differ somewhat from regular hot mix regardless of what type of aggregate is used. Selected items are discussed below.

Crusting. The problem of crusting on top of the load is more prevalent with open-graded mixtures. Evaporative cooling is a primary cause for this. The use of insulating covers for the haul units is mentioned elsewhere in the report as a means of minimizing the problem. Another version of this problem is that of caking in the corners of the truck beds where more rapid cooling takes place. Through efforts to solve another problem a solution to this problem was discovered Truck beds are easily cleaned by loading them with heated (350°F±) aggregate. The hot aggregate is dumped directly into the haul unit where it is allowed to remain for 15 to 20 minutes. When the hot aggregate is dumped, caked mix and residual binder slips from the truck.

To avoid the sticking problem some districts of THD allow the use of diesel as a spray in the truck bed but care must be exercised to see that all units are well drained before loading the mixture. At best, some trucks slip by and the excess solvent causes problems out on the road.

One district has solved this problem by using a hydrated lime slurry to coat the inside of the truck beds. The method is energy conservative, effective and no ill side effects have been observed.

Patching Flaws. Patching flaws behind the finishing machine is no easy task. Consequently, the need for such repairs should be kept to an absolute minimum. If such repairs are required, every effort should be made to select the hottest material from the finishing machine hopper and to immediately transfer this to the area to be repaired. Hot material is quickly transferred by shovel as shown in Figure 8a to the area to be repaired. The mix is spread with a minimum of raking or stirring and although the patch is clearly visible at this point, it usually "disappears" after rolling (Figure 8b).

Compaction Equipment. Both tamping and vibrating screeds have been used in placing these mixtures; however, it was the opinion of most of those with whom the authors discussed the question that the vibrating screed does the better job.

A variety of compaction equipment has been used behind the finishing machine with different and sometimes conflicting claims regarding efficiencies. It is the opinion of the authors that the effectiveness of the various types of rollers is not greatly different with the possible exception of medium to light weight vibratory rollers. At least in theory, compaction of this type material is most effectively done with this equipment. Heavy and/or excessive rolling is to be avoided particularly on mixtures containing aggregates of low crushing strength and included in this group are most of the synthetic aggregates currently used in Texas.

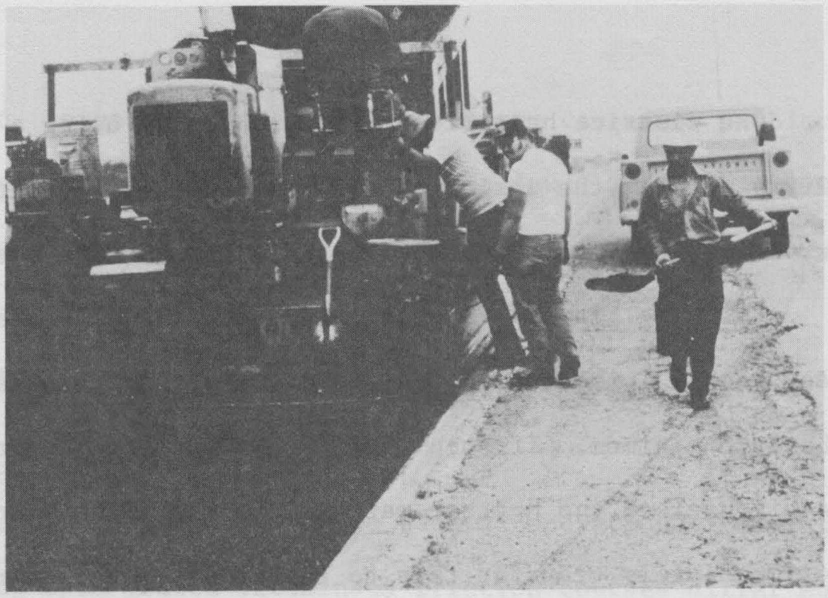


Figure 8a. Hot material is rapidly transferred to the area to be patched.

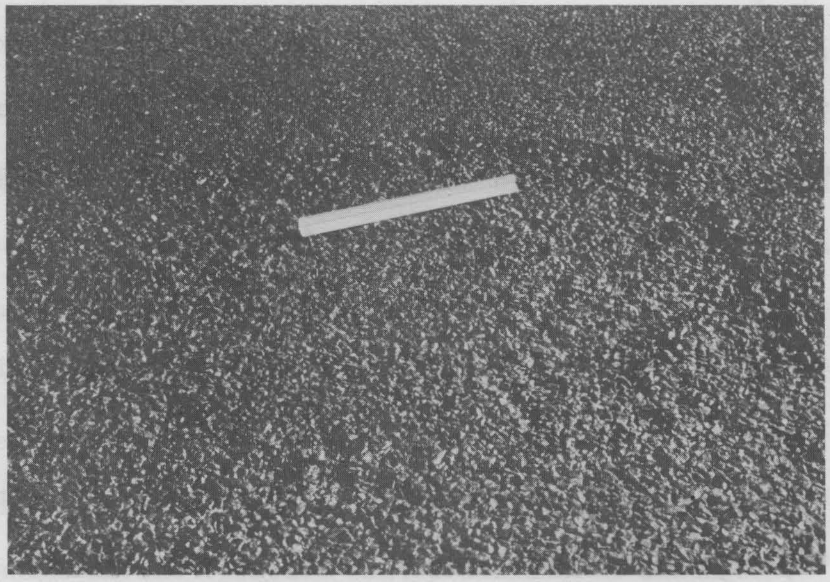


Figure 8b. Repaired area before rolling. Rolling usually eliminates all evidence of the repair.

For a selected aggregate, crushing will be minimized by reducing the top size in the grading and by the use of intermediate sized particles. If these adjustments are not acceptable, changes in the weight and type of roller are in order. Also the number of roller passes may be reduced.

Since binder and/or mix may stick to the roller, use of a release agent in the roller water may be required. Liquid detergent has been found effective and there are products on the market which are specifically designed for this use.

Laydown. The question of finishing machine speed of travel has been examined in the field and here again conflicting claims have been exposed. According to claims of equipment manufacturers and reports from NAPA, a good general rule is to adjust the speed of the finishing machine so that it is not a factor in the uniform and continuous placing of the mat. Such an operation improves the probability of producing a smooth riding pavement. That is, the fewer starts and stops on a job, the smoother will be the surface.

Shown in Figure 9 is evidence of a surface irregularity caused by stopping the finishing machine. A well planned construction operation will have as few stops and starts as possible. A smoother ride is the reward for this planning. Field observations on Texas jobs indicate that a speed of about 50 feet per minute is common.

Tack Coat. The use of tack in various amounts has been tried and the authors have already given their opinion on this facet of the operation but reasons for adjusting the amount of tack are varied. In at least one case the amount of tack (RC-250 in this case) was reduced from about 0.1 gallons per square yard to about 0.02 because of construction

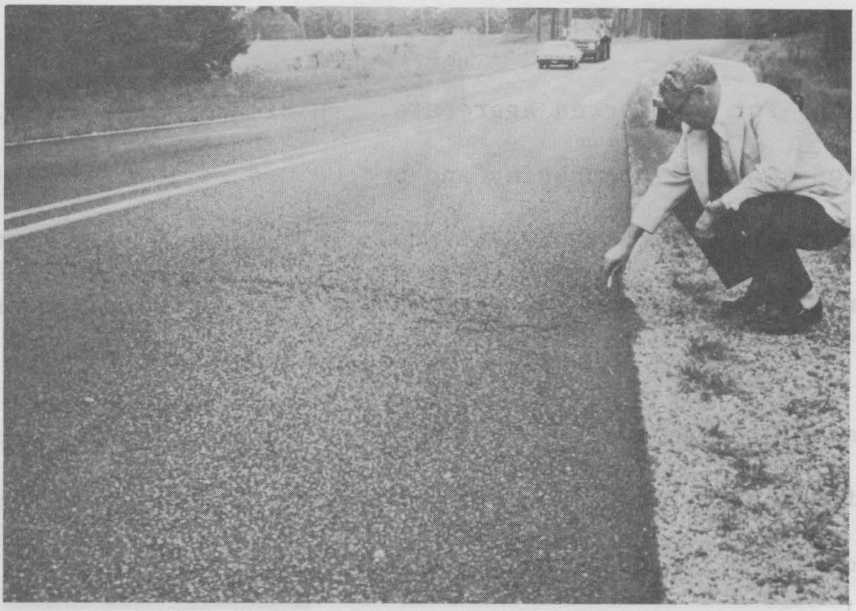


Figure 9. Surface irregularity caused by stopping the laydown machine.

Figure 10. Photographed during rain of about ½-inch per hour. Water is draining through the mat and out the edge of the surfacing.

equipment traction problems. On this particular job the finisher was mounted on rubber tires and was operating in rolling terrain. On another job a crawler track machine had no difficulty pushing loaded trucks during dumping and a heavy tack was used on this job.

There is no question but what adequate tack will assist bonding of the thin overlay to the substrate particularly for very open designs which contain very little material passing the No. 8 or 10 sieve. Although most design methods allow some extra binder for flow down during and immediately after placement, such flow is not always assured. Should the amount of tack be minimal and concurrently should little or no flow down occur, distress in the form of delamination or slippage is quite likely.

As a word of warning neither tack nor flow down should be considered a waterproofing device. Open-graded mixtures, however placed, must never be considered to form a waterproof cover on a pavement being modified by their use. To the contrary, they invite the intrusion of water.

Paving Intersections. Because open-graded mixes are high performers frictionwise they are particularly appropriate for use on at-grade intersections. Many such intersections are not simple tees or crosses but involve medians and islands to channelize the traffic and such intersections present placing problems for finishing machines. This problem has been solved by a contractor who thought it could not be done! The segments of the intersection connecting the main lanes were paved first with the material extended into the main arteries. A front end loader was then used to pick up that part of the recently placed material that extended into the main artery. The salvaged material was immediately returned to the hopper of the finishing machine to be successfully placed again. Such an approach avoids shoveling and raking corners and fillets, a difficult job even with regular hot mix but almost impossible with open-graded mixes placed in very thin lifts.

PERFORMANCE

The excellent surface drainage properties of open-graded mixtures is a basic design property and prime reason for popular acclaim, but this property is at the same time a source of trouble.

Early experiments with trial sections of open-graded mixes in District 17 of THD were highly successful as may be noted from the photograph (Figure 2) of adjoining lanes on a super elevated curve taken during a rain. Note that the lane on the inside (low side) of the curve is free of surface water; whereas, the other lane contains considerable surface water. The difference in evidence is caused by differences in void content. The "dry" lane is sufficiently open-graded to accept surface water which drains through the 1 1/2-inch mat then across the pavement and out at the edge of the paved surface. (See Figure 10.)

The final drainage from open-graded mats takes time as evidenced by the scene shown in Figure 11 where water was found to be draining from the mat two hours after the rainfall ceased. This creates problems of structural distress such as that observed on the trial sections on FM 1687 in Brazos County. All trial sections of open-graded surfaces on this job showed premature structural distress, because water entered the base and subgrade. This led to early distress.

Additional evidence of this type distress is shown in Figure 12, where structural distress was evident in a few months after the surface was placed.

Water may be held in open-graded surface mats from hours to days depending on weather conditions, cross slope and longitudinal grades.

Figure 11. Drainage of water from open graded surface continued for more than two hours after rainfall ceased.

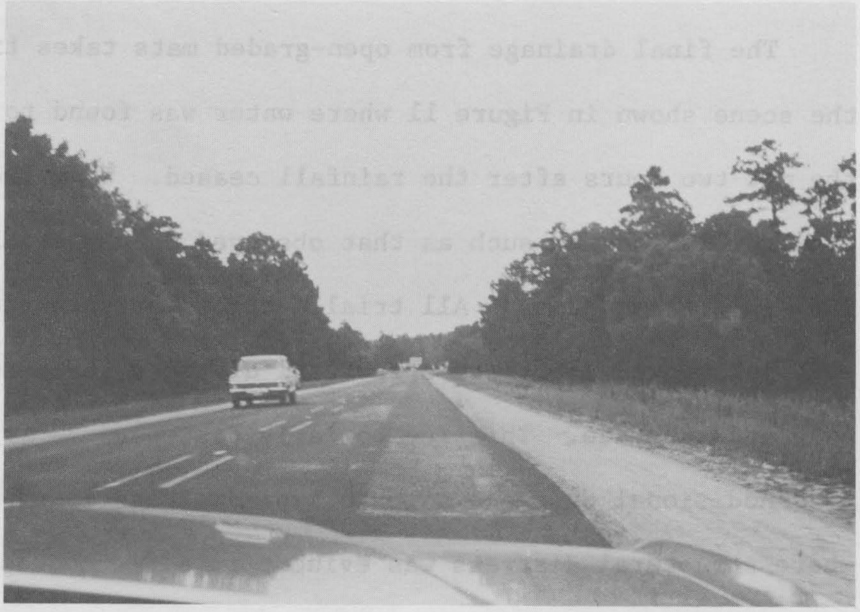


Figure 12. Entry of water causes early structural distress in East Texas pavement.

Whereas, for good quality dense-graded surfaces, water may drain quickly from the surface allowing little opportunity for intrusion.

Knowledge of this observation should lead one to the conclusion that surfaces on which open-graded mixes are placed should be essentially watertight. Some will argue against this need and in arid regions the argument has definite merit. Rolling terrain would also be a factor minimizing the probability of this type distress. The problem is, however, a real one, more particularly in areas with poor quality subgrade soils such as water sensitive clays.

The question may be asked whether or not excess binder that may drain from the mixture after it is placed will effect a seal to prevent water damage of the base or existing structure. The answer from field observations is a definite "no".

It is true that the open-graded mixes placed in the District 17 sections differed from those placed in Districts 2, 11, 19, and 20, but at the same time a tack coat in the amount of more than 0.1 gallons per square yard was applied (see Figure 13) and this was insufficient to prevent water intrustion.

The design procedure recommended in this report includes a provision for the use of a tack coat but no assurance of waterproofing is given. The tack coat is often damaged during construction as shown in Figure 14 and may not serve as a waterproofing membrane.

Field evidence to date is lacking from the other three districts but it may only be a matter of time before the distress is observed. There are definite hints in some of the earlier sections placed in

Figure 13. Application of heavy tack coat did not provide adequate underseal for open graded mix.

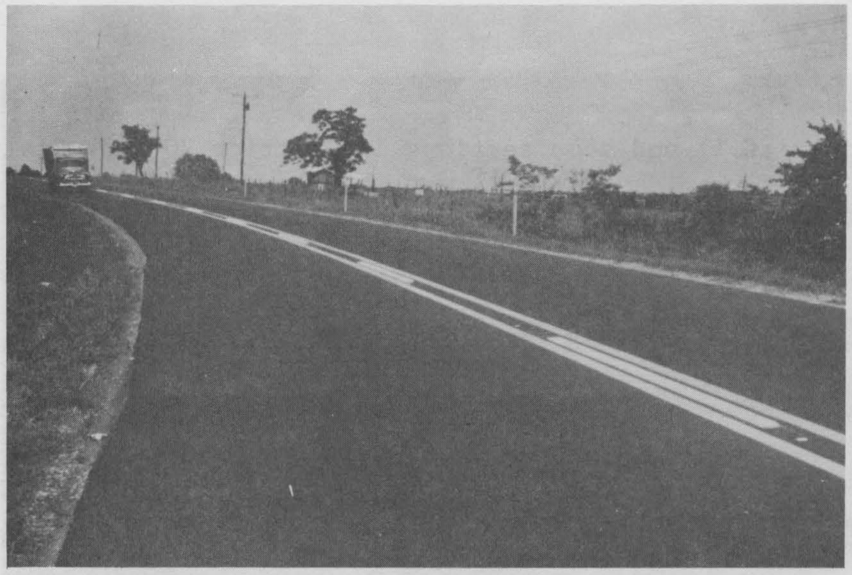
Figure 14. The tack coat is often damaged by construction traffic. Its effectiveness as a waterproof is questionable.

District 11 and some sections in District 20 show distress after about six months of service.

To minimize the probability of this type distress one should avoid placing open-graded mixes that do not allow free drainage at the pavement edge. For example, one should not place a dense-graded plant mix on the shoulder abutting an open-graded mix in the traveled lane. To do so would cause water ponding in the mat near the juncture at the shoulder. Should economics and service dictate such an arrangement, a solution to the problem would be to saw small transverse channels in the shoulder surface course at 4 to 6 foot intervals for drainage.

There is little question regarding the dark color of newly constructed open-graded mixtures but some observers have argued the safety advantage of this dark color. Reference is made to Figure 15 (a) and (b) where the excellent contrast of lane markings is shown. It is good safety practice to reestablish lane markings as quickly as possible after overlaying but in urban areas the "life" of the first application of paint on this type mixture may be short. Some bleed through takes place and tire tracking of the excess binder at the surface often "washes out" what was a clear contrasting stripe. The use of a harder binder will minimize these problems.

In spite of the early life problems with marking paint, most agencies claim much longer average life for paints placed on open-graded mixtures. And, too, better night visability is claimed for markings on these mixtures - due probably to the pebbly nature of the surface and minimal surface water.



(a)

(b)

Figure 15. Lane markings on open graded mixtures present clear contrasts and marking life is improved.

SELECTION OF MAT THICKNESS

Overlay thickness is often dictated by costs but the final decision is affected by several inputs most of which are field oriented. In earlier discussions of laboratory design of this type paving material, mixture stability, as measured by such tests as Marshall and Hveem, is usually considered relatively unimportant. Cost, on the other hand, is of primary concern and it is therefore important to keep the mat thickness as thin as practical; however, there are constraints that may demand a thicker mat.

In arriving at an optimum mat thickness the man in the field will consider in addition to cost such factors as (a) surface irregularities, (b) condition of the surface being overlaid, (c) structure clearances and (d) dead weight on bridges. Before going into a discussion of these field factors the effect of mat thickness on costs should be considered.

Cost data from 1973 and 1974 contracts in Texas indicate a range of about $35.00 to $50.00 per ton of mixture in place. These figures should be compared with the range for standard surface course mixtures which is from about $15.00 to $25.00 per ton in place. Immediately the question is asked, "Why is the cost for open-graded mixtures so much higher?" The uncertainties of materials costs and availability are about the same for both mix designs. However, two factors come into play that do affect bid price and these are production rate and unknown problems of mixing, handling, placing and rolling. Price is the contractor's shield against these problems.

We now come back to the question of lift thickness and how thickness and price are related. On an equal lift thickness basis the tonnage of mix per lane mile of these two types of mixture will differ by about 40 percent with the standard mix being the higher tonnage. If we couple with this fact the normal practice of placing open-graded mixtures about 5/8 to 3/4 inches in thickness compared to 1 to 1 1/2 inches for the standard hot mix surface the tonnage difference becomes (on a lane mile basis) about 100 percent more tonnage placed for the standard mix. Restricting the contractor's capacity to produce and place the finished product will increase the quoted price of the open-graded mix. It then becomes a possibility that the unit price of open-graded mixes would be quoted lower if the lift thickness were increased. The question of whether or not there are other advantages to increasing lift thickness should also be discussed.

Some advantages may exist and include (a) easier placing and compaction, (b) improved riding quality and (c) lower probability of bleed through where such mixes are placed on flushed areas. These advantages may assist in improving the contractor's confidence regarding the successful placement of this material and this in turn, should further reduce the bid price. Even with these price advantages, open-graded mixes will continue to be priced above standard surface courses, at least for the foreseeable future, but the price difference between standard hot mix for surface work compared to open-graded mixture should drop, particularly, i somewhat thicker lifts are specified.

To this point optimum mat thickness, per se, has not been defined. Indeed, one must fit mat thickness to the job. Flushed areas and surface irregularities dictate thicker mats.

In Figure 16 (a) and (b) is is evident that for the surface irregularities of this section of the road the mat was too thin. The distress was evident immediately behind the laydown machine. Before this overlay was placed definite depressions existed in the wheel paths of the old pavement such as that shown in Figure 17. Alterations were not made to provide for extra material required.

Flushed areas such as those shown in Figure 18 can be significantly minimized or even eliminated by increasing mat thickness. As shown in Figure 19, where a 2-inch mat of open-graded mixture was placed over a flushed area, the old binder flowed to the pavement edge rather than to the surface. On a 5/8-inch mat the excess binder would quite likely have been brought to the surface causing a flushed condition. The observed condition can also be caused by too much binder and/or an operating temperature that is too high. If flushing is avoided, no harm has been done.

Costs and critical clearances infer thinner mats. Weather at the time of placement is also a factor to be reckoned with. Cool weather dictates thicker mats, since more heat is carried in a thick mat, thus allowing more time for compaction. Wheel track depressions also call for thicker mats since the average mat being placed may not be sufficiently thick to avoid a dragging screed between wheel paths, an example of which has just been covered.

Figure 16a. A dragging screed causes aggregate crushing and raveling between wheelpaths where overlay is too thin.

Figure 16b. Close-up of damaged area.

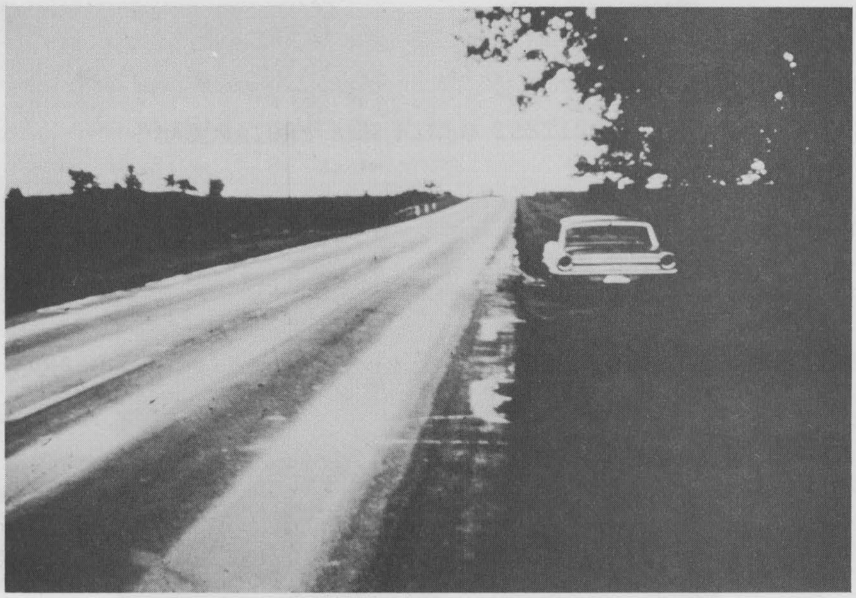


Figure 17. Wheel track depressions collect excessive amounts of water and increase the probability of dynamic hydroplaning. Such surfaces require thicker than usual overlays.

Figure 18. Flushing caused by fat spots that existed in old surface. Thicker lifts of open graded mix is an answer to this problem.

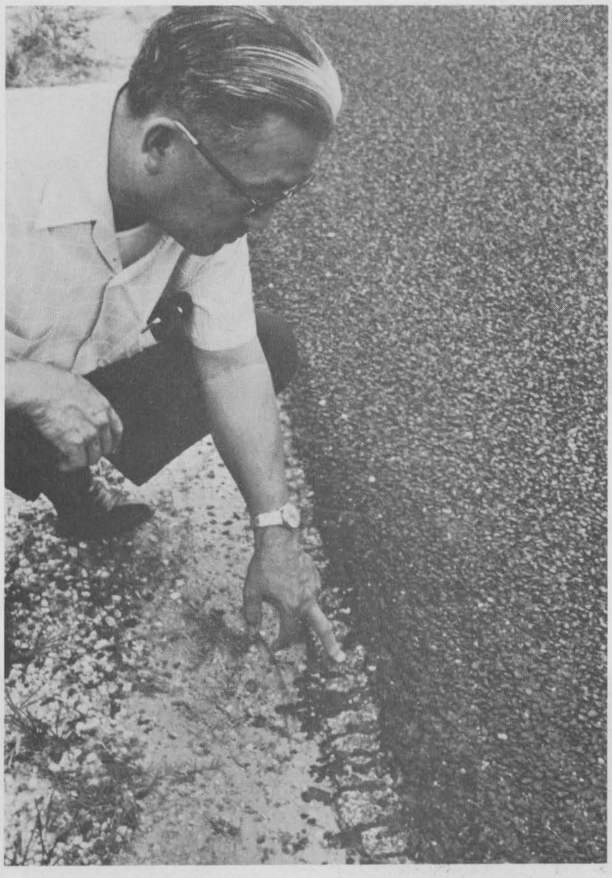


Figure 19. Asphalt leakage from beneath a 2-inch mat.

LABORATORY AND FIELD TESTING

One of the questions that is often raised regarding open-graded mixtures is that of durability. To examine durability a laboratory freeze-thaw test has been developed (Appendix D). Test results are contained in this section of the report together with surface texture, permeability, skid resistance and road roughness measurements made at selected field sites.

Freeze-Thaw Testing

Because the open-graded plant mix seal is, by design, one of a very high void content, speculation is that the detrimental effect of alternate cycles of freezing and thawing would be a serious problem. As a consequence, field cores were taken from in-service pavements for laboratory freeze-thaw testing and evaluation. These tests were limited in nature but when the results were analyzed and compared with field inspection data and information from other agencies the authors concluded that damage to be expected from this environmental factor is minimal.

Seal coat samples as listed in Table 3 were selected at random within limitations allowing maximum amounts of information to be gathered to satisfy all variables being studied. These variables are listed as follows:

1. Partial freezing test variable
2. Wheel path
3. Asphalt content
4. Type of aggregate

TABLE 3 Testing Plans for Laboratory
Freeze-Thaw Analysis of Field Cares

		Partial Freezing Test			
		Bottom to Top		Bottom to Top	
		Wheel Path		Wheel Path	
Aggregate Used	% Asphalt Content	BWP	OWP	BWP	OWP
Crushed Limestone District #2 IH35	6.7	0	0	0	X
Lightweight - Eastland District #2 IH30	10.7	0	0	0	X
Rhyolite - Allamodre District #2 LH820	6.7	0	0	X	X
Lightweight - Eastland District #11 US59 South	10.5 11.0 11.5	- X -	- 0 -	X X 0	X X X
Lightweight - Superock District #11 US59 South	12.5	0	0	0	X
Lightweight - Dallas District #11 US59 North	12.0 12.5 13.0	- X -	- X -	0 X 0	X X X
Trap Rock - Knippa District #11 US59 North	6.0 6.5 6.8	- X -	- X -	X X 0	0 X X
Crushed Stone - Hable District #11 US59 North	6.0 6.3 6.5	- 0 -	- X -	X X 0	0 X X
Crushed Stone and Sand - E.T.S. District #11 US59 North	6.5	0	0	0	X
Crushed Slag District #11 US59 North	8.0	X	X	X	X
Trap Rock - (MIX) District #20 US96	6.0	0	0	0	X
Limestone District #20 FM563	7.0 9.0	0 -	X -	X X	X X

TABLE 1A: SAMPLES SELECTED FOR FREEZE AND THAW TEST

(X) = 3 CORES TESTED
(O) = CORES TAKEN BUT NOT TESTED
(-) = NO CORES TAKEN

In order to formulate a test procedure several sets of samples were selected and tested on a trial basis. Subsequently forty sets of three replicates each were tested for a total of 120 samples.

To aid in evaluating the information, data were grouped as shown in Table 4. Written observations were reduced to numerical values by using code numbers. The chart contains descriptive information of the designs with test observations relating to each. The higher number indicates greater damage. For the visual observations, this was a two-part number being separated with a dash. The first number tells the type of damage as follows:

0 = No damage visible

1 = Used only for beginning observations - aggregate was not coated when layed; damage not due to wear

2 = Used where cracks or breaks were in the aggregate; loss was visible

3 = Used where loss in part or total has occurred to the individual aggregate

The second part of the visual number is the percent of the aggregate affected. Example: 2-4 is fractured aggregate with 4 percent affected.

As for the "Brush Test", this number is simply the average weight loss in grams for the three replicate samples tested.

Effects of partial freezing were determined early in order that the largest majority of samples would be tested with the most severe conditions.

The first groups were subjected to 100 cycles. The number of cycles for other groups was reduced from 100 to 50 cycles. It was felt that as these roadways had been in service for some time, 50 cycles should be sufficient to evaluate freeze and thaw effects.

TABLE 4

Test Results for Laboratory Freeze-Thaw Study

SAMPLE DESCRIPTION			TEST OBSERVATION (AVERAGE OF 3 SAMPLES EACH)																			
AGGREGATE USED	ASPHALT CONTENT	THD AGGREGATE ITEM & GRADE #	DIRECTION OF FREEZE : BOTTOM TO TOP										DIRECTION OF FREEZE : TOP TO BOTTOM									
			VISUAL OBSERVATION AT								BRUSH TEST		VISUAL OBSERVATION AT								BRUSH TEST	
			0 TO 25 CYCLES		50 CYCLES		75 CYCLES		100 CYCLES				0 CYCLES		25 CYCLES		50 CYCLES		75 CYCLES			
			BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP	OWP
CRUSHED LIMESTONE DIST. #2 IH 35	6.7	302 Gr.4												0		0		0		---		.2
LIGHTWEIGHT-EASTLAND DIST. #2 IH 30	10.7	303 Gr.4												2-1		2-1		2-2		---		0
RHYOLITE-ALLAMODRE DIST. #2 LP 820	6.7	302 Gr.4											2-1	0	2-1	0	3-2	3-2	---	---	.1	.1
LIGHTWEIGHT-EASTLAND DIST. #11 US 59 SOUTH	10.5 11.0 11.5	303 Gr.4	0		0*		0*		0*		.1		0 0	2-1 0 0	2-0 0	2-1 0 0	3-2* 0	3-1* 0 0	--- 2-1	--- --- ---	-1 .1	.1 .1 0
LIGHTWEIGHT-SUPEROCK DIST. #11 US 59 SOUTH	12.5	303 Gr.4												0		0		0		---		.2
LIGHTWEIGHT-DALLAS DIST. #11 US 59 NORTH	12.0 12.5 13.0	302 Gr.5	0	0	0	0*	0*	0*	0*	0*	.1	.1	0	1-2 0 0	0	2-1 0 0	0	3-1* 0 2-2	0	0 ---	.1	.1 .1 .3
TRAP ROCK-KNIPPA DIST. #11 US 59 NORTH	6.0 6.5 6.8	302 Gr.5	0	0	0*	0*	0*	0*	0*	0*	.1	0	0 0 0	0	0 0 0	0	0* 0* 0	0*	--- 0* ---	--- 0*	0 .3 0	.1
CRUSHED STONE DIST. #11 US 59 NORTH	6.0 6.3 6.5	302 Gr.4		0		0*		0*		0*		0	0 0 0	0 0 0	0 0 0	0 0* 0	2-1 0 0	0* 0* 0*	--- --- 0	--- ---	0 .1 0	0 .1 .1
CRUSHED STONE & SAND DIST. #11 US 59 NORTH	6.5	302 Gr.4												0		0*		0*		---		0
CRUSHED SLAG DIST. #11 US 59 NORTH	8.0	302 Gr.5	0	0	0*	0*	0*	0*	0*	0*	0	0	0	0	0	0*	0	0*	0	---	0	0
TRAP ROCK DIST. #20 US 96	5.2 6.0	302												0		0		0		---		0
LIMESTONE DIST. #20 FM 563	7.0 9.0	302		0		0		2-5*		3-5*		.1	0 0	0 0	2-5 2-4	2-6 2-4	3-6 3-6	3-5* 3-8*	--- ---	3-10* ---	.2 .3	.5 .3

SAMPLE CONDITION OF SEAL COAT (FIRST NO.)

0 = NO DAMAGE VISIBLE
1 = UNCOATED AGGREGATE (0 CYCLES ONLY)
2 = FRACTURED AGGREGATE
3 = AGGREGATE LOSS

SECOND NUMBER IS % AGGREGATE EFFECTED

* = DAMAGE TO BASE

Nine sets of three samples each were tested, freezing from bottom to top. A replicate set (of three samples each) of the first nine sets of samples were then tested, freezing from top to bottom. It was determined that the most destructive method was the latter (top to bottom).

The greatest base damage occurred on samples frozen from bottom to top. The samples frozen top to bottom sustained slight to no damage.

The samples receiving the most damage were the limestone aggregate designs from District 20.

Freezing bottom to top damage was first evident between 50 to 75 cycles, wheras from top to bottom damage occurred before 25 cycles.

For the wheel path variable, 20 pairs of sets (three replicates each) were used to observe outer versus between wheel path. These samples behaved similarly for the most part. Some outer wheel path samples showing a greater amount of wear, appear to have performed a little better than did the between wheel path samples. Greater damage to between wheel path samples was noted in only two sets tested.

In an attempt to determine the effect of asphalt content of the samples tested, six sets were paired for design asphalt content versus a higher asphalt content. Three of the materials with lower asphalt contents showed some light damage as compared to no damage for like materials with design content asphalt. With the higher content of asphalt no distress was noted. Neither did the design asphalt content mixtures sustain visual damage.

A total of twenty-one different designs were tested with eleven different aggregates. As stated earlier, limestone asphalt samples from

District 20 (FM 563) suffered the most damage with no apparent benefit from increase from 7% to 9% asphalt content. No explanation is offered for the damage observed.

The brushing test verified visual observations as to damage. However, the test appears to be only secondary to visual. It is felt that better information can be obtained by brush testing at each observation period and by increasing the number of brush strokes per sample. Additional work is needed to determine an optimum number of brush strokes.

Photographs are presented in Figures 20, 21, and 22 which show equipment arrangement and typical visual evidence of test results. The test method is descriped in Appendix D.

Field Testing

Table 5 lists nine different aggregates used for open-graded mixes in different districts of THD. Three of these surfaces were placed in service in 1971, five in 1973 and one in 1974. Estimated traffic on the surface is also shown in Table.5.

Surface Texture--Texture measurements were made by modification of two methods in current use by several agencies across the country. Both of these methods, the sand patch and the silicone putty methods, required modification because this type surface usually has a rather high void content. The authors do not consider the sand patch method to be as reliable as the silicone putty method for measuring texture of open-graded mixtures. Test results are shown on Table 5.

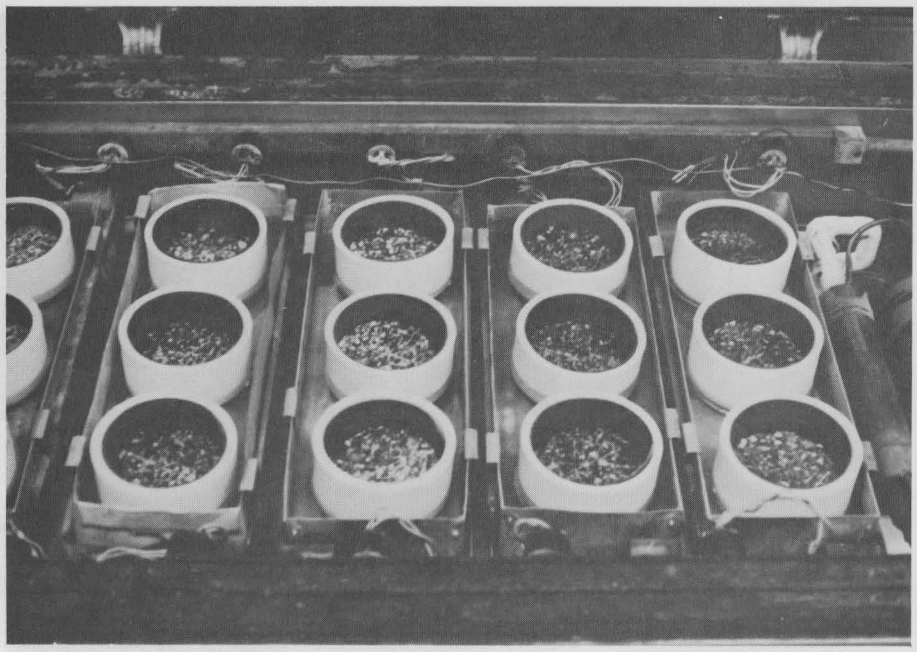


Figure 20a. Sample arrangement in freezer.

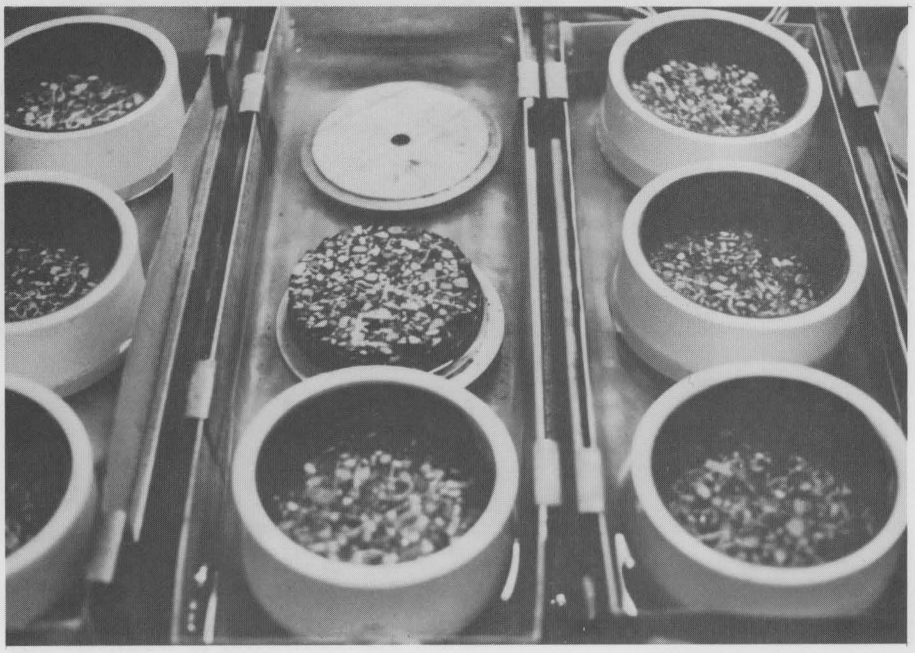
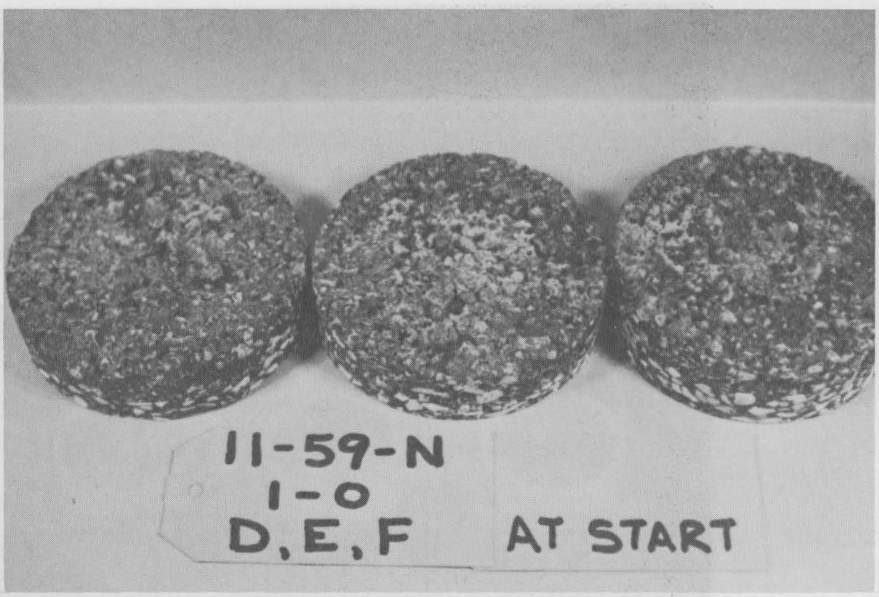
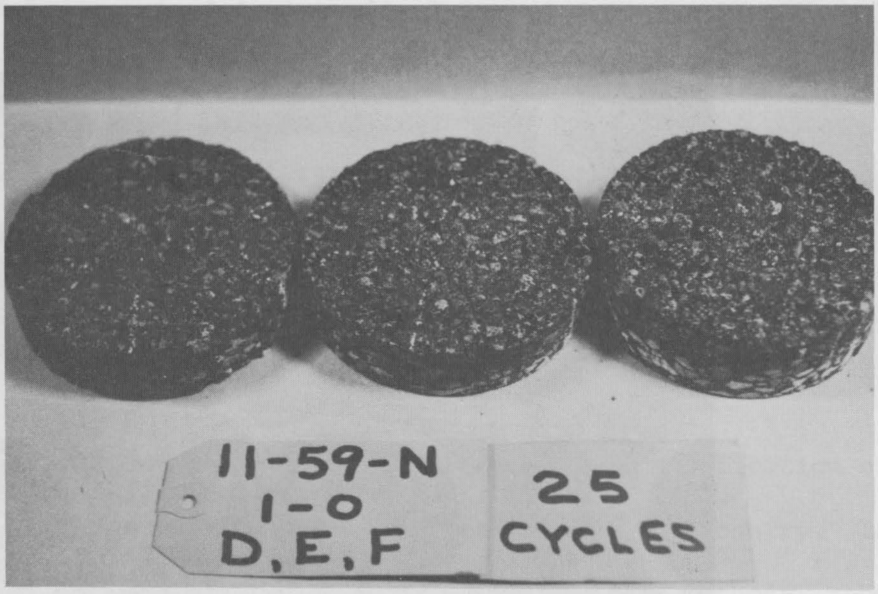


Figure 20b. Pedestal and collar details preparatory to adding water.

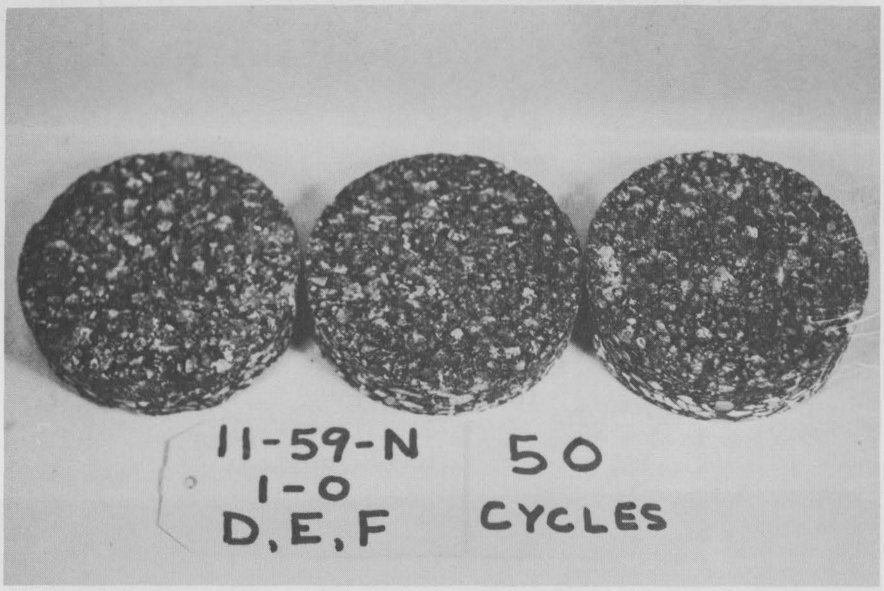


(a) at start



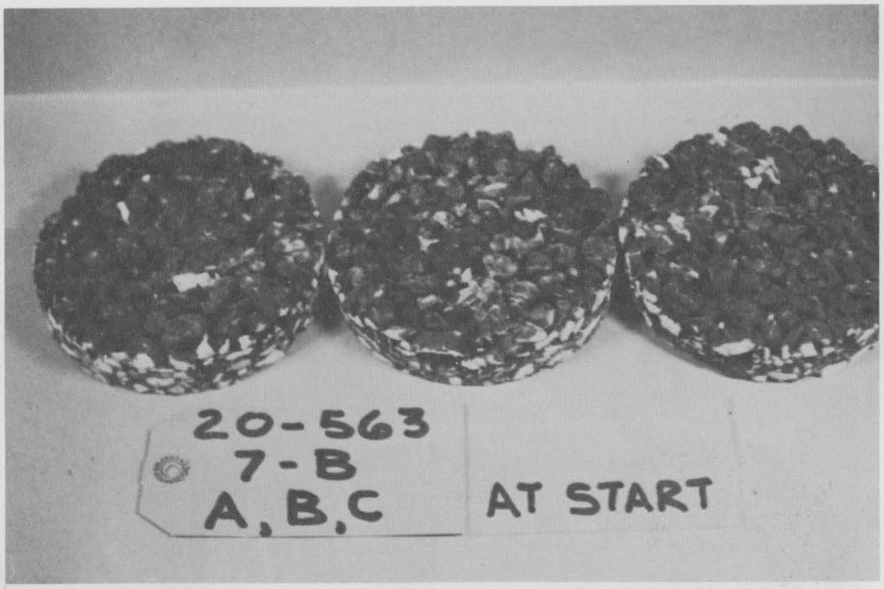
(b) 25 cycles

Figure 21. Typical visual results for samples showing little or no damage.

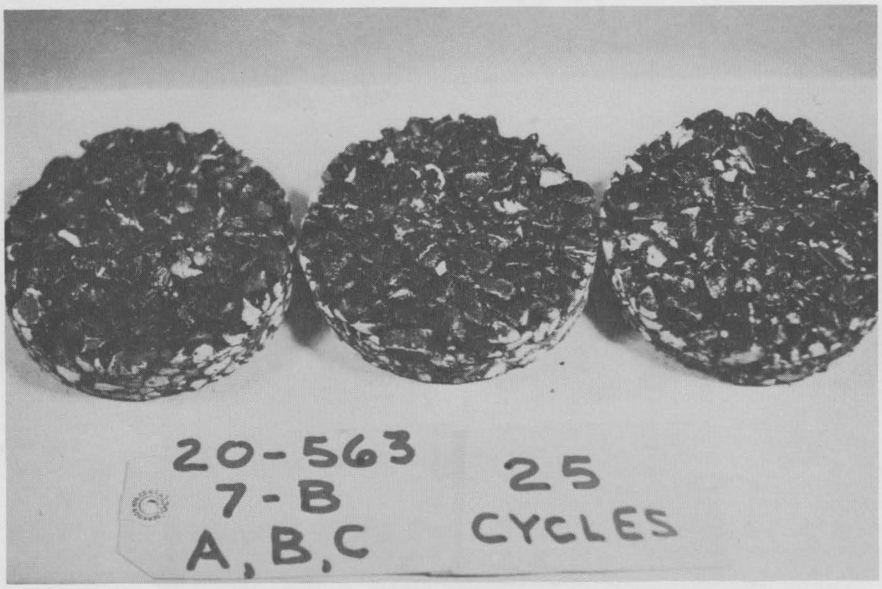


(c) 50 cycles

Figure 21 (continued).

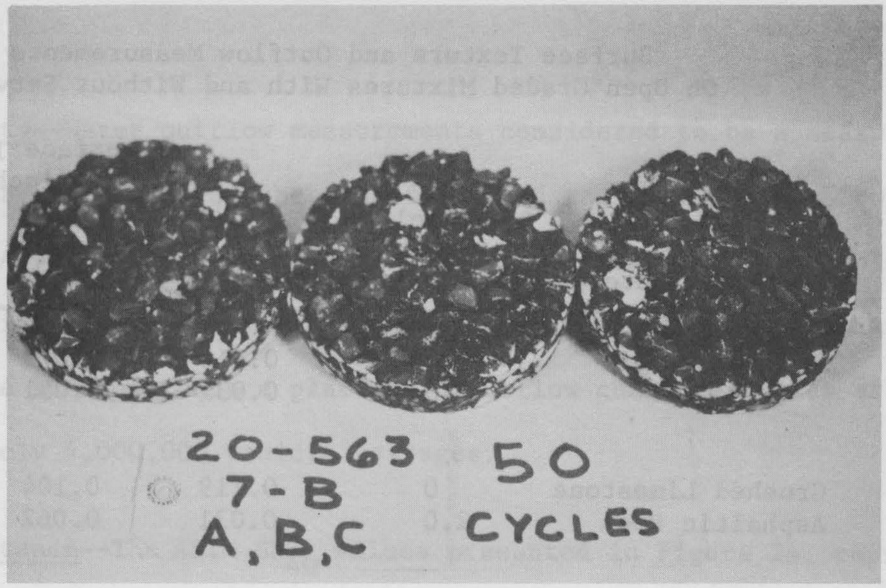


(a) at start

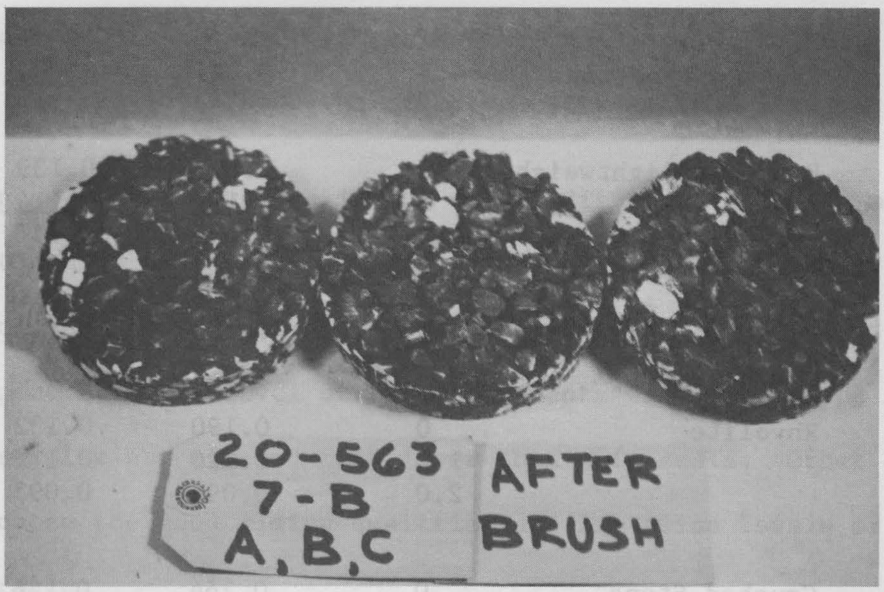


(b) 25 cycles

Figure 22. Typical samples damaged most by freeze-thaw cycle. Time intervals as indicated.



(c) 50 cycles



(d) 50 cycles plus brushing

Figure 22 (continued).

TABLE 5

Surface Texture and Outflow Measurements On Open Graded Mixtures With and Without Service

Aggregate Material	Vehicle Passes (Millions)	Outflow* (Sec^{-1})	Surface Textures (inches)	
			Silicone Putty	Sand Patch
Crushed Slag	0	0.110	0.071	-
	2.0	0.031	0.051	0.049
Crushed Limestone Asphaltic Rock	0	0.119	0.104	0.131
	2.0	0.031	0.062	0.061
Crushed Traprock	4.5	0.025	0.059	0.054
Dallas lightweight	4.5	0.024	0.041	0.042
	5.0	0.060	0.075	0.080
Crushed Sandstone	4.5	0.029	0.067	0.066
Eastland lightweight	0	0.083	0.139	0.129
	0	0.152	0.114	0.210
	0	0.066	0.114	0.120
Super-rock lightweight	0	0.195	0.101	0.179
Rhyolite	0	0.190	0.132	0.184
	1.0	0.120	0.115	0.131
	2.0	0.095	0.095	0.120
Crushed Stone Springtown Okla.	0	0.264	0.126	0.237
	3.0	0.085	0.100	0.119
Light-weight	0	0.285	0.152	0.300
	2.0	0.115	0.105	0.120
	5.0	0.060	0.076	0.078

*A measure of surface texture is given for outflow time in reciprocal seconds.

Permeability--Water outflow measurements considered to be a measure of permeability were made on these surfaces and the results are shown in Table 5. A plot of the outflow data as a function of traffic volume is shown in Figure 23. The limited data appear to indicate that mixtures of the type studied reach a plateau in outflow characteristics after approximately 4,000,000 vehicle passages.

Skid Resistance--The ASTM SN_{40} values presented in Figure 24, representing data from Ft. Worth, indicate that the lightweight aggregate is outperforming both the rhyolite and the crushed calcareous material, although the data in Table 5 indicate that the lightweight material has a lower outflow value (longer outflow time). All three materials appear to have adequate texture as determined by both the silicone putty and the sand patch methods.

Road Roughness--The riding quality of eleven different jobs was measured by use of the Mays Ride Meter. The results are shown in Table 6. It is evident from these data that riding quality is good.* From field observations the general noise level of these pavements was found to be lower than adjoining regular hot mix and much lower than chip seals. Other observers have also noted the good riding qualities and low noise levels of this type of surface.

*Average serviceability index values for Texas highways based on a random sampling is 3.3. Typical values for new asphalt concrete overlays range from 4.0 to 4.7.

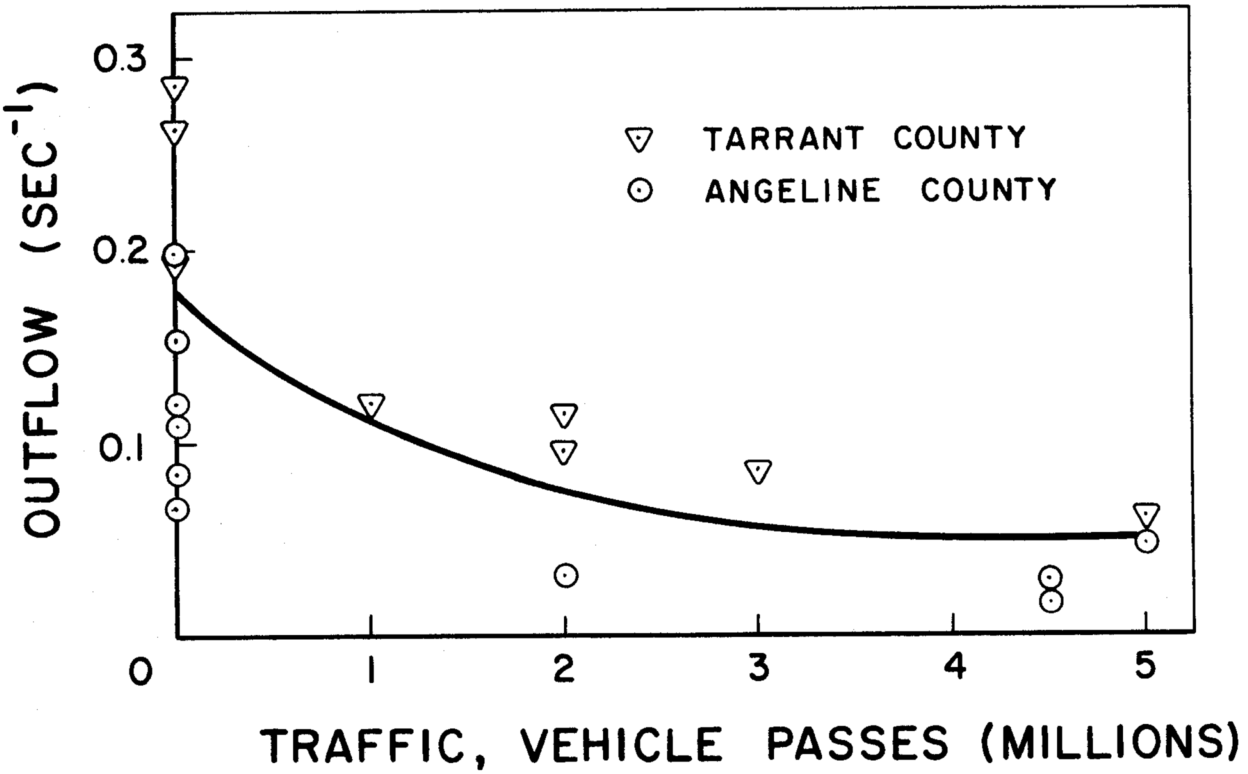
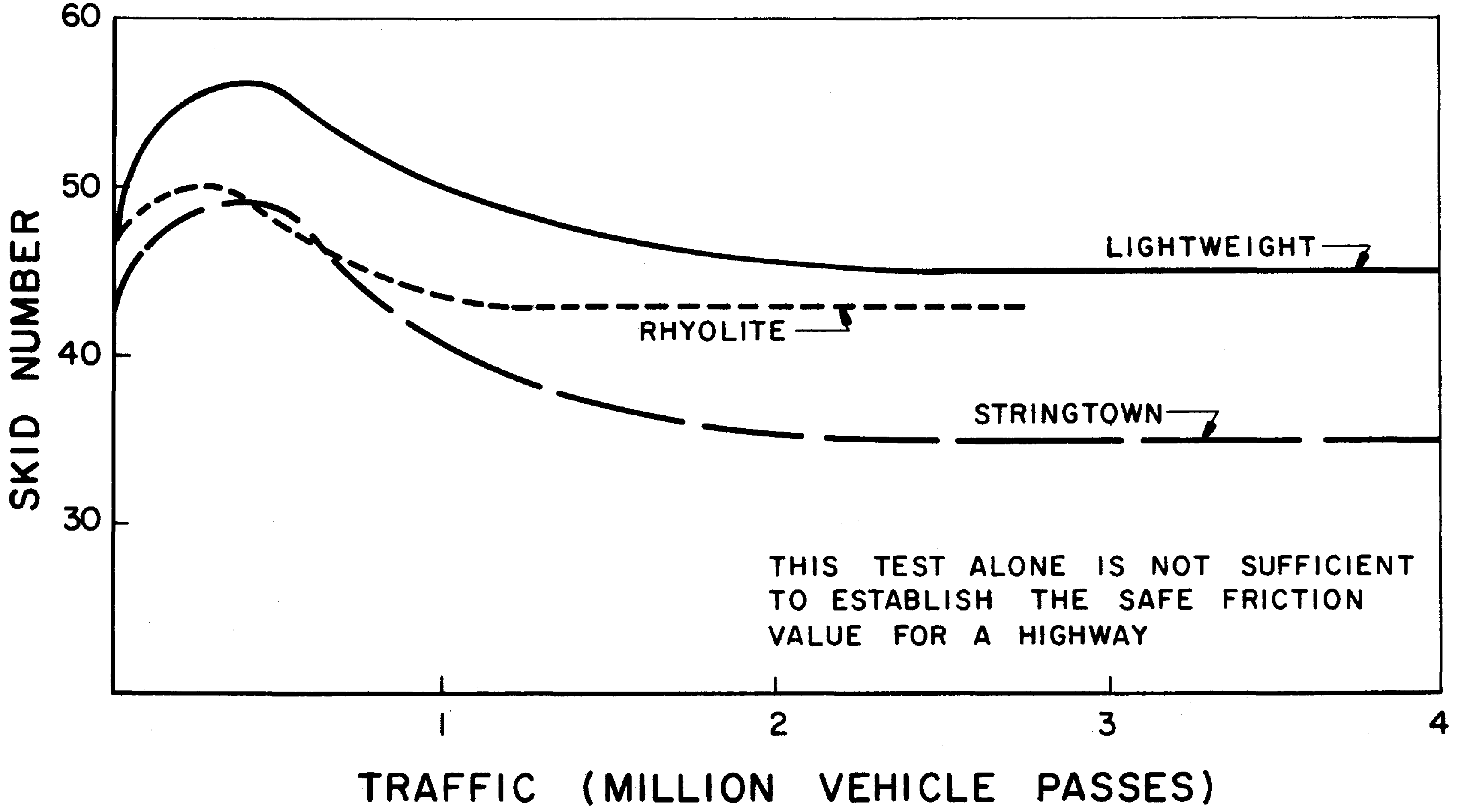


FIG. 23 OUTFLOW METER SHOWS TRAFFI
EFFECTS ON OPEN GRADED
FRICTION COURSE



THIS TEST ALONE IS NOT SUFFICIENT TO ESTABLISH THE SAFE FRICTION VALUE FOR A HIGHWAY

FIG. 24 SKID RESISTANCE OF PLANT MIX SURFACE COURSE

TABLE 6

Surface Smoothness
As Determined by the Mays Ride Meter

County	Highway	Pavement Type	SI[3]	SD[4]	CV[5]
Angelina	US 59	PMSC[1] (Lightweight)[2]	3.5	.16	4.4%
	South of Lufkin		3.9	.19	4.9%
	US 59	PMSC	4.0	.32	8.0%
	North of Lufkin		4.2	.14	3.3%
	HWY 103	Lightweight Seal Coat	3.9	.20	5.2%
			3.8	.26	6.8%
Chambers	FM 563	PMSC (Limestone)	3.8	.34	9.0%
			3.9	.30	9.9%
Fort Worth	LP 820	PMSC (Rhyolite)	3.9	.31	7.9%
			3.9	.05	1.4%
	IH 35	PMSC (Rhyolite)	3.8	.19	5.1%
	IH30 US80	PMSC (Rhyolite)	3.5	.07	2.0%
	US180 US377		3.9	.22	5.5%
	IH 30	PMSC (Rhyolite)	3.6	.20	5.5%
Harrison	US 59	PMSC (Slag)	4.3	.07	1.0%
	SH 43	PMSC (Slag)	4.3	.07	1.7%
Jasper	US 96	PMSC (Knippa Traprock)	4.0	.37	9.4%
			4.0	.36	8.9%

1. Plant Mix Seal Coat
2. Parenthesis indicate type of Aggregate
3. Servicability Index
4. Standard Deviation
5. Coefficient of Variation

SUMMARY

The laboratory design of open-graded bituminous mixtures to be used as thin overlays has been the subject of several studies in recent years as this type surfacing offers promise for improved safety on the nations' highways. A review of these studies together with field experience gained in Texas has resulted in a modification of the Federal Highway Administration design method for open-graded asphalt friction courses. Design curves are included in the report which allow for the utilization of aggregates of a wide specific gravity range (synthetic or lightweight aggregates) and air void contents of 15, 20 and 25 percent.

Construction guidelines and performance trends of open-graded bituminous mixtures placed in Texas are reviewed in the report. Construction problems created by water absorption of the aggregates are discussed in considerable detail together with problems associated with crusting, application of tack coat, patching flaws, compaction, laydown and paving intersections.

Performance of this type of surface course in Texas has not been successful in all cases. The infiltration of water into the subgrade accelerated by the presence of these permeable mixtures has resulted in early pavement distress at some locations.

Field surveys were made in five districts of the Texas Highway Department. Data collected included freeze-thaw of field cores, road roughness measurements, surface texture measurements by two methods, permeability as measured by a water outflow method and frictional performance.

At this point in time it appears that open graded friction courses offer one of the best methods available to minimize hydroplaning and maintain a fairly high and reasonable uniform friction coefficient. As long as the surface remains sufficiently open to avoid appreciable hydrodynamic lift at the tire-pavement interface such surface course designs should give good service.

The recommended design procedure with the modifications offered by the authors should make it possible for the man in the field to design suitable mix for a variety of service demands.

The discussions relating to field distress mechanisms and the suggestions regarding the avoidance of these problems should improve the success-to-failure ratio of those who work with this type of material.

Suggestions have been made regarding how the cost of this type mixture may be reduced or made more competitive.

Implementation of the finding are timely in view of the need for road surface friction improvement in inclement weather and the need to extend our limited supplies of non-polishing aggregates.

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APPENDIX A

Federal Highway Administration Design Method
for
Open-Graded Asphalt Friction Courses
modified for use with
Synthetic Aggregates and Air Void Contents From
15 to 25 percent.*

*based on Reference 16

Material Requirements

1.1 It is recommended that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse aggregate fraction (material retained on No. 8 sieve). In addition, the coarse aggregate fraction should have at least 75 percent by weight of particles with at least two fractured faces and 90 percent with one or more fractured faces. The abrasion loss (AASHO T 96) should not exceed 40 percent.

1.2 Recommended Gradation for Open-Graded Asphalt Friction Course.

Sieve Size[a]	Percent Passing[b]
3/8"	100
#4	30-50
#8	5-15
#2000	0-5

[a] U. S. Sieve Series

[b] By weight

1.3 The recommended grade of asphalt cement is AC-10 or AR-40, AASHO M 226-73 I. For AC-10, Table 2 requirements should apply where such asphalt is available. AR-40 requirements are given in Table 3.

Preliminary Data

2.1 Test coarse and fine aggregates as received for the project for gradation unless otherwise provided. If mineral filler is submitted as a separate item it should also be tested for specification compliance. Analyze gradation results to determine if proportions of aggregates and batching operations proposed by the contractor will meet his job-mix formula and the specification limits of section 1.2.

2.2 Determine bulk and apparent specific gravity for the coarse and fine aggregate fractions (retained and passing No. 8 sieve) for each type of material submitted. Additional specific gravity tests are not warranted where the only distinction between aggregates is size of grading. Utilizing the information verified in section 2.1, mathematically compute the bulk and apparent specific gravity for the coarse and fine aggregate fractions (retained and passing No.8 sieve) for the proposed job-mix gradation.

2.3 Test the asphalt cement to be used for specification compliance (AASHO M 226-73 I), viscosity-temperature data, and specific gravity at 77.0 F.

Asphalt Content

3.1 Determine the surface capacity of the aggregate fraction that is retained on a No. 4 sieve in accordance with the following procedure (10):

Kc is determined from the percent of S. A. E. No. 10 oil retained, which represents the total effect of superficial area, the aggregate's absorptive properties and surface roughness.

3.1.1 Quarter out 105 g. representative of the passing three-eighth-inch and retained No. 4 sieve material.

3.1.2 Dry sample on hot plate or in 230 ± 9 F oven to constant weight and allow to cool.

3.1.3 Weigh out 100.0 g. and place in a metal funnel (top diameter 3-1/2 inches, height 4-1/2 inches, orifice one-half-inch with a piece of No. 10 sieve soldered to the bottom of the opening).

3.1.4 Completely immerse specimen in S. A. E. No. 10 lubricating oil for 5 minutes.

3.1.5 Drain for 2 minutes.

3.1.6 Place funnel containing sample in 140 F oven for 15 minutes of additional draining.

3.1.7 Pour sample from funnel into tared pan; cool, and reweigh sample to nearest 0.1 g. Subtract original weight and record difference as percent oil retained (based on 100 g. of dry aggregate).

3.1.8 Use chart shown in Figure A-1 for determination of "KC."

(1) If specific gravity for the fraction is greater than 2.70 or less than 2.60, apply correction to oil retained, using formula at bottom of chart in Figure A-1.

(2) Start at the bottom of chart in Figure A-1 with the corrected percent of oil retained; follow straightedge vertically upward to intersection with the diagonal line; hold point, and follow the straightedge horizontally to the left. The value obtained will be the surface constant for the retained fraction and is know as "Kc."

3.2 Determine the required asphalt content which is based on weight of aggregate from the following relationship (5):

Percent Asphalt = 2.0 (Kc) + 4.0[a/]

No correction need be applied for viscosity. The asphalt content computed from the above formula would be the same regardless of the asphalt grade.

Void Capacity of Coarse Aggregate

4.1 Determine the vibrated unit weight and void capacity of the coarse aggregate fraction (material retained on a No. 8 sieve) of the proposed job-mix gradation by the following procedure (11).

4.1.1 - Apparatus

Rammer. - A portable electromagnetic vibrating rammer as shown in Figure A-2, having a frequency of 3,600 cycles a minute, suitable for use with 115-volt alternating current. The rammer shall have a tamper foot and extension as shown in Figure A-3.

Mold. - A solid-wall metal cylinder with a detachable metal base plate, and a detachable metal guide-reference bar as shown in Figure A-4.

Wooden Base. - A plywood disc 15 inches in diameter, 2 inches thick, with a cushion or rubber hose attached to the bottom. The disc shall be constructed so it can be firmly attached to the base plate of the compaction mold.

Timer. - A stopwatch or other timing device graduated in divisions of 1.0-second and accurate to 1.0-second, and capable of timing the unit for up to 2 minutes. An electric timing device or electrical circuits to start and stop the vibratory rammer may be used.

Dial Indicator. - A dial indicator graduated in 0.001-inch with a travel range of 3.0 inches.

4.1.2 - Sample

Select a 5-lb. sample of the coarse aggregate fraction from the proposed job-mix formula as verified in section 2.1.

4.1.3 - Procedure

Pour the selected sample into the compaction mold and place the tamper foot on the sample.

[a/] Other equations which have been used are: EOA = 1.5 (Kc) + 3.5 and EOA = 1.5 (Kc) + 4.0 by California and Colorado, respectively.

Place the guide-reference bar over the shaft of the tamper foot and secure the bar to the mold with the thumb screws.

Place the vibratory rammer on the shaft of the tamper foot and vibrate for 15 seconds. During the vibration period, the operator must exert just enough pressure on the hammer to maintain contact between the sample and the tamper foot.

Remove the vibratory rammer from the shaft of the tamper foot and brush any fines from the top of the tamper foot. Measure the thickness (t) of the compacted material to the nearest 0.001-inch.

Note - The thickness (t) of the compacted sample is determined by adding the dial reading minus the thickness of the tamper foot to the measured distance from the inside bottom of the mold and the end of the dial gage when it is seated on the guide-reference bar with stem fully extended.

4.1.4 - Calculations

Calculate the vibrated unit weight (X) as follows:

$X = 6912(w)/\pi(d)^2 t$ (in pounds per cubic feet)

Where w = weight of coarse aggregate fraction in pounds

d = diameter of compaction mold in inches

if w = 5 lb. and d = 6 inches

$X = 305.73/t$ (in pounds per cubic foot)

where t is in inches

Determine the void capacity (VMA) as follows:

$VMA = 100(1 - X/Uc)$ (in percent)

where Uc = bulk solid unit weight in pcf of the coarse aggregate fraction. Uc is calculated from vulk specific gravity as determined in section 2.2 multiplied by 62.4 pcf.

Optimum Content of Fine Aggregate

5.1 Determine the optimum content of fine aggregate fraction with the following relationship:

$Y = [\% \text{ VMA} - V]-[(\% \text{ AC})\ (X)/Ua] \div [(\% \text{ VMA} - V)/100] + [(X)/Uf]$

Where: Y = Percent Passing No. 8 Sieve by Weight

X = Actual vibrated unit weight of coarse aggregate (retained No. 8 sieve)

Uf = Theoretical bulk dry solid unit weight of fine aggregate (passing No. 8 sieve)

% AC = Percent asphalt by total weight of aggregate = 2.0 (Kc) + 4.0

V = Design percent air voids = 15.0%

% VMA = Percent voids mineral aggregate of the coarse aggregate (retained No. 8 sieve)

Uc = Theoretical bulk dry solid unit weight of coarse aggregate (retained No. 8 sieve)

Note - X, Ua, Uc, Uf are in pounds/cubic foot.

In the above relationship, asphalt absorption by aggregate has been assumed to be negligible. Since asphalt absorption requirements are considered in the test for Kc (section 3.1), the estimated air voids of 15 percent in the mixture will actually be greater by an amount equivalent to the volume of asphalt absorbed, in percent. This condition, if anything, provides an additional factor of safety.

As an alternative to the use of the mathematical relationship, one may utilize the design charts shown in Figures A-5 to A-19. These design charts were established to consider ranges in coarse and fine aggregate specific gravity and air void content. The designer of the design chart which will satisfy the condition for his aggregates and the desired air void content.

5.2 Compare the optimum fine aggregate content (Y) determined under section 5.1 to the amount passing the No. 8 sieve of the contractor's proposed job-mix formula. If these values differ by more than plus or minus 1 percentage point, reconstruct a revised or adjusted job-mix formula using the value determined for optimum fine aggregate content. Recompute the proportions of coarse and fine aggregates (as received) to meet the revised job-mix formula for submission to the contractor.

Note - If the proposed and revised job-mix gradations are significantly different, it may be necessary to rerun portions of this procedure.

Optimum Mixing Temperature

6.1 Prepare a 1000 gram-sample of aggregate in the proportions determined under section 5. Mix this sample at the asphalt content determined under section 3.2 at a temperature corresponding to an asphalt viscosity of 800 centistokes determined under section 2.3. When completely coated, transfer the mixture to a pyrex glass plate (8-9-in. diameter) and spread the mixture with a minimum of manipulation. Return to the oven at the mixing temperature. Observe the bottom of the plate after 15 and 60 minutes. A slight puddle at points of contact between aggregate and glass plate is suitable and desirable. Otherwise, repeat the test at a lower mixing temperature, or higher if necessary.

> Note - If asphalt drainage occurs at a mixing temperature which is too low to provide for adequate drying of the aggregate, an asphalt of a higher grade should be used (AC-20 or AR-80).

Resistance to Effects of Water

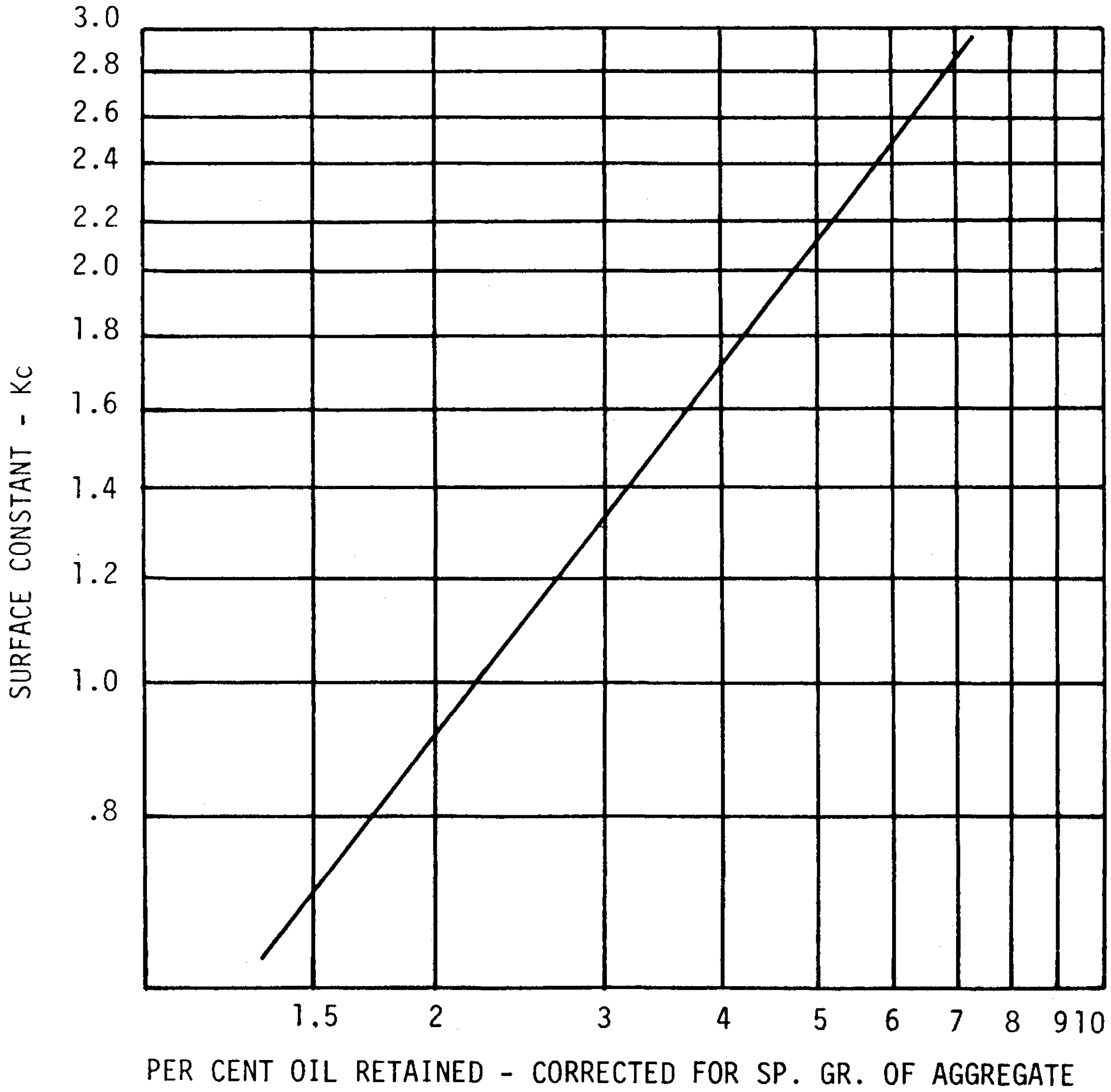
7.1 Conduct the Immersion-Compression Test (AASHO T 165 and T 167) on the designed mixture. Prepare samples at the optimum mixing temperature determined in section 6.1. Use a molding pressure of 2000 psi rather than the specified value of 3000 psi.

After 4-day immersion at 120 F, the index of retained strength shall not be less than 50 percent unless otherwise permitted.

> Note - Additives to promote adhesion that will provide adequate retained strength may be used when necessary.

Table A-1: Selection of Design Chart

FIGURE NUMBER	AIR VOID CONTENT, PERCENT	AGGREGATE SPECIFIC GRAVITY	
		COARSE	FINE
A-5	15	2.65	2.65
A-6	20	2.65	2.65
A-7	25	2.65	2.65
A-8	15	1.80	2.65
A-9	20	1.80	2.65
A-10	25	1.80	2.65
A-11	15	1.60	2.65
A-12	20	1.60	2.65
A-13	25	1.60	2.65
A-14	15	1.40	2.65
A-15	20	1.40	2.65
A-16	25	1.40	2.65
A-17	15	1.20	2.65
A-18	20	1.20	2.65
A-19	25	1.20	2.65



Material Used: Aggregate - Passing 3/8", Ret. No. 4 Sieve
Oil - SAE 10

Oil Retained Corrected (%) = Oil Retained (%) x

$$\frac{\text{"apparent" sp. gr. of Coarse Aggregate}}{2.65}$$

Figure A-1. Chart for determining surface capacity (Kc) of coarse aggregate (from Reference 10).

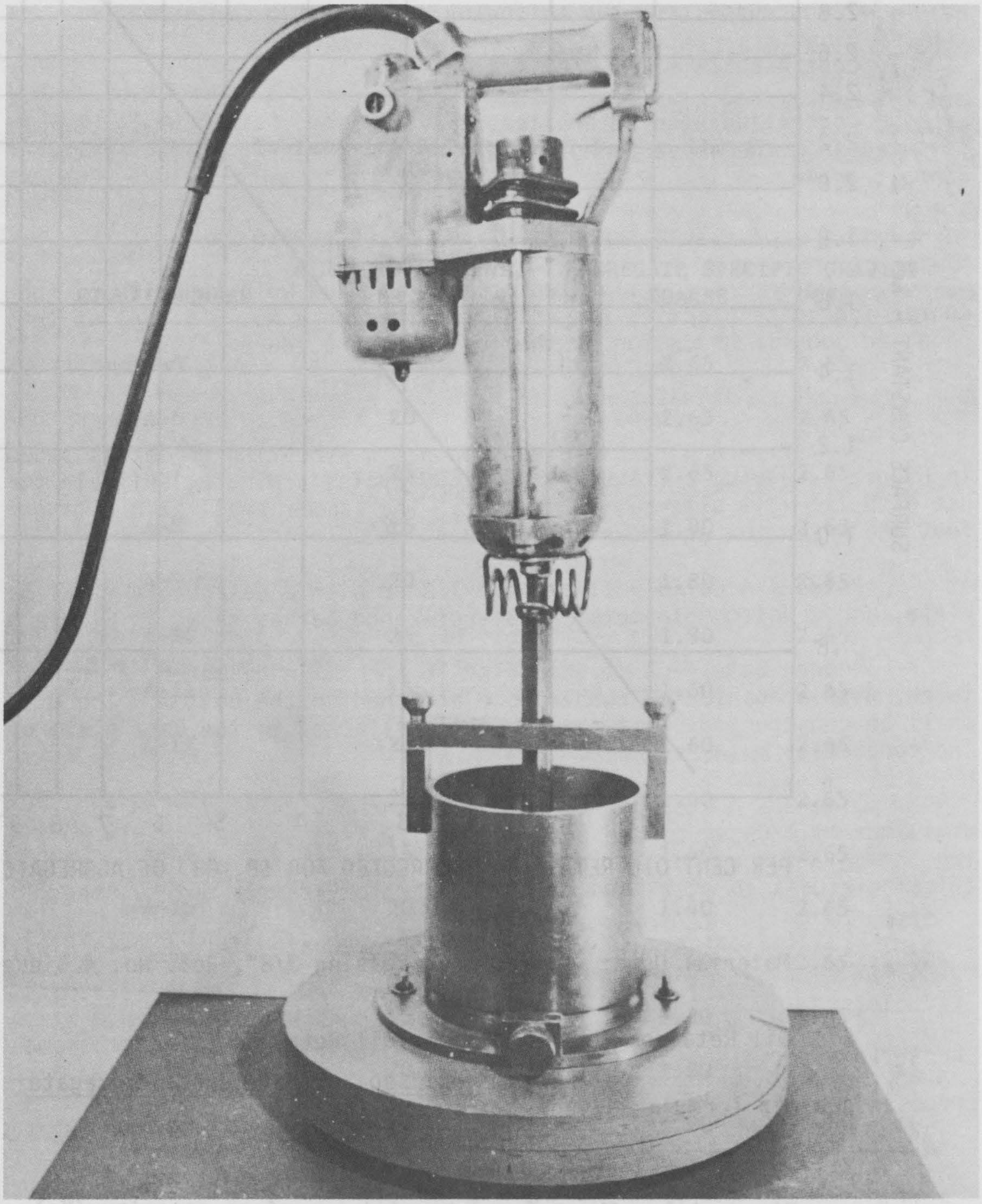


Figure A-2. FHWA vibratory compaction apparatus (from Reference 11).

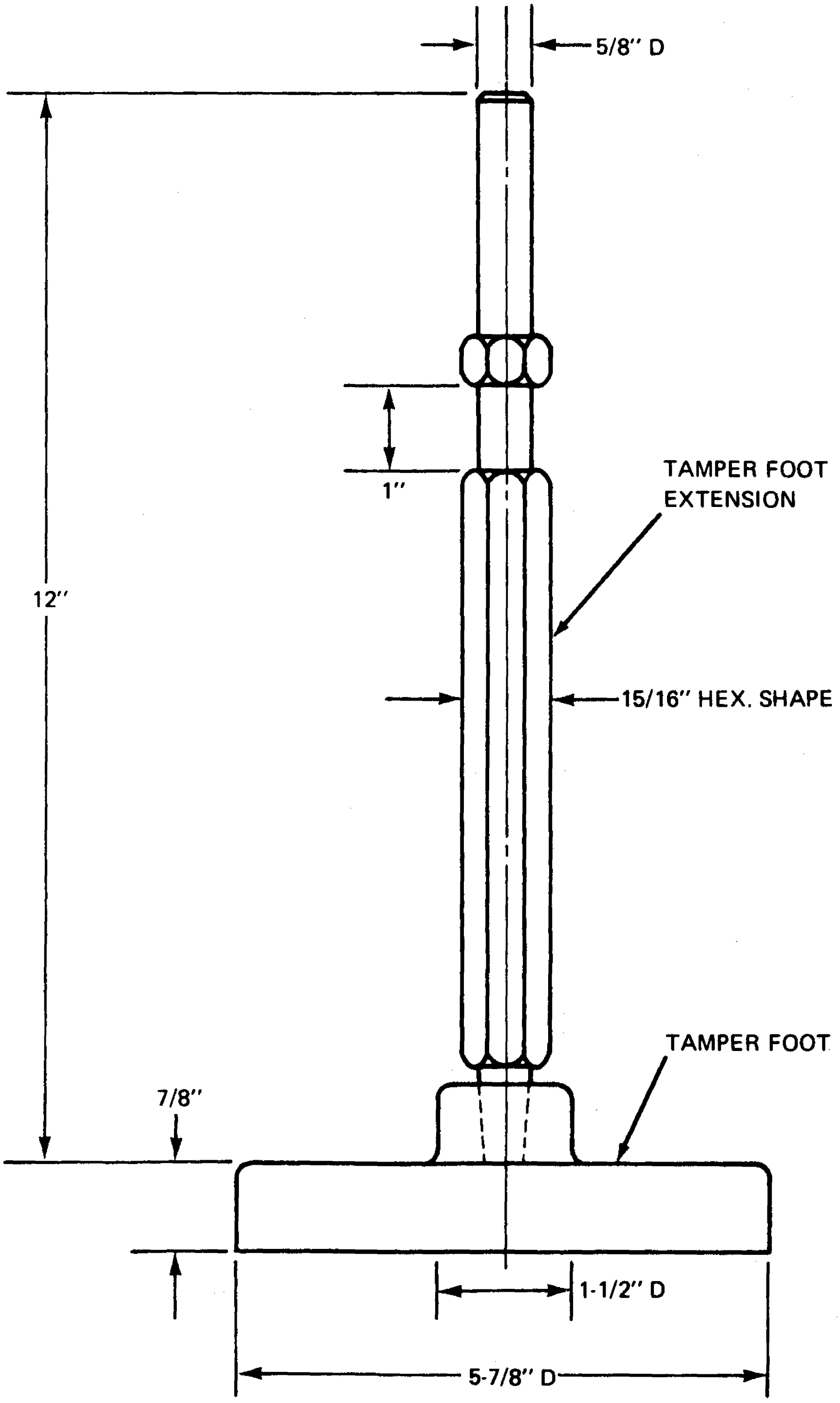


Figure A-3. Tamper foot and extension (from Reference 11).

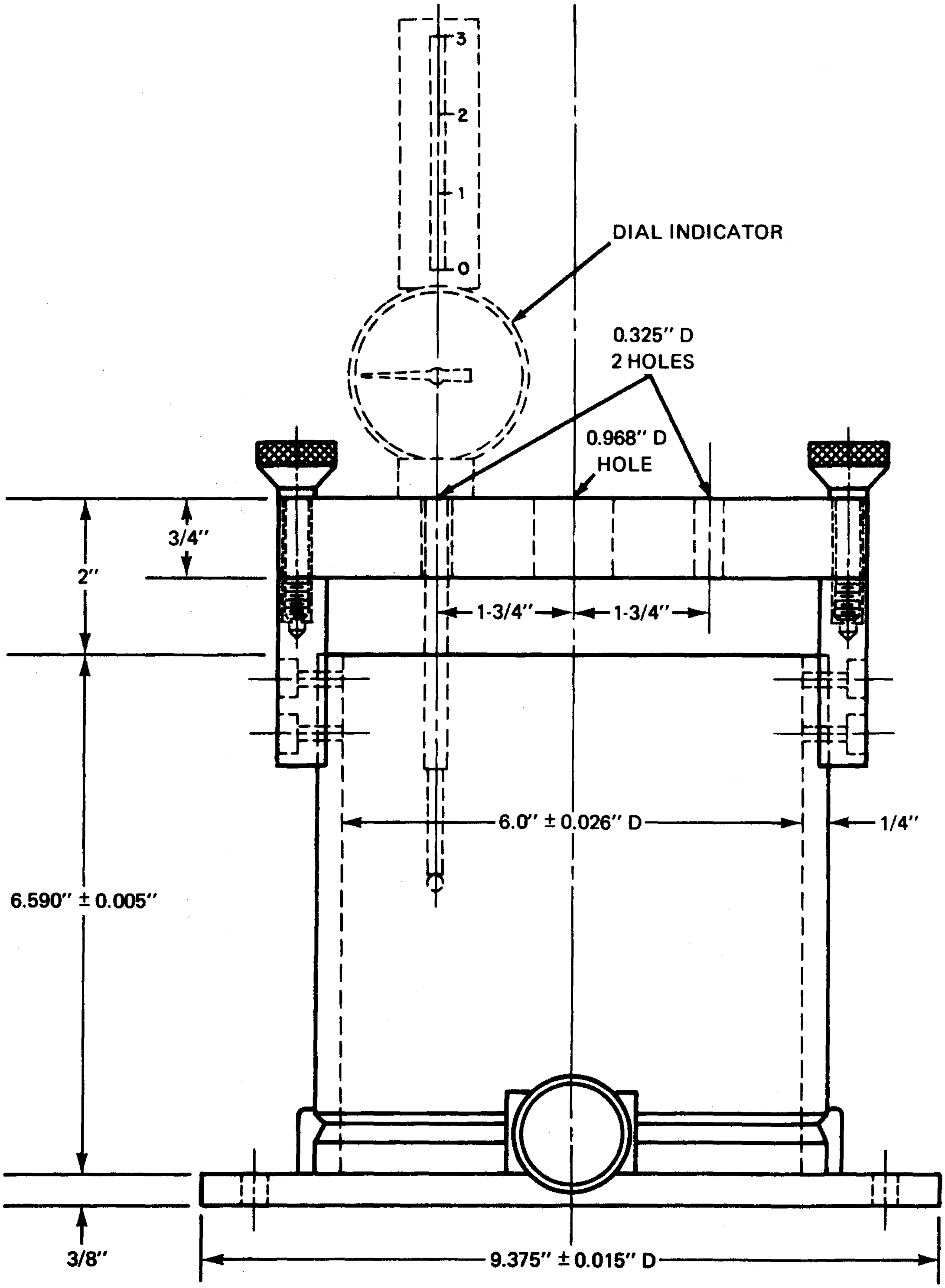
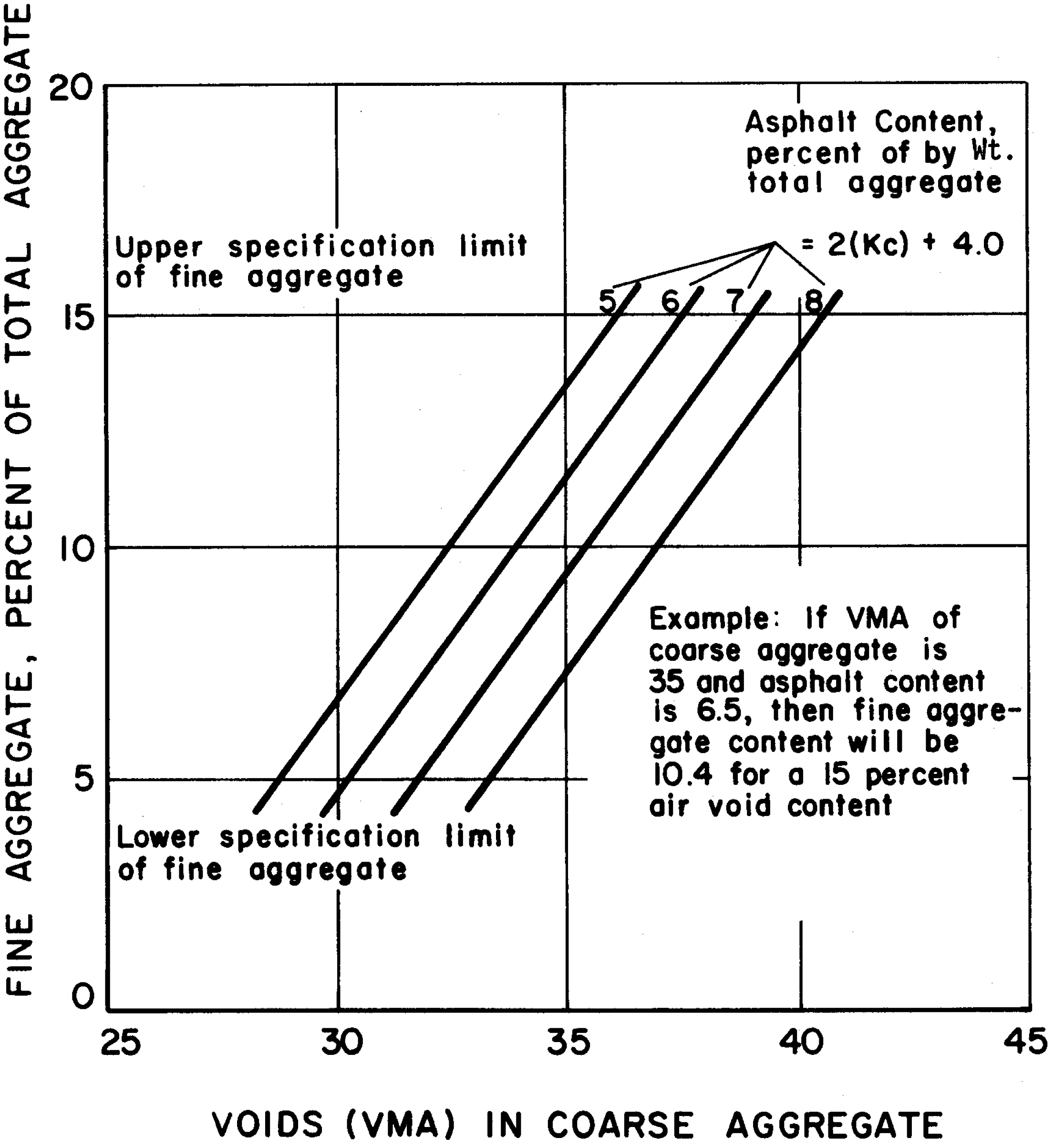


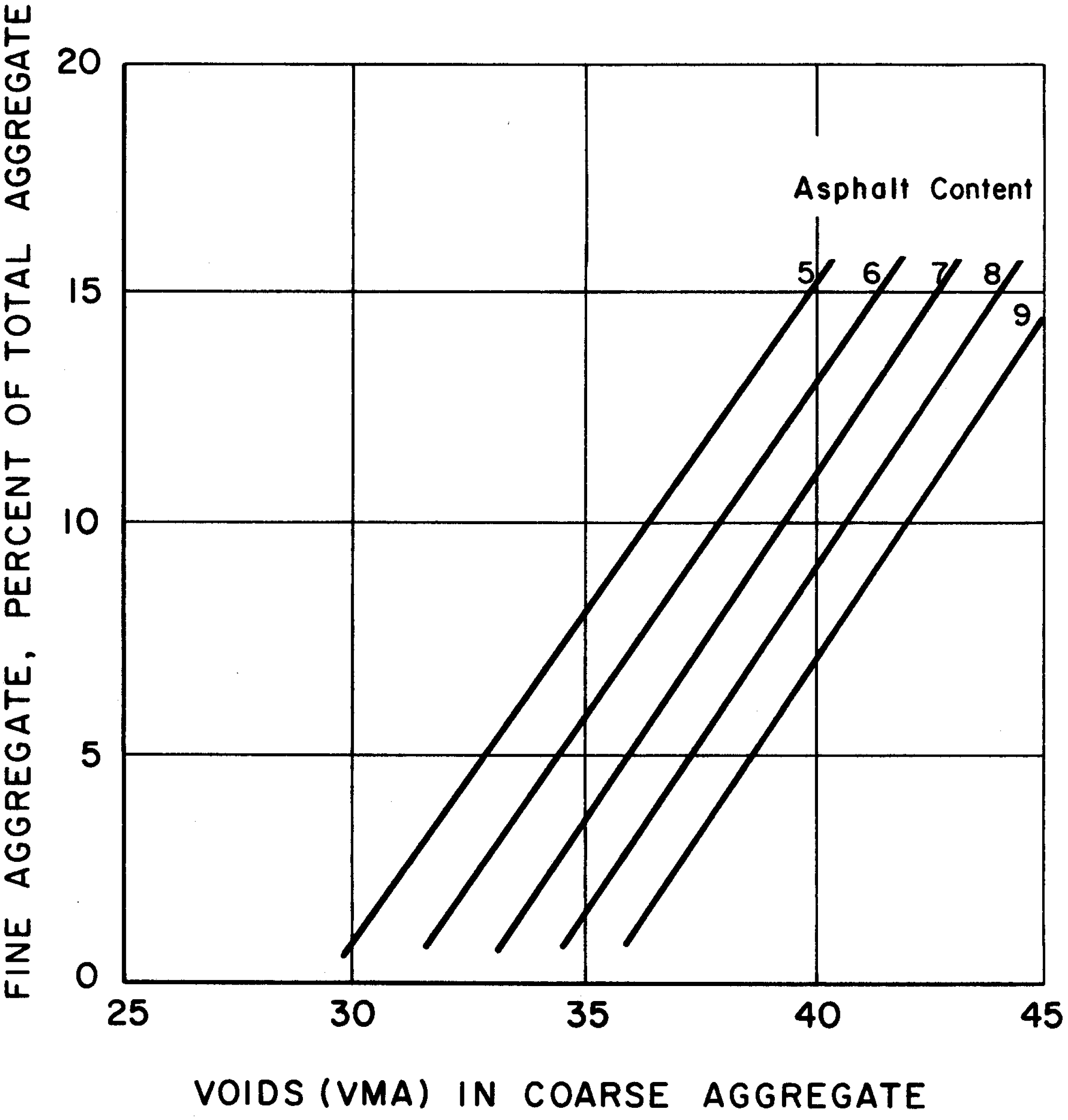
Figure A-4. Cylindrical mold for testing granular materials (from Reference 11)



Assumptions Used in Deriving Chart:

Uc = 165.4 pcf (sp. gr. = 2.650)
Uf = 165.4 pcf (sp. gr. = 2.650)
Ua = 62.4 pcf (sp. gr. = 1.000)
V = 15.0 percent

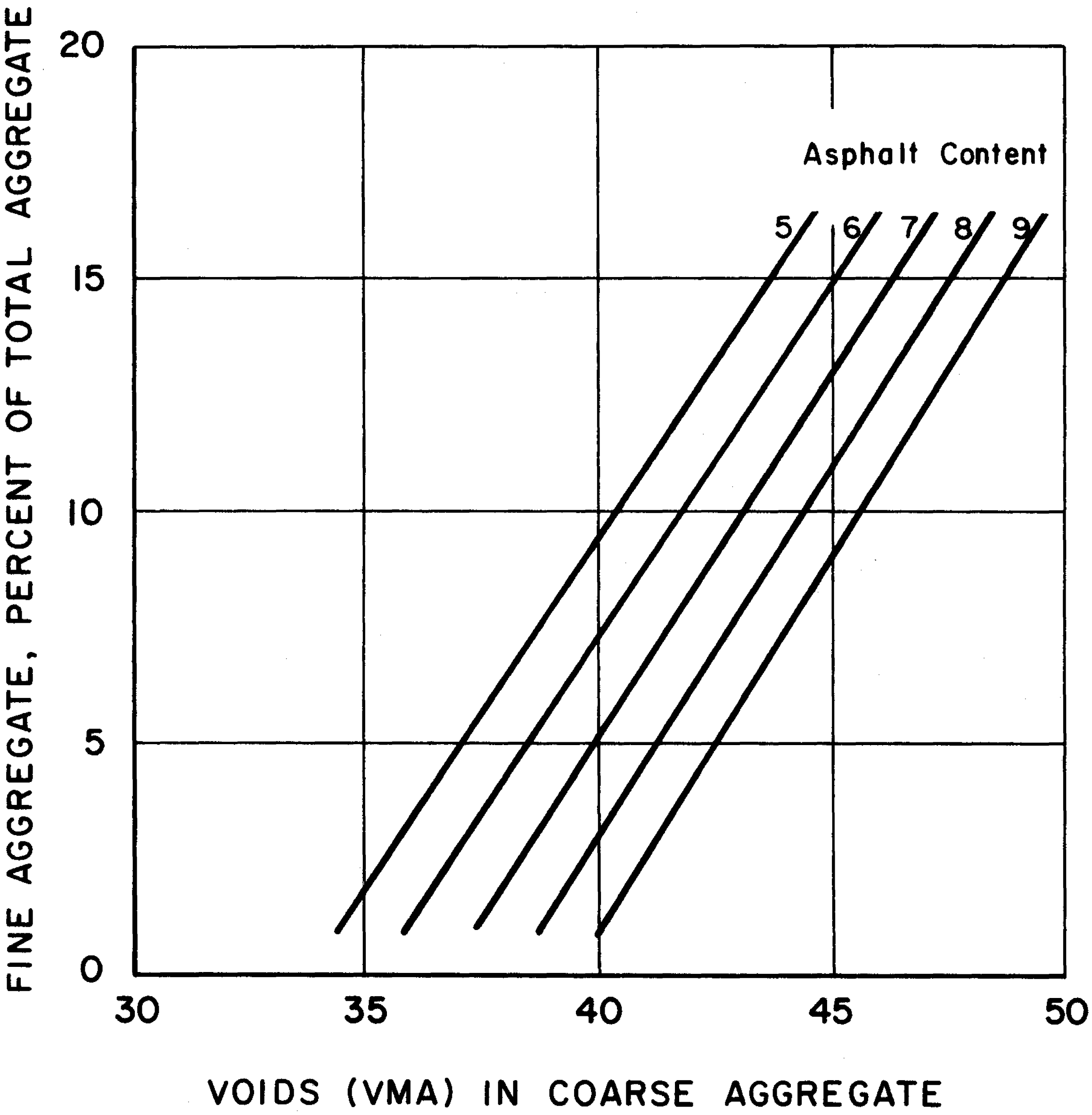
Figure A-5. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 165.4 pcf (sp. gr. = 2.65)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.0)
V = 20.0 percent

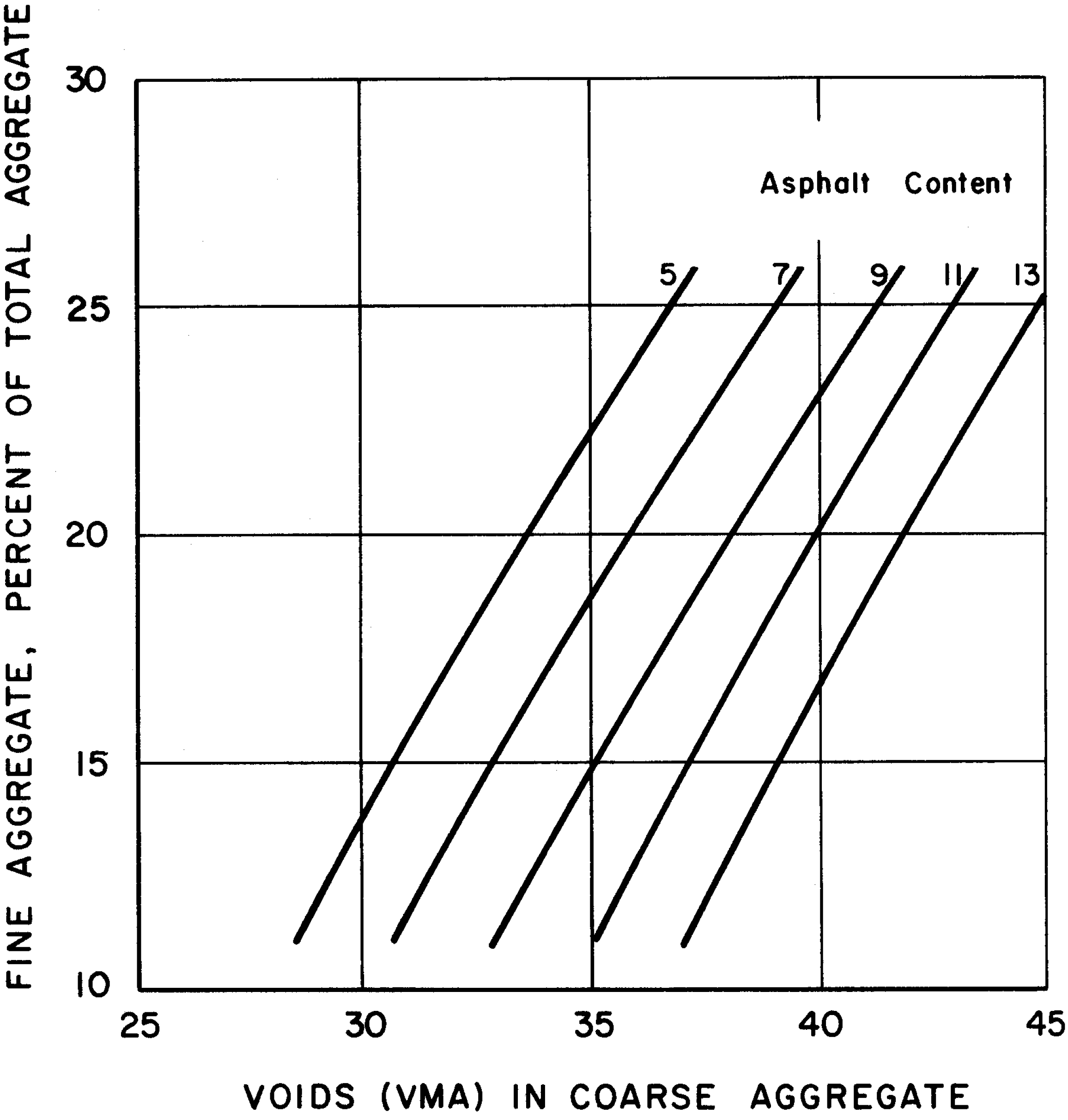
Figure A-6. Determination of Optimum Fine Aggregate Content.



<u>Assumptions Used in Deriving Chart</u>:

Uc = 165.4 pcf (sp. gr. = 2.65)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 25.0 percent

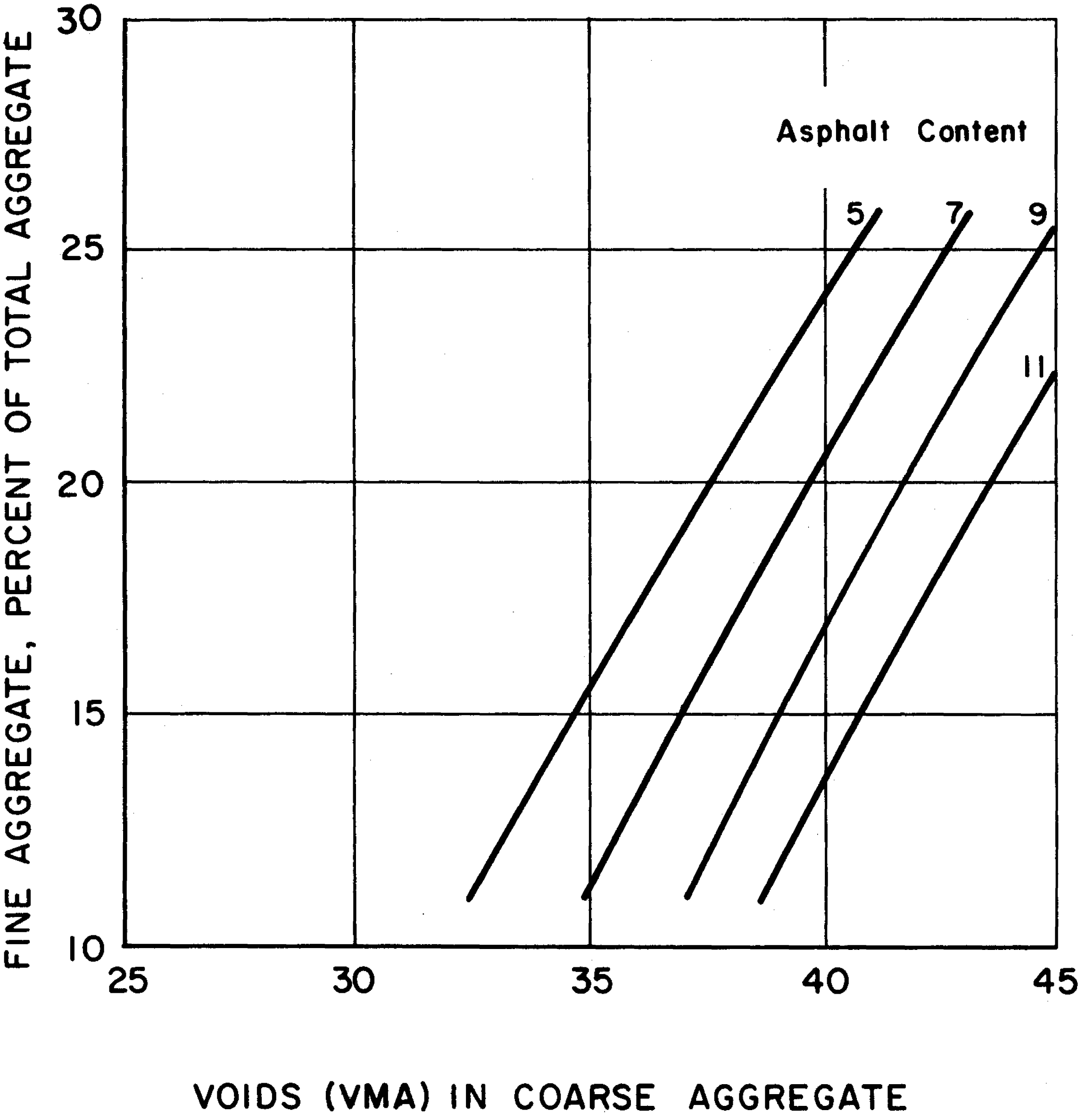
Figure A-7. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 112.3 pcf (sp. gr. = 1.80)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 15 percent

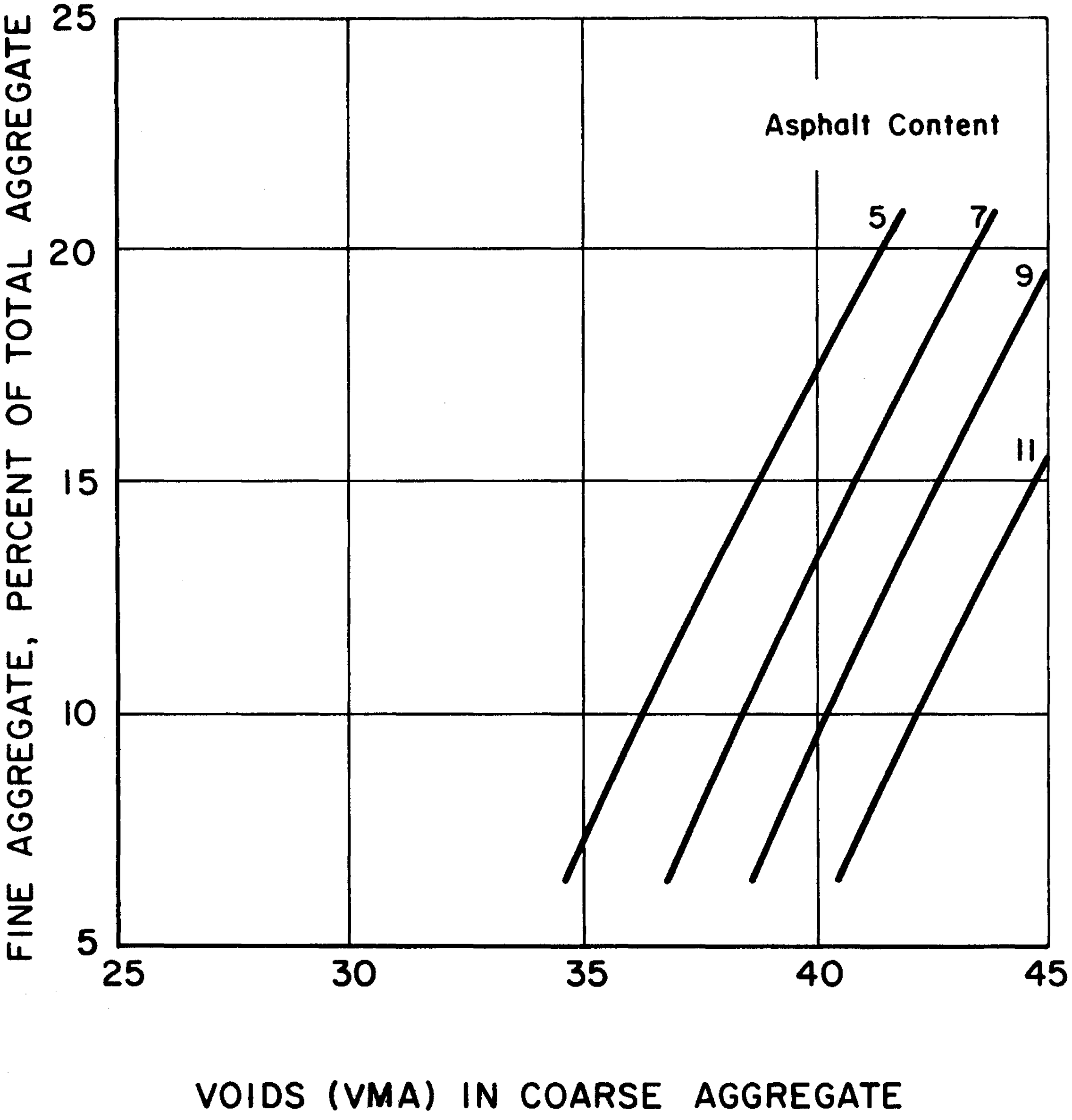
Figure A-8. Determination of Optimum Fine Aggregate Content.



Assumption Used in Deriving Chart:

Uc = 112.3 pcf (sp. gr. = 1.80)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 20 percent

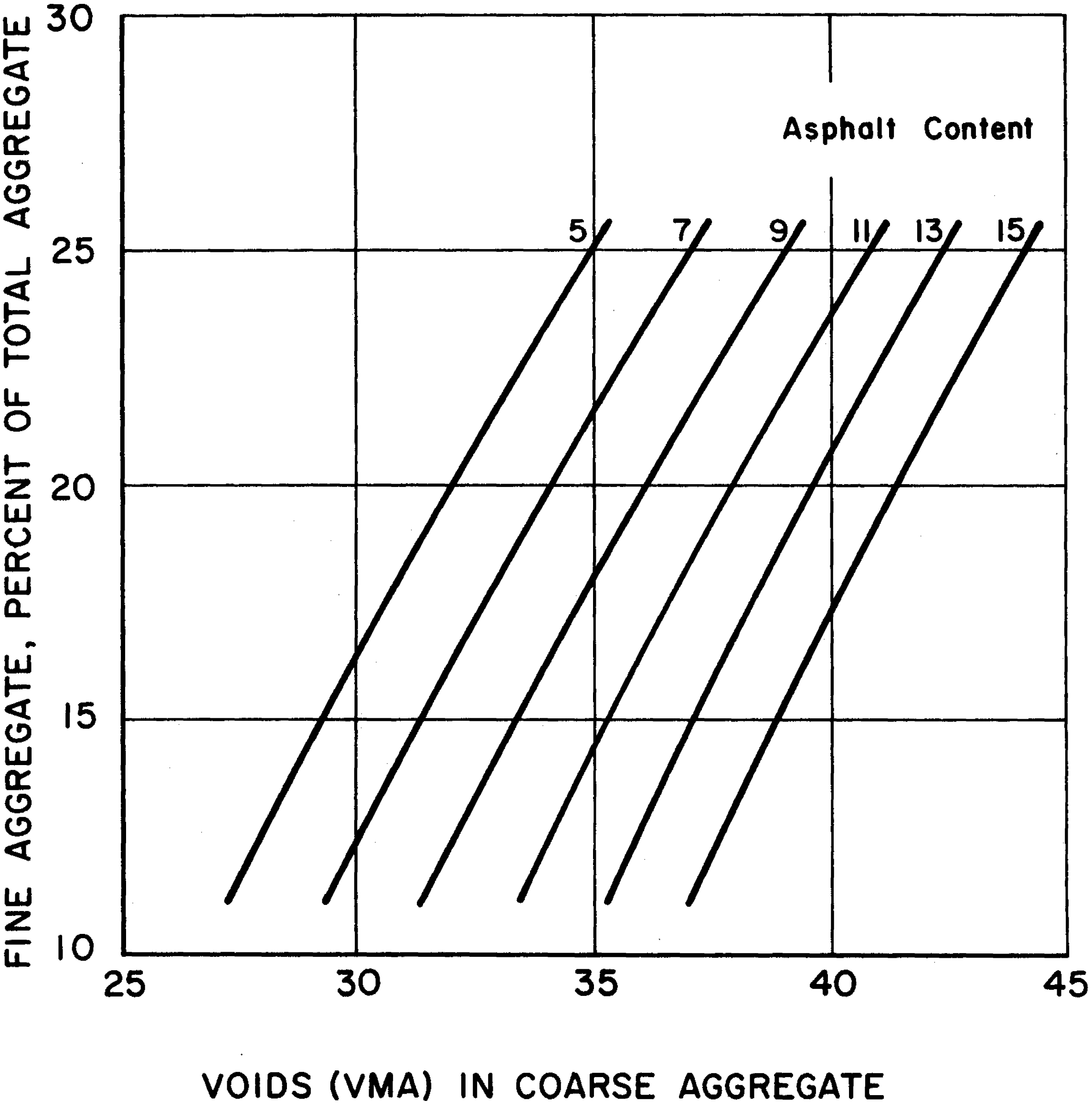
Figure A-9. Determination of Optimum Fine Aggregate Content.



Assumption Used in Deriving Chart:

Uc = 112.3 pcf (sp. gr. = 1.80)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 25 percent

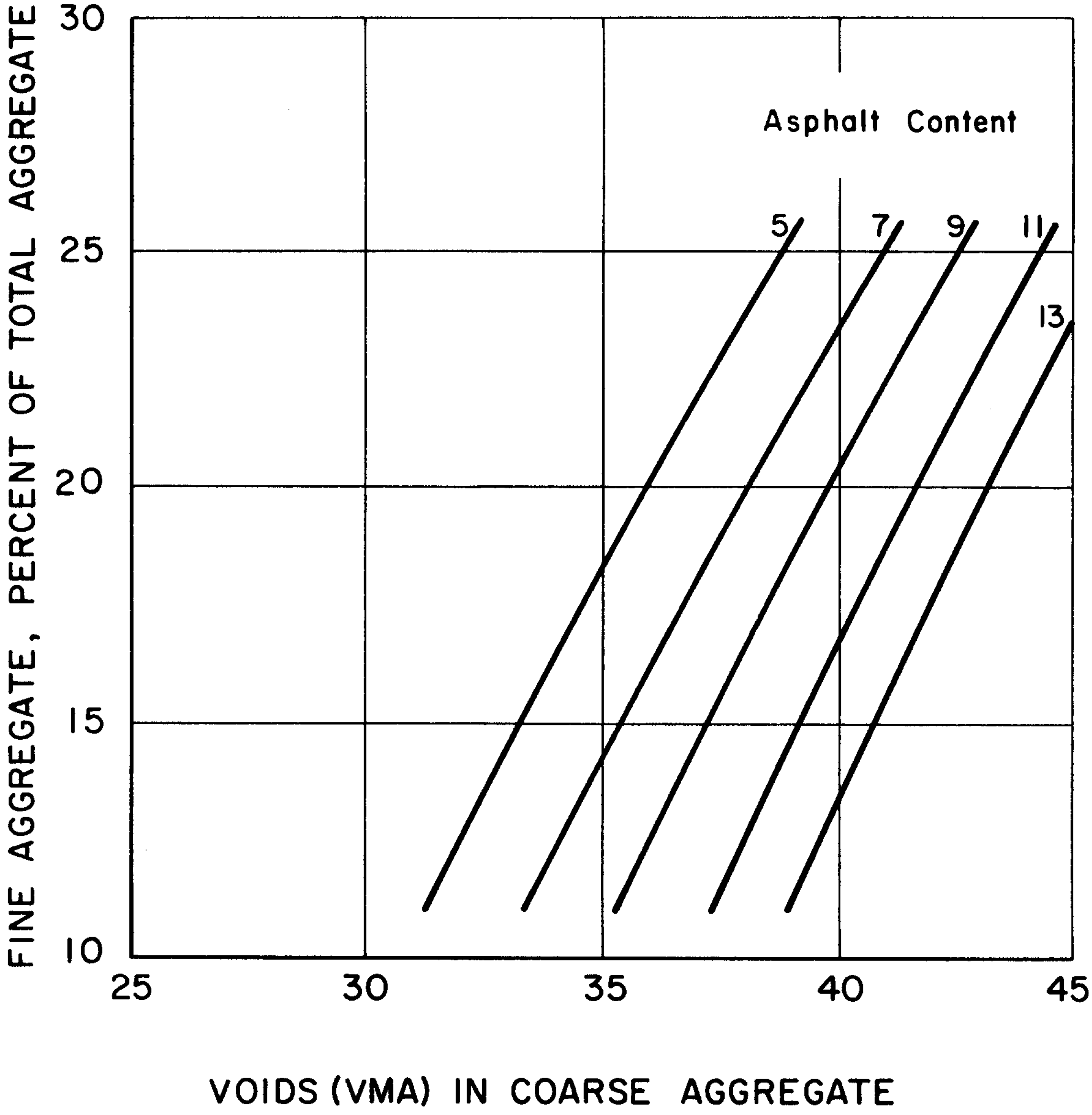
Figure A-10. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 99.8 pcf (sp. gr. = 1.60)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 15 percent

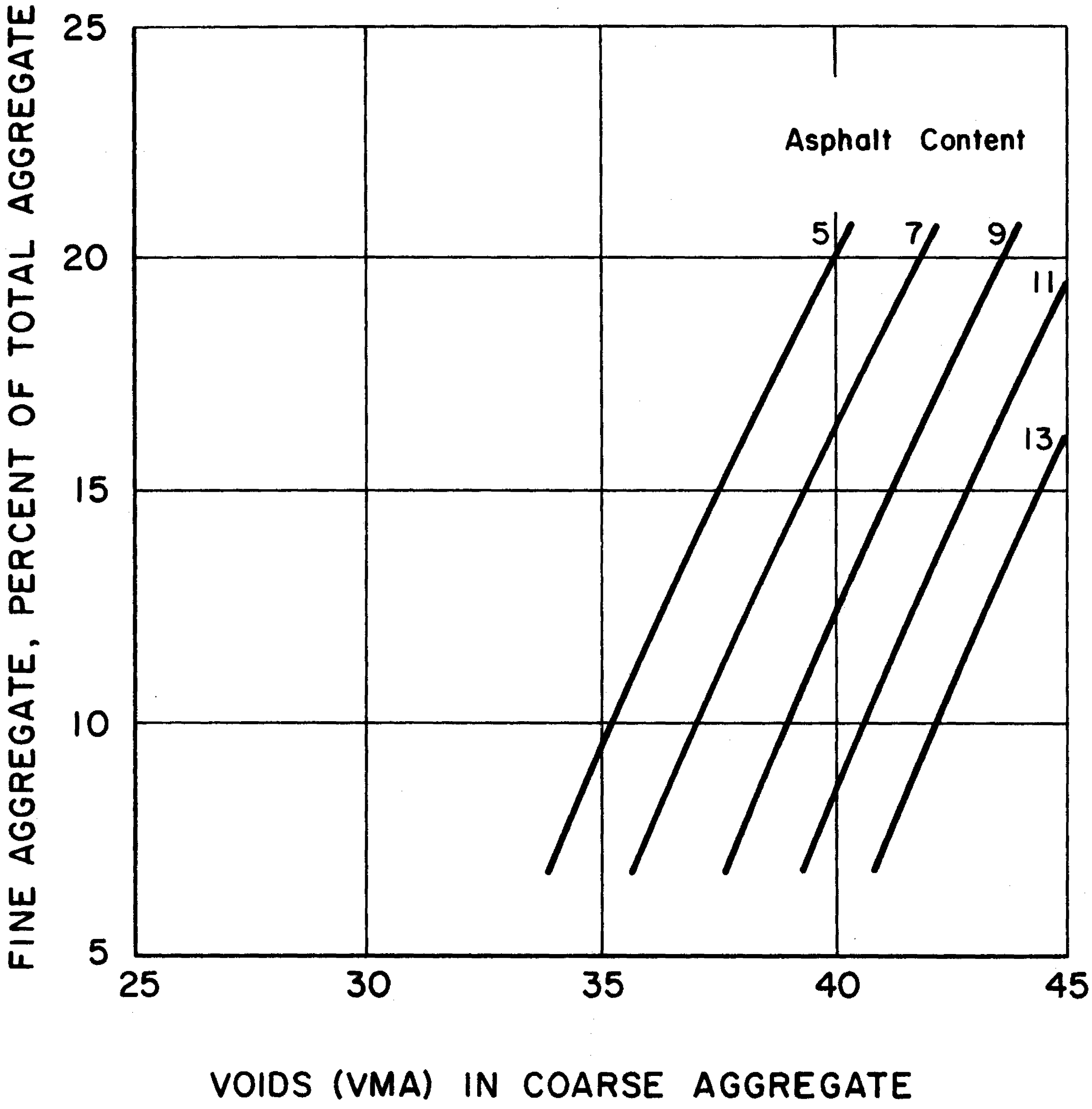
Figure A-11. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 99.8 pcf (sp. gr. = 1.60)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 20 percent

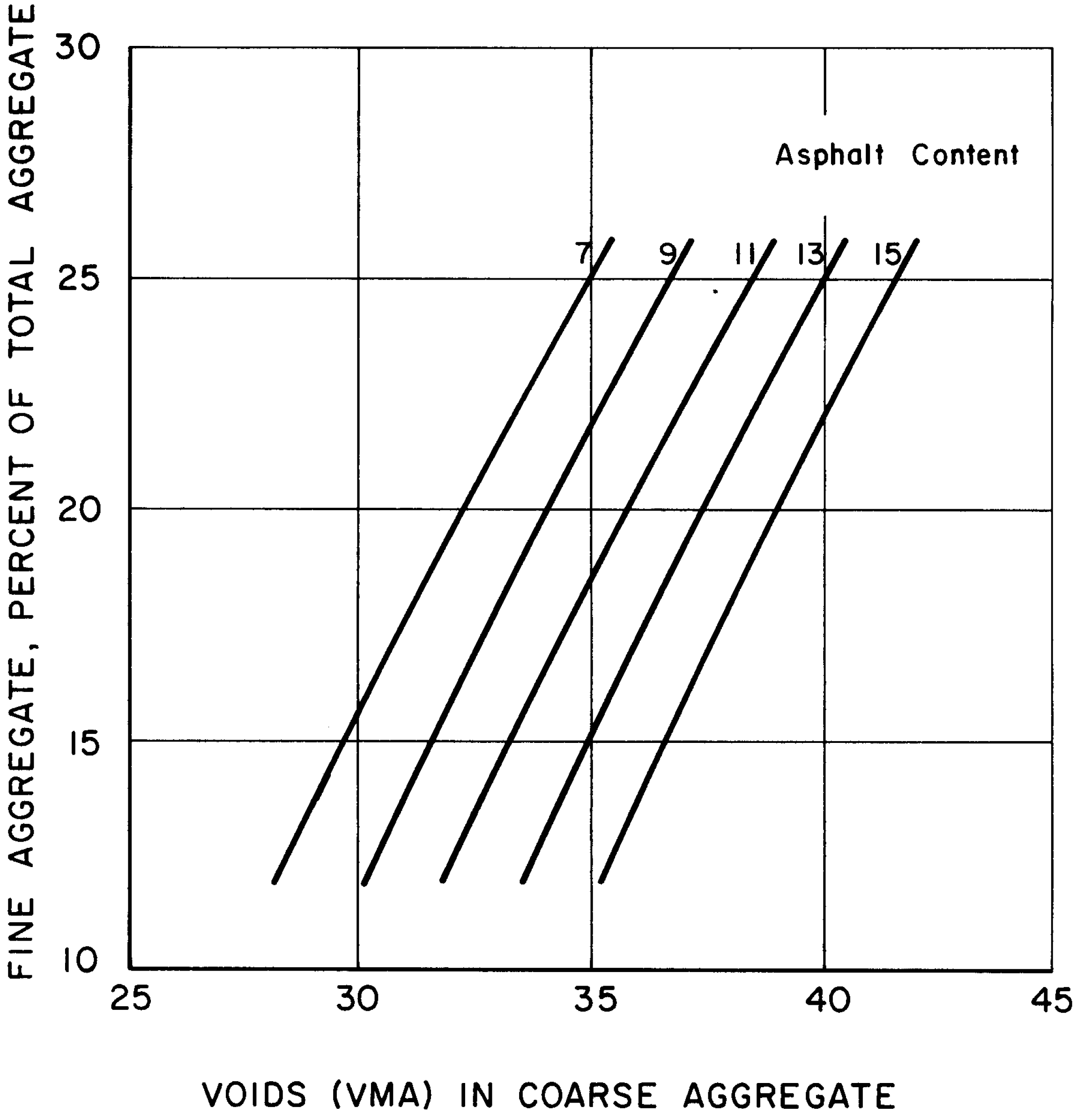
Figure A-12. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 99.8 pcf (sp. gr. = 1.60)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 25 percent

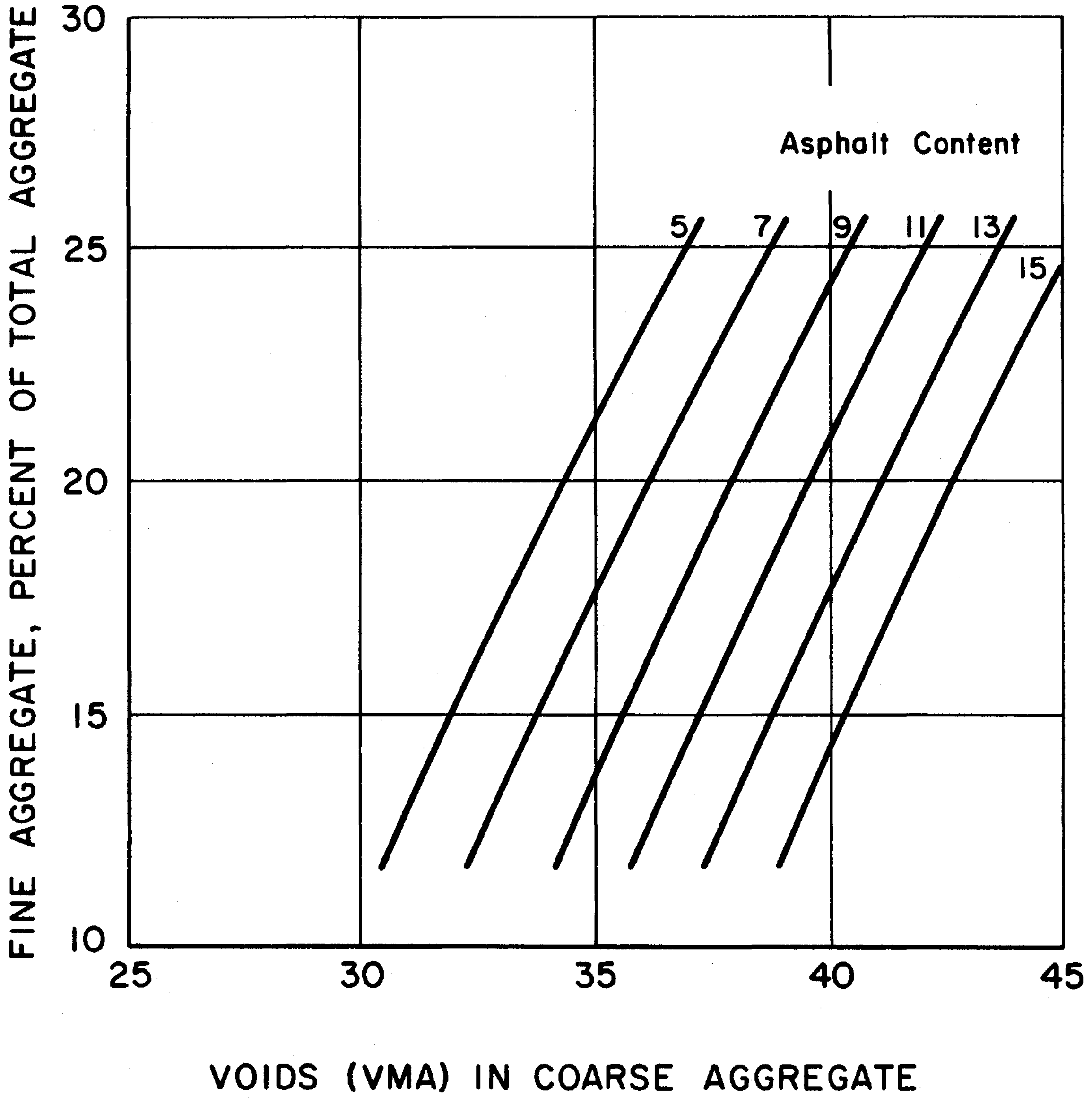
Figure A-13. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 87.4 pcf (sp. gr. = 1.40)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 15 percent

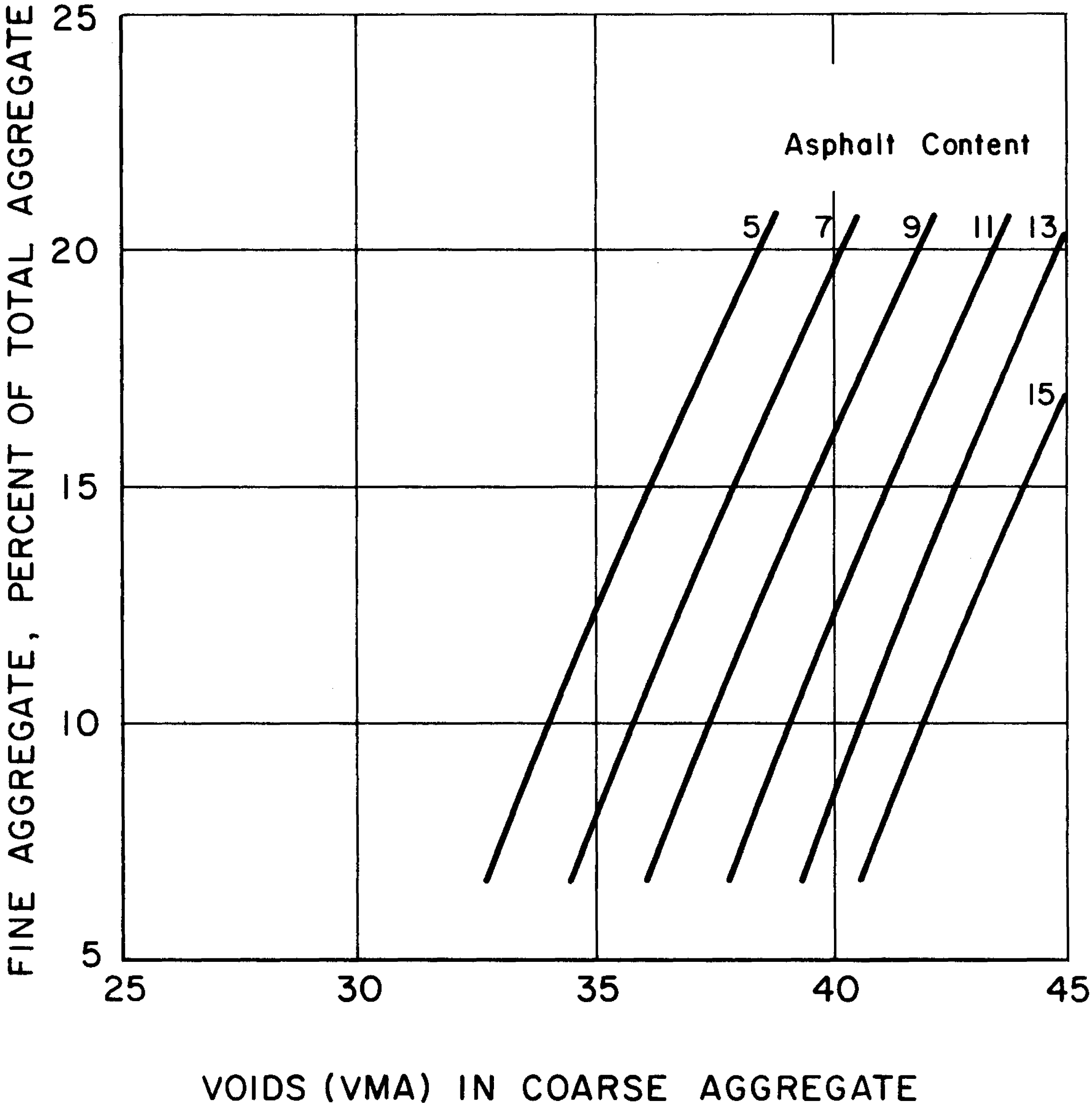
Figure A-14. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 87.4 pcf (sp. gr. = 1.40)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 20 percent

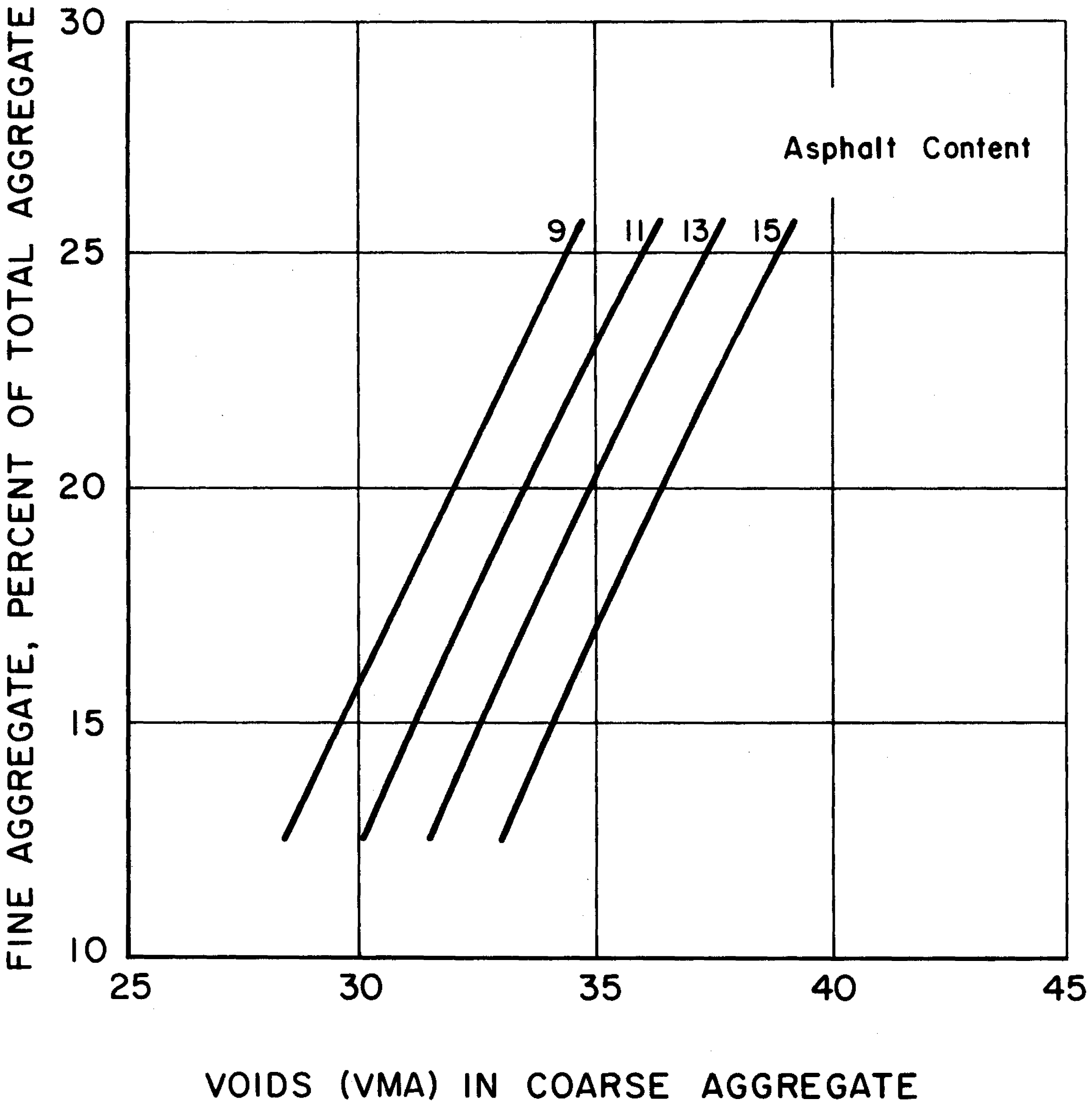
Figure A-15. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 87.4 pcf (sp. gr. = 1.40)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 25 percent

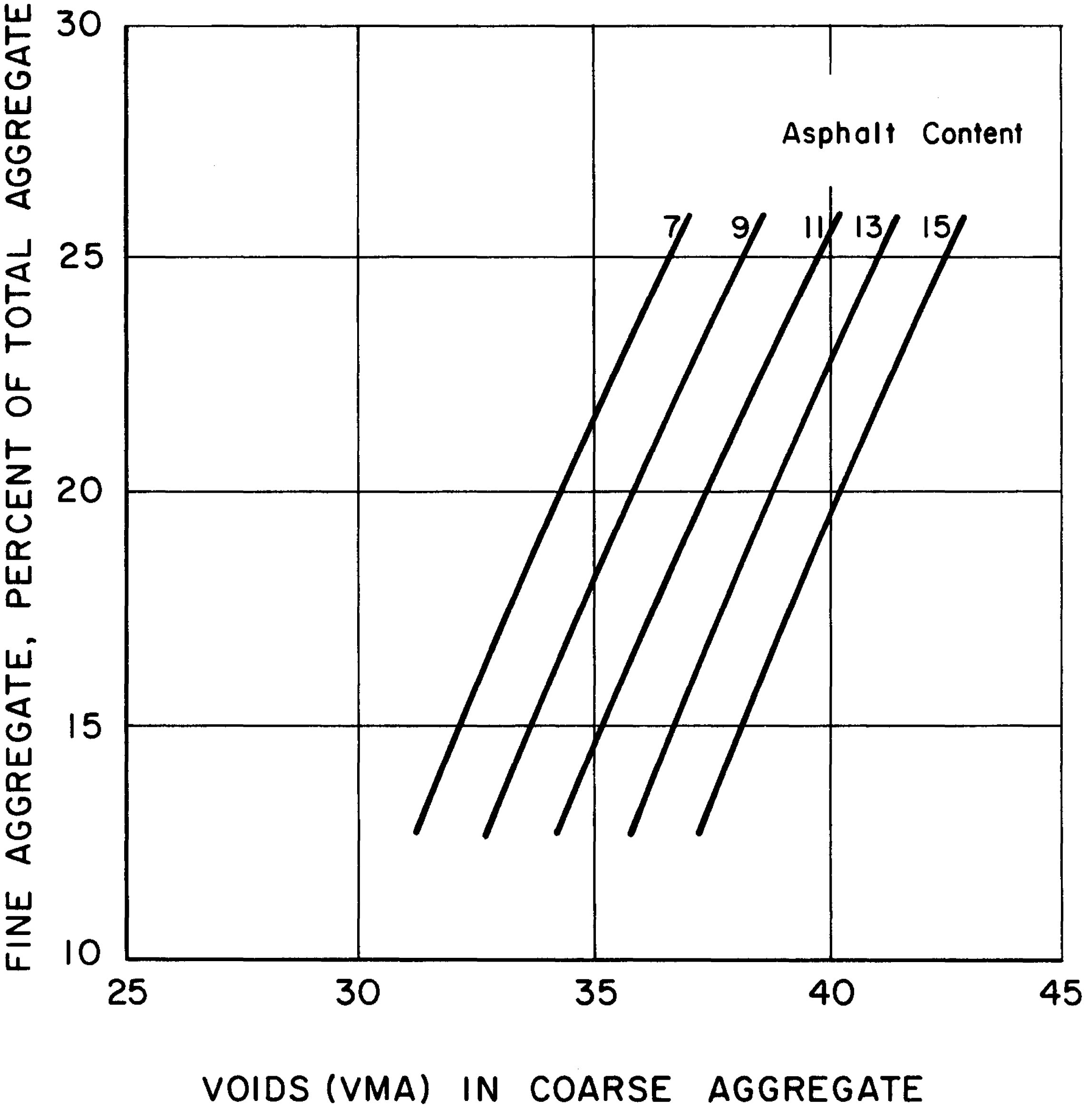
Figure A-16. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 74.9 pcf (sp. gr. = 1.20)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 15 percent

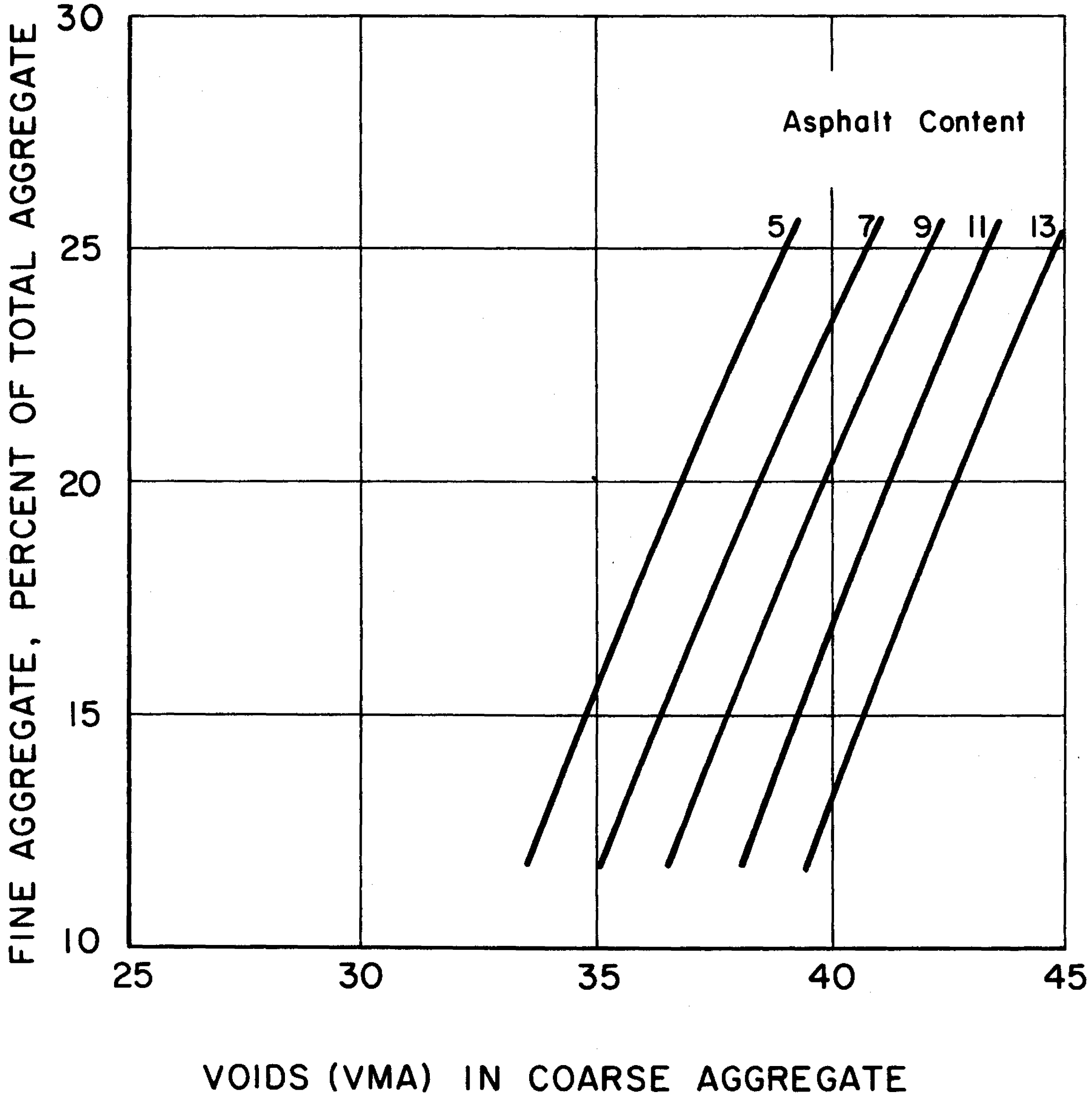
Figure A-17. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 74.9 pcf (sp. gr. = 1.2)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 20 percent

Figure A-18. Determination of Optimum Fine Aggregate Content.



Assumptions Used in Deriving Chart:

Uc = 74.9 pcf (sp. gr. = 1.2)
Uf = 165.4 pcf (sp. gr. = 2.65)
Ua = 62.4 pcf (sp. gr. = 1.00)
V = 25 percent

Figure A-19. Determination of Optimum Fine Aggregate Content.

APPENDIX B

DETERMINATION OF ASPHALT CONTENT FOR OPEN-GRADED ASPHALT FRICTION COURSE CONTAINING LIGHTWEIGHT AGGREGATE*

(FHWA Alternate Procedure)

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*after reference 23

Determination of Asphalt Content for Open-Graded Asphalt Friction Course Containing Lightweight Aggregate

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This is an extension of the discussion on selection of asphalt content contained in Research Report FHWA-RD-74-2, "Design of Open-Graded Asphalt Friction Courses." It will be recalled that asphalt content percentage (based on aggregate weight) is computed from the following formula:

$$\text{Percent Asphalt} = 2.0(K_c) + 4.0$$

Although the above formula is empirical, it does provide excellent results for a wide range of aggregate materials. It should be recognized, however, that the relationship is actually only applicable for those conditions upon which the equation is founded. These conditions have never been stated primarily because they are not exactly known and except for a few unusual circumstances they are not particularly needed.

Probably the most important conditional property which could be considered is aggregate specific gravity. This is because asphalt cement requirements are volume related whereas asphalt quantities are specified by weight. Considering the evolutionary development of the above equation, it probably would not be incorrect to assume that a conditional requirement is an aggregate apparent specific gravity of 2.65. Then, as in the test for K_c, for aggregate with apparent specific gravities significantly different from 2.65, a correction would be required and made to the value computed for asphalt content. The following illustrates this correction, which happens to be the reciprocal of the correction in the K_c test.

$$\begin{array}{l}\text{Percent Asphalt}\\ \text{Corrected}\end{array} = \begin{array}{l}\text{Percent Asphalt}\\ (2.0\ K_c + 4.0)\end{array} \times \frac{2.65}{\begin{array}{l}\text{Apparent Sp. Gr. of}\\ \text{Coarse Aggregate}\\ \text{(3/8-inc. to No. 4)}\end{array}}$$

The corrected value for percent asphalt should then be used in all subsequent portions of the design procedure. The magnitude of the correction to the percent asphalt value would depend on the apparent specific gravity of the aggregate under test and also on the value determined for percent asphalt ($2.0\ K_c + 4.0$). These correction values have been determined for illustrative purposes and are listed in Table B-1. Considering the empirical nature of the asphalt content formula and that most aggregates have apparent specific gravities within the range of 2.50 to 2.80, the use of a correction factor would seem superfluous. However, for low specific gravity aggregate materials the correction can be quite significant as is shown in Table B-1.

For informational purposes, a review was made of all the past mixture designs prepared by the Materials Division for Region 15 Demonstration Project 10 in order to visualize what effect such a correction factor would have had on those designs. Comparative results are shown in Table B-2. All mixtures were designed for fine aggregate content with the uncorrected percent asphalt value ($2.0\ K_c + 4.0$) except for the Louisiana mixture, which was designed with the corrected value.

It should be noted that in 10 out of 13 cases an equal or greater amount of asphalt was used to that which would have been used utilizing a correction factor. While this may not necessarily be satisfactory, it would seem preferable to be on the high side without the correction because the air void and gradation requirements on these mixes were also satisfactory. However, for the Minnesota, Mississippi No. 2, and the Hawaii designs, the corrected value was considerably different.

Therefore, in order to obtain consistency between mixture designs and to avoid any further possible confusion, it is suggested that a correction factor for aggregate specific gravity be included in the design procedure as a general practice in determining asphalt content. The recommended refinement to the design procedure described in Report FHWA-RD-74-2 is as follows:

> 3.2 Determine the required asphalt content which is based on weight of aggregate from the following relationship (16):

$$\text{Percent Asphalt} = 2.0(K_c) + 4.0^{a/}$$

(1) If apparent specific gravity for the coarse aggregate fraction (3/8-in. to No. 4) is greater than 2.70 or less than 2.60, apply a correction to the value obtained for percent asphalt using the following relationship:

$$\begin{array}{c}\text{Percent Asphalt}\\ \text{(corrected)}\end{array} = \begin{array}{c}\text{Percent}\\ \text{Asphalt}\end{array} \times \frac{2.65}{\begin{array}{l}\text{Apparent Sp. Gr. of}\\ \text{Coarse Aggregate}\\ \text{(3/8-in. to No. 4)}\end{array}}$$

Use the corrected value for asphalt content in all subsequent portions of the procedure.

No correction need be applied for viscosity. The asphalt content computed from the above formula would be the same regardless of the asphalt grade.

[a/] Other equations which have been used are: $EOA = 1.5(K_c) + 3.5$ and $EOA = 1.5(K_c) + 4.0$ by California and Colorado, respectively.

Another situation which someone may yet encounter and which would usually be associated with low specific gravity aggregates (although not necessarily so) is the highly absorptive aggregate. The relationship for K_c does not provide for corrected oil retained values larger than about 8 percent, so if one were to encounter such an aggregate the following procedure is suggested (beginning with the determination of asphalt content):

a. Follow the recommended design procedure from step 3.1 through step 3.1.3.

b. Follow the instructions in step 3.1.4 except immerse the specimen for 30 minutes.

c. Follow the recommended procedure from step 3.1.5 through step 3.1.7.

d. Then pour sample onto a clean, dry, absorptive cloth; obtain a saturated surface dry condition; pour sample from cloth into a tared pan; reweigh sample to nearest 0.1 gram. Subtract original weight of aggregate and record difference as percent oil absorbed (based on 100 g. of aggregate).

e. Subtract the percent oil absorbed value (see d above) from the percent oil retained value (see c above) and obtain the percent (free) oil retained value.

This value then represents the percent oil retained value that would have been obtained had the aggregate been a nonabsorptive type. The above technique allows one to evaluate the aggregate's surface and shape characteristics without the overwhelming influence of a large quantity of absorbed oil.

f. Follow the recommended procedure from steps 3.1.8 through step 3.2 including also the refinement to asphalt content for specific gravity of aggregate. The only exception is that the percent (free) oil retained value is used (from par. e) to obtain K_c. Thus the asphalt quantity determined is the "effective" asphalt content.

g. Follow the recommended procedure as indicated through sections 4 and 5. Since asphalt absorption is not presently included in the formula for the determination of fine aggregate content, it is particularly desirable that the effects of oil absorption in the K_c test be excluded for the case of the highly absorptive aggregate.

h. Prepare a trial mixture using an asphalt content equal or somewhat greater (try to estimate amount that will be absorbed) than the effective asphalt content determined above (in par. f) and also using the aggregate gradation as determined above (in par. g).

Using a suitable technique, such as the test for maximum specific gravity of asphalt mixtures (AASHTO T 209), determine the actual quantity of asphalt absorbed (in percent, based on total weight of aggregate).

i. Determine the total asphalt content of the subject mixture by adding the effective asphalt content (from par. f) to the absorbed asphalt content (from par. h).

j. Follow the recommended procedure as indicated in sections 6 and 7 using the total asphalt content for all subsequent computations and trials (from par. i).

The following are two example calculations which will help clarify the above discussion. The data for these illustrations were obtained from the Louisiana, Demonstration Project 10 design problem.

Method A - Low specific gravity aggregate and normal procedure of handling oil absorption.

Given: Apparent specific gravity of 3/8-in. to No. 4 coarse aggregate = 1.423

Oil retention (grams of oil per 100 gram aggregate) = 9.8

1) Compute corrected oil retained value.

$$9.8 \text{ X } \frac{1.423}{2.65} = 5.26$$

2) Determine K_c (from chart) $K_c = 2.25$

3) Compute percent asphalt (Agg. basis)

Percent AC = $2\ K_c + 4.0$

Percent AC = 4.50 + 4.0

Percent AC = 8.50

4) Compute corrected percent AC value.

$$\text{Percent AC} = 8.50 \text{ X } \frac{2.65}{1.423} = 15.83 \text{ (Agg. basis)}$$

$$= 13.67 \text{ (Mix basis)}$$

Method B - Low specific gravity aggregate and alternate procedure for handling oil absorption.

Given: Apparent specific gravity of 3/8-in. to No. 4

Coarse aggregate = 1.423

Oil retention (grams of oil per 100 grams of aggregate, 30-minute soak = 11.8 (par. b and c)

Oil absorbed (grams of oil per 100 grams of aggregate = 6.2 (par. d).

1) Compute free oil retained - 11.8 - 6.2 = 5.6 (par. e).

2) Compute corrected free oil retained value (par. f)

$$5.6 \text{ X } \frac{1.423}{2.65} = 3.01$$

3) Determine K_c (from chart) - K_c = 1.33 (par. f)

4) Compute percent effective asphalt content (par. f)

$$\text{Percent AC} = 2\ K_c + 4.0$$

$$\text{Percent AC} = 2.66 + 4.0$$

$$\text{Percent AC} = 6.66$$

5) Compute corrected percent AC value (par. f)

$$\text{Percent AC} = 6.66 \text{ X } \frac{2.65}{1.423} = 12.40 \text{ (Agg. basis)}$$

6) Conduct AASHTO T 209 - determine asphalt absorption (par. h)

Given: Sp. gr. of asphalt = 1.030

Sp. gr. of aggregate gradation = 1.200 (bulk, dry basis)

Trial asphalt content = 15.83 (Agg. basis)
= 13.67 (Mix basis)

Total weight of mixture = 834.6 gram

By test is was found that effective volume of mixture by vacuum immersion = 689.3 cm^3

(a) Asphalt: $\text{Weight} = \frac{13.67}{100}(834.6) = 114.1$

$$\text{Volume} = \frac{114.1}{1.030(1.0)} = 110.78$$

Aggregate: Weight = 834.6 - 114.1 = 720.5

$$\text{Volume} = \frac{720.5}{1.200(1.0)} = 600.42$$

Total volume (bulk) = 711.20 cc

(b) Volume of absorbed asphalt - 711.20 - 689.3 = 21.9 cm^3

(c) Weight of absorbed asphalt - (21.9) (1.030) (1.0) = 22.6 g

(d) Weight of asphalt absorbed per weight of aggregate

$$\frac{22.6}{720.5} = 0.0313 \text{ or } 3.13 \text{ percent}$$

7) Determine total asphalt content

Total percent AC = 12.40 + 3.13 = 15.53 (Agg. basis)
= 13.44 (Mix basis)

Summary of Results (Mix basis)

Louisiana experience = 14 percent (Approx.)

Method A = 13.67

Method B = 13.44

Table B-1 - Correction Values for Percent Asphalt Value

Apparent Specific Gravity of Coarse Aggregate (3/8-in. to No. 4)	Percent Asphalt Value[a] (Percent AC = $2.0\ K_c + 4.0$				
	5.0	6.0	7.0	8.0	9.0
3.10	(.73[b])	(.87)	(1.02)	(1.16)	(1.31)
3.00	(.58)	(.70)	(.82)	(.93)	(1.05)
2.90	(.43)	(.52)	(.60)	(.69)	(.78)
2.80	(.27)	(.32)	(.38)	(.43)	(.48)
2.70	(.09)	(.11)	(.13)	(.15)	(.17)
2.65	0	0	0	0	0
2.60	.10	.12	.13	.15	.17
2.50	.30	.36	.42	.48	.54
2.40	.52	.62	.73	.83	.94
2.30	.76	.91	1.06	1.22	1.37
2.20	1.02	1.23	1.43	1.64	1.84
---	---	---	---	---	---
2.00	1.62	1.95	2.28	2.60	2.92
---	---	---	---	---	---
1.50	3.83	4.60	5.37	6.13	6.90

[a] Based on weight of aggregate.

[b] Values enclosed in parentheses are negative corrections.

Example: Percent asphalt value = $2.0\ K_c + 4.0$

(Let $K_c = 1.0$) $= 2.0(1.0) + 4.0 = 6.0$

Suppose apparent specific gravity = 3.00 (traprock)

Then corrected percent asphalt value = $6.0 - 0.70 =$ 5.30 percent

Table B-2 - Significance of Correction Factor on Previous Design Mixtures

State Project	Apparent Specific Gravity (3/8-in. to No. 4)	Percent Asphalt ($2 K_c + 4.0$)	Difference in Percent Asphalt Used to That Required	
Minnesota	3.019	7.20	6.32	+0.88
New Hampshire	2.800	7.00	6.62	+0.38
Michigan	2.765	6.40	6.13	+0.27
Kentucky	2.650	6.50	6.50	0
New York	2.732	6.60	6.40	+0.20
Mississippi No. 1	2.682	7.24	7.15	+0.09
Mississippi No. 2[a/]	2.478	8.52	9.11	-0.59
Mississippi No. 3	2.743	7.86	7.59	+0.27
Mississippi No. 4	2.621	6.60	6.67	-0.07
Ohio	2.632	8.70	8.76	-0.06
California	2.714	6.44	6.29	+0.15
Hawaii	2.974	7.00	6.24	+0.76
Delaware	2.667	7.10	7.05	+0.05
Louisiana[b/]	1.423	8.50	15.83	-7.33

a/ 59 percent crushed gravel, 39 percent expanded clay (lightweight) and 92 percent filler by weight.

b/ 100 percent lightweight expanded clay.

APPENDIX C

TEXAS HIGHWAY DEPARTMENT SPECIFICATIONS FOR PLANT MIX SEALS

TEXAS HIGHWAY DEPARTMENT

SPECIAL SPECIFICATION

ITEM 3014

PLANT MIX SEAL

1. DESCRIPTION:

This item shall consist of a wearing surface composed of a compacted mixture of mineral aggregate and asphaltic material, constructed on prepared bases or surface in accordance with these specifications and to the dimensions as shown on the plans.

2. MATERIALS:

(1) Asphaltic Materials.

(a) Plant Mix Seal Asphaltic Material shall be of the types of asphalt cement as indicated on the plans and shall meet the requirements of the Item, "Asphalts, Oils and Emulsions". The Contractor shall notify the Engineer of the source of asphaltic material prior to production of the surfacing mixture and this source shall not be changed during the course of the project except on written permission of the Engineer.

(b) Tack Coat. The asphaltic material for tack coat shall meet the requirements for emulsified asphalt EA-11M, cut-back asphalt RC-2,*or shall be a cut-back asphalt made by combining 50 to 70 percent by volume of the asphaltic material as specified for the asphalt-aggregate mixture with 30 to 50 percent by volume of gasoline and/or kerosene. If RC-2 cut-back asphalt is used, it may, upon instructions from the Engineer, be diluted by the addition of an approved grade of gasoline and/or kerosene, not to exceed 15 percent by volume. Asphaltic materials shall meet the requirements of the Item, "Asphalts, Oils and Emulsions".

(2) Mineral Aggregate.

(a) Description. The mineral aggregate used shall be either crushed stone conforming to the requirements of Item 302, "Aggregate for Surface Treatments", lightweight aggregate conforming to the requirements of Item 303, "Aggregate for Surface Treatments (Lightweight)" or that material as shown on the plans.

In addition to the above requirements, the mineral aggregate shall have a "Polish Value" of not less than 35, when tested in accordance with Test Method Tex-438-A.

(b) Grades. When tested by Test Method Tex-200-F, the mineral aggregate shall conform to the following gradation limits or that shown on the plans:

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*An RC-250 is equally suitable.

		Percent by weight
GRADE 1:	Retained on 5/8" sieve	0
	Retained on 1/2" sieve	0-2
	Retained on 3/8" sieve	5-25
	Retained on No. 4 sieve	80-100
	Retained on No. 10 sieve	95-100
GRADE 2:	Retained on 5/8" sieve	0
	Retained on 1/2" sieve	0-2
	Retained on 3/8" sieve	20-35
	Retained on No. 4 sieve	95-100
	Retained on No. 10 sieve	98-100

GRADE 3: As Shown on Plans.

3. SURFACING MIXTURE:

(1) General. The mixture shall be uniform and consist of mineral aggregate and asphaltic material. For mixtures composed of crushed stone, the asphaltic material shall form from 5.0 to 7.5 percent of the mixture by weight unless otherwise shown on the plans. For mixtures composed of lightweight aggregate, the asphaltic material shall form from 10.5 to 14.0 percent of the mixture by weight unless otherwise shown on the plans.

(2) Tolerances. The Engineer will designate the asphalt content to be used in the mixture after tests have been made with the aggregate to be used in the project. When tested, as determined by the Engineer, samples of the mixture shall not vary from the asphalt content designated by the Engineer by more than 0.5 percent dry weight (based on total mixture).

4. EQUIPMENT:

(1) Mixing Plants. Mixing plants that will not continuously meet all the requirements of this specification shall be condemned.

Mixing plants may be either the weight-batching type or the continuous mixing type. Both types of plants shall be equipped with satisfactory conveyors, power units, aggregate handling equipment, aggregate screens and bins and shall consist of the following essential pieces of equipment:

(a) Weight-batching Type.

Cold Aggregate Bin and Proportioning Device. The cold aggregate bins or aggregate stockpiles shall be of sufficient number and size to supply the amount of aggregate required to keep the plant in continuous operation. The proportioning device shall be such as will provide a uniform and continuous flow of aggregate in the desired proportion to the plant.

Dryer. The dryer shall be of the type that continually agitates the aggregate during heating and in which the temperature can be so controlled that aggregate will not be injured in the necessary drying and heating operations required to obtain a mixture of the specified temperature.

The burner, or combination of burners, and type of fuel used shall be such that in the process of heating the aggregate to the desired or specified temperatures, no residue from the fuel shall adhere to the heated aggregate. A recording thermometer shall be provided which will record the temperature of the aggregate when it leaves the dryer. The dryer shall be of sufficient size to keep the plant in continuous operation.

Screening and Proportioning. The screening capacity and size of the bins shall be sufficient to screen and store the amount of aggregate required to properly operate the plant and keep the plant in continuous operation at full capacity. Proper provisions shall be made to enable inspection forces to have easy and safe access to the proper location on the mixing plant where accurate representative samples of aggregate may be taken from the bins for testing. Separation of hot bin into compartments will not be required providing uniform grading and asphalt content are consistently produced in the completed mix.

Aggregate Weigh Box and Batching Scales. The aggregate weigh box and batching scales shall be of sufficient capacity to hold and weigh a complete batch of aggregate. The weigh box and scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment".

Asphaltic Material Bucket and Scales. The asphaltic material bucket and scales shall be of sufficient capacity to hold and weigh the necessary asphaltic material for one batch. If the material is measured by weight, the bucket and scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment".

If a pressure type flow meter is used to measure the asphaltic material, the requirements of the Item, "Weighing and Measuring Equipment" shall apply.

Mixer. The mixer shall be of the pug mill type and shall have a capacity of not less than 20 cubic feet unless otherwise shown on the plans. The number of blades and the position of same shall be such as to give a uniform and complete circulation of the batch in the mixer. The mixer shall be equipped with an approved spray bar that will distribute the asphaltic material quickly and uniforml throughout the mixer. Any mixer that has a tendency to segregate the mineral aggregate or fails to secure a thorough and uniform mixing with the asphaltic material shall not be used. This shall be determined by mixing the standard batch for the required time, then dumping the mixture and taking samples from its different parts. This will be tested by the extraction test and must show that the batch is uniform throughout. All mixers shall be provided with an automatic time lock that will lock the discharge doors of the mixer for the required mixing period. The dump door or doors and the shaft seals of the mixer shall be tight enough to prevent spilling of aggregate or mixture from the pug mill.

(b) Continuous Mixing Type.

Cold Aggregate Bin and Proportioning Device. Same as for weight-batching type of plant.

Dryer. Same as for weight-batching type of plant.

Screening and Proportioning. Same as for weight-batching type of plant.

Aggregate Proportioning Device. The hot aggregate proportioning device shall be so designed that when properly operated a uniform and continuous flow of aggregate into the mixer will be maintained.

Asphaltic Material Spray Bar. The asphaltic material spray bar shall be so designed that the asphalt will spray uniformly and continuously into the mixer.

Asphaltic Material Meter. An accurate asphaltic material recording meter shall be placed in the asphalt line leading to the spray bar so that the cumulative amount of asphalt used can be accurately determined. Provisions of a permanent nature shall be made for checking the accuracy of the meter output. The asphalt meter and line to the meter shall be protected with a jacket of hot oil or other approved means to maintain the temperature of the line and meter near the temperature specified for the asphaltic material.

If a pressure type flow meter is used to measure the asphaltic material, the requirements of the Item "Weighing and Measuring Equipment" shall apply.

Mixer. The mixer shall be of the pug mill continuous type and shall have a capacity of not less than 40 tons of mixture per hour. Any mixer that has a tendency to segregate the aggregate or fails to secure a thorough and uniform mixing of the aggregate with the asphaltic material shall not be used. The dam gate at the discharge end of the pug mixer and/or pitch of the mixing paddles shall be so adjusted to maintain a level of mixture in the pug mixer between the paddle shaft and the paddle tips (except at the discharge end).

Truck Scales. A set of standard platform truck scales, conforming to the Item, "Weighing and Measuring Equipment", shall be placed at a location approved by the Engineer.

(2) Asphaltic Material Heating Equipment. Asphaltic material heating equipment shall be adequate to heat the amount of asphaltic material required to the desired temperature. Asphaltic material may be heated by steam coils which shall be absolutely tight. Direct fire heating of asphaltic material will be permitted, provided the heater used is manufactured by a reputable concern and there is positive circulation of the asphalt throughout the heater. Agitation with steam or air will not be permitted. The heating apparatus shall be equipped with a recording thermometer with a 24-hour chart that will record the temperature of the asphaltic material at the highest temperature.

(3) Spreading and Finishing Machine. The spreading and finishing machine shall be of a type approved by the Engineer, shall be capable of producing a surface that will meet the requirements of the typical cross section and a surface test, when required, and when the mixture is dumped directly into the finishing machine shall have adequate power to propel the delivery vehicles in a satisfactory manner. The finishing machine shall be equipped with a flexible spring and/or hydraulic type hitch sufficient in design and capacity to maintain contact between the rear wheels of the hauling equipment and the pusher rollers of the finishing machine while the mixture is being unloaded.

The use of any vehicle which requires dumping directly into the finishing machine and which the finishing machine cannot push or propel in such a manner as to obtain the desired lines and grades without resorting to hand finishing will not be allowed.

Automatic screed controls, if required, shall meet the requirements of the Item, "Automatic Screed Controls for Asphaltic Concrete Spreading and Finishing Machines".

(4) Pneumatic Tire Rollers. The rollers shall be acceptable medium pneumatic tire

rollers conforming to the requirements of the Item "Rolling (Pneumatic Tire)", Type B unless otherwise specified on plans.

The tire pressure of each tire shall be adjusted as directed by the Engineer and this pressure shall not vary by more than 5 pounds per square inch.

(5) Two Axle Tandem Roller. This roller shall be an acceptable power driven tandem roller weighing not less than 8 tons.

(6) Three Wheel Roller. This roller shall be an acceptable power driven three wheel roller weighing not less than 10 tons.

(7) All equipment shall be maintained in good repair and operating condition and shall be approved by the Engineer.

(8) Alternate Equipment. When permitted by the Engineer in writing, equipment other than that specified which will consistently produce satisfactory results may be used.

5. STOCKPILING, STORAGE, PROPORTIONING AND MIXING:

(1) Aggregate Storage. If the mineral aggregates are stored or stockpiled, they shall be handled in such a manner as to prevent segregation, mixing of the various materials or sizes, and contamination with foreign materials. The grading of aggregates proposed for use and as supplied to the mixing plant shall be uniform. Suitable equipment of acceptable size shall be furnished by the Contractor to work the stockpiles and prevent segregation of the aggregates.

(2) Storage and Heating of Asphaltic Materials. The asphaltic material storage shall be ample to meet the requirements of the plant. Asphalt shall not be heated to a temperature in excess of that specified in the Item, "Asphalts, Oils and Emulsions". All equipment used in the storage and handling of asphaltic material shall be kept in a clean condition at all times and shall be operated in such manner that there will be no contamination with foreign matter.

(3) Feeding and Drying of Aggregate. The feeding of various sizes of aggregate to the dryer shall be done through the cold aggregate bin and proportioning device in such a manner that a uniform and constant flow of materials in the required proportions will be maintained. When specified on the plans, the cold aggregate bins shall be charged by use of a clamshell, dragline, shovel or front end loader. The aggregate shall be dried and heated to the temperature necessary to produce a mixture having the specified temperature.

(4) Proportioning. The proportioning of the various materials entering the asphaltic mixture shall be as directed by the Engineer and in accordance with these specifications. Aggregate shall be proportioned by weight using the weigh box and batching scales herein specified when the weight-batch type of plant is used and by volume using the hot aggregate proportioning device when the continuous mixer type of plant is used. The asphaltic material shall be proportioned by weight or by volume based on weight using the specified equipment.

(5) Mixing.

(a) Batch Type Mixer. In the charging of the weigh box and in the charging of the mixer from the weigh box, such methods or devices shall be used as are necessary to secure a uniform asphaltic mixture. In introducing the batch into the mixer, the mineral aggregate shall be introduced first; shall be mixed thoroughly for a period of 5 to 20 seconds, as directed, to uniformly distribute the various sizes throughout the batch before the asphaltic material is added; the asphaltic material shall then be added and the mixing continued for a total mixing period of not less than 30 seconds. This mixing period may be increased, if, in the opinion of the Engineer, the mixture is not uniform.

(b) Continuous Type Mixer. The amount of aggregate and asphaltic material entering the mixer and the rate of travel through the mixer shall be so coordinated that a uniform mixture of the specified grading and asphalt content will be produced. Checks on asphalt used shall be made at least twice daily by comparing the asphalt used in ten loads of completed mix as shown on the asphalt recording meter and the design amount for these ten loads. The acceptable percent of variation between the asphalt used and the design amount will be as shown on the plans or as determined by the Engineer.

(c) The Mixture produced from each type of mixer shall not vary from the specified mixture by more than the tolerances herein specified.

(d) The Surfacing Mixture from each type of mixer will not exceed a temperature of 260° F and shall be specified by the Engineer. The temperature of the mixture will not be lower than 180° F when placed on the road.

CONSTRUCTION METHODS:

The tack coat or surfacing mixture shall not be placed when the air temperature is below 50° F and is falling, but it may be placed when the air temperature is above 40° F and is rising. The air temperature shall be taken in the shade away from artificial heat. It is further provided that the tack coat or surfacing mixture shall be placed only when the humidity, general weather conditions and temperature and moisture condition of the pavement surface, in the opinion of the Engineer, are suitable.

(1) Tack Coat. Before the surfacing mixture is laid, the surface upon which the tack coat is to be placed shall be cleaned thoroughly to the satisfaction of the Engineer. The surface shall be given a uniform application of tack coat using asphaltic materials of this specification. This tack coat shall be applied, as directed by the Engineer, with an approved sprayer at a rate not to exceed 0.07 gallon per square yard of surface. Where the mixture will adhere to the surface on which it is to be placed without the use of a tack coat, the tack coat may be eliminated by the Engineer. The tack coat shall be rolled with a pneumatic tire roller when directed by the Engineer.

(2) Transporting the Surfacing Mixture. The mixture, prepared as specified above, shall be hauled to the work in tight vehicles previously cleaned of all foreign material. The dispatching of vehicles shall be arranged so that all material delivered may be placed, and all rolling shall be completed during daylight hours. In cool weather or for long hauls, canvas covers and insulating of the truck bodies may be required. The inside of the truck body may be given a light coating of oil, lime slurry or other material satisfactory to the Engineer, if necessary, to prevent the mixture from adhering to the body.

(3) Placing. The asphaltic mixture shall be dumped directly into the specified

spreading and finishing machine and spread on the approved prepared surface in such a manner that, when properly compacted, the finished surface will be smooth and of uniform texture and density. The spreading and finishing machine shall be operated at a speed satisfactory to the Engineer. During application of asphaltic material, care shall be taken to prevent splattering of adjacent pavement, curb and gutter and structures.

(4) Compacting.

(a) As directed by the Engineer, the surface mixture shall be compressed thoroughly and uniformly with the specified rollers and/or other approved rollers.

(b) Immediately, following placement of the asphaltic mixture, the surface shall be given complete rolling with a tandem or three wheel roller of such weight as to accomplish good density without excessive breakage of the mineral aggregate. Immediately following initial rolling, the entire surface will be rolled with the pneumatic roller as directed by the Engineer. The motion of the rollers shall be slow enough at all times to avoid displacement of the mixture. If any displacement occurs, it shall be corrected at once by the use of rakes and of fresh mixture where required. To prevent adhesion of the surfacing mixture to the roller, the wheels shall be kept thoroughly moistened with a soap-water solution. Necessary precautions shall be taken to prevent the dropping of gasoline, oil, grease or other foreign matter on the pavement, either when the rollers are in operation or when standing.

7. MEASUREMENT:

(1) The surfacing mixture will be measured separately by the ton of 2,000 pounds of "Asphalt" and by the cubic yard of dry, loose "Aggregate" of the type actually used in the completed and accepted work in accordance with the plans and specifications for the project. The volume of aggregate in the compacted mix shall be calculated from the measured weights of the surfacing mixture by use of the following formula:

$$V = \frac{(W - A)}{(27)K}$$

V = Cubic Yards of aggregate, dry, loose

W = Total weight of surfacing mixture in pounds

A = Weight of Asphalt in pounds

K = Unit Weight of Aggregate in pounds per cubic foot

The value "K" shall be the average of two or more tests determined by the Engineer in the following manner:

At the beginning of plant operations, a specified weight of dried mineral aggregate shall be placed in an acceptable container that will contain a minimum volume of three cubic yards. The aggregate shall be leveled or "struck-off" and measured, to determine the volume of the mineral aggregate, in cubic feet. The unit weight of the mineral aggregate shall be obtained by dividing the specified weight of dried aggregate in pounds by the measured volume in cubic feet. The value "K" is an average of two or more of the above described tests.

The value "K" shall be checked a minimum of one time for each 3,000 cubic yards of mineral aggregate. If in the opinion of the Engineer or the Contractor's representative, the value of "K" has changed, a check test shall be made. A new value for "K" shall be determined if the checked value of "K" varies more than two percent (plus or minus) from the value being used.

The weight, "W", if mixing is done by a continuous mixer, will be determined by truck scales. The weight, if batched, will be determined on batch scales and records of the number of batches, batch designs and weight of "Asphalt" and "Aggregate" shall be kept.

(2) Tack coat will be measured at the point of application on the road in gallons at the applied temperature. When gasoline and/or kerosene is added to the cut-back asphalt for tack coat, as ordered, measurement will be made after mixing.

PAYMENT:

(1) The work performed and materials furnished as prescribed by this item and measured as provided under "Measurement", will be paid for at the unit prices bid for "Asphalt" and "Aggregate", of the types specified, which prices shall each be full compensation for quarrying, furnishing all materials and freight involved; for all heating, mixing, hauling, cleaning the existing pavement, placing asphalt-aggregate surfacing mixture, rolling and finishing; and for all manipulations, labor, tools, equipment and incidentals necessary to complete the work except tack coat.

(2) The tack coat, measured as provided under "Measurement" will be paid for at the unit price bid for "Tack Coat", which price shall be full compensation for furnishing, preparing, hauling and placing the asphaltic materials of the grade used; and for all manipulations, labor, tools, equipment and incidentals necessary to complete the work.

(3) All templates, straightedges, scales and other weighing and measuring devices necessary for the proper construction, measuring and checking of the work shall be furnished, operated and maintained by the Contractor at his expense.

APPENDIX D

TENTATIVE METHOD OF TEST FOR RESISTANCE OF BITUMINOUS PLANT-MIX FRICTION COURSES (OR SEAL COATS) TO RAPID FREEZING AND THAWING IN WATER (USING FIELD CORES)

ALTERNATE METHOD FOR TEST SAMPLES

REF. AASHO T135

Tentative Method of Test for
RESISTANCE OF BITUMINOUS PLANT-MIX FRICTION COURSES (OR SEAL COATS) TO RAPID FREEZING AND THAWING IN WATER (USING FIELD CORES)

Scope

1. This method covers the determination of resistance of plant-mix friction courses (or seal coats) to rapidly repeated cycles of freezing and thawing in water in the laboratory. It is intended for use in determining the effects of the high air void content and relatively thin ($\leq$ 1 in.) mat thickness on the resistance of the plant-mix course to damage caused by the freezing-and-thawing cycles specified in the method. This method is not intended to provide a quantitative measure of durability of a specific mix design.

Apparatus

2. (a) Freezing-and-Thawing Apparatus:

(1) The freezing-and-thawing apparatus shall consist of a suitable chamber or chambers in which the specimens may be subjected to the specified freezing-and-thawing cycles, together with the necessary refrigerating and heating equipment and controls to produce continously and automatically, reproducible cycles within the specified temperature requirements. In the event that the equipment does not operate automatically, provision shall be made for either its continuous manual operation on a 24-hour-a-day basis or for the storage of all specimens in a frozen condition when the equipment is not in operation.

(2) The apparatus shall be so arranged that each specimen is immersed in water to about the mid-point of the layer to be tested.

(3) The temperature of the heat-exchanging medium shall be uniform within 6F (3.3 C) throughout the specimen cabinet when measured at any given time, except during the transition between freezing and thawing and vice versa, at any point on the surface of any specimen.

(b) Specimen-Holding Apparatus: Each set of three specimens is held in a pan 6 in. wide, 4 in. deep, and 19 in. long. Also, each specimen is placed on a pedestal and inside a confining collar (see Fig. D1). The confining collar is to be of plastic (PVC) with a cork liner. The diameter of the collar and thickness should be such that the inner diameter of the collar is 1/16 to 3/16 greater than the outer diameter of the sample being tested. The depth of the collars need only be greater than the sample depth. A small bull's eye level that is mounted so that it can be used inside the confining collars is necessary for leveling the specimens in accordance with Section 5(c).

(c) Temperature-Measuring Equipment: The temperature-measuring equipment shall consist of thermometers, resistance thermometers, or thermocouples, capable of measuring the temperature at various points within the specimen chamber and adjacent to control specimens to within 2F (1.1C).

Freezing-and-Thawing Cycle

3. (a) The nominal freezing-and-thawing cycle for this method shall consist of alternately lowering the temperature of the specimens from 40 to 0F (4.4 to -17.8C) in a period of not more than 3 hours and

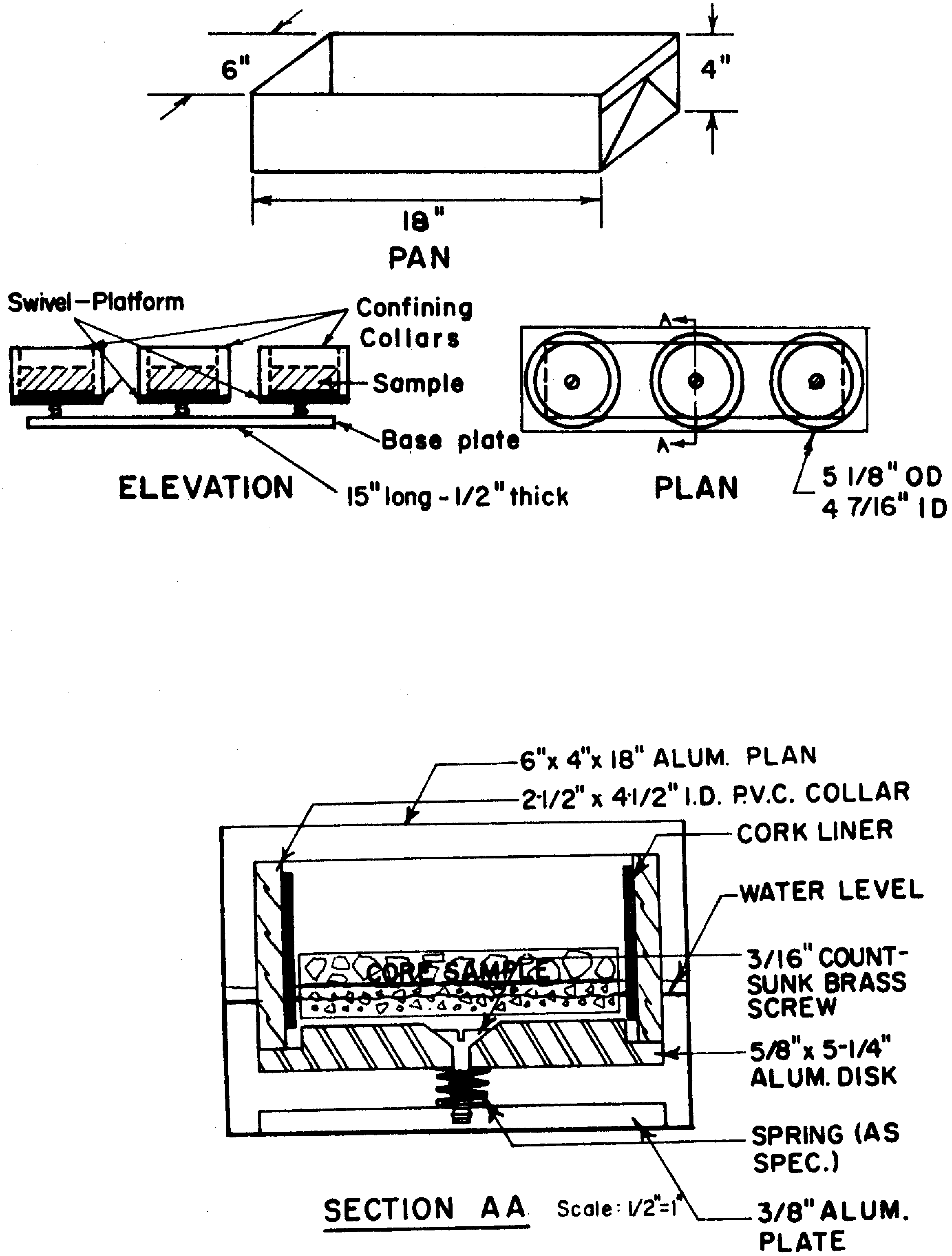

FIG. D-1: SPECIMEN HOLDING APPARATUS

raising it from 0 to 40F (-17.8 to 4.4C) in a period of not more than 1 hour. At the end of the cooling period the temperature of the specimens shall be 0 ± 3F (-17.8 ± 1.7C), and at the end of the heating period shall be 40 ± 3F (4.4 ± 1.7C), with no specimen at any time reaching a temperature lower than -3F (-19.4C) nor higher than 43F (6.1C). The time required for the temperature of any single specimen to be reduced from 37 to 3F (2.8 to -16.1C) shall be not less than half the length of the cooling period, and the time required for the temperature of any single specimen to be raised from 3 to 37F (-16.1 to 2.8C) shall be not less than half the length of the heating period.

(b) The period of transition from the freezing to the thawing phase of the cycle or vice versa shall not exceed 10 min.

Test Specimens

4. (a) The specimens for use in this test shall be short cylinders formed by sawing the plant-mix friction course off the top of 4-in. field cores. The cores should be sawed off at a point about 1/2-in. below the bottom of the plant-mix friction course.

> [Note 1. - This test method contemplates the use of specimens not less than 3.90 in. nor more than 4.25 in. in diameter and not less than 1.00 in. nor more than 1.75 in. in total height (i.e., plant-mix friction course plus the thin layer of asphalt concrete left to act as a base for the layer to be tested).]

(b) The specimens to be used in this test should be stored in a cool (40 to 70F (4.4 to 21.1C)), dry place at all times prior to the start of freezing-and-thawing tests.

Procedure

5. (a) A detailed description of each specimen shall be recorded, noting defects or evidence of previous deterioration such as cracks, stripping, flushing, or deformation. As much information as possible about the mix design, source of cores, etc., should also be recorded.

(b) Collect and assemble the parts of the number of specimen-holding apparatuses (each apparatus as per Fig. D-1) necessary to test the number of specimens desired. Each apparatus hold 3 specimens.

(c) One base plate (with its three swivel-platforms and three specimens) shall be placed into each pan. Each pan shall then be filled with water to a depth of approximately 1.5 in. and placed into the freezing-and-thawing cabinet. After placing each pan into the freezing-and-thawing cabinet (the platform or shelves on which the sample-holding pans are placed shall be level), the height of each swivel-platform shall be adjusted so as to place the water surface at about the <u>lower quarter-point</u> of the plant-mix friction layer to be tested. A small bull's eye level shall be used to level the surface of each specimen individually. The confining collars shall then be placed around the specimens. Immediately after placing the collars, each specimen shall be checked to insure that the surface is level and that the water surface is at about the <u>mid-point</u> of the plant-mix friction layer, and any necessary corrections shall be made.

(d) A pan filled with wet sand shall be placed at about the center position in the freezing-and-thawing cabinet and the cabinet's temperature sensors shall be embedded in the sand at about the center of volume of the pan. The specimen-holding pans shall be positioned symmetrically on either side of the sensor pan. One cooling-heating element shall be attached on each side of each pan. This shall be accomplished by using a 60-A (500-W) cooling-heating element attached between two adjacent pans, touching both pans. On the end pans in the row, 30-A cooling-heating elements shall be used; one on each of the outer pan sides. As the freezing-and-thawing cycles are begun, modifications in the arrangement of the pans and cooling-heating elements may be necessary in order to insure full and complete freezing and thawing.

The equalizing of the sensor's pan and specimen pans can be accomplished by altering the quantity of sand and/or water. Larger numbers of specimens being tested at one time may require additional heaters on each pan to reduce thaw time. The general arrangement is shown in Fig. D-2.

(e) Freezing-and-thawing tests shall be started at the beginning of the thawing phase of the cycle. The specimens shall be removed from the apparatus, in a thawed condition, at intervals of 25 cycles of exposure to the freezing-and-thawing cycle, examined closely, and returned to the apparatus. A detailed description of each specimen shall be recorded after each set of 25 cycles, noting specifically any apparent damage. The test shall be continued until the specimens have been subjected to a minimum of 50 cycles. After each specimen has been subjected to at least 50 cycles, and a final description has been recorded, other tests (which may include the wire-brush test, etc.) may be performed to ascertain the effects of the freezing-and-thawing test.

Report

6. The report shall include such of the following data as are

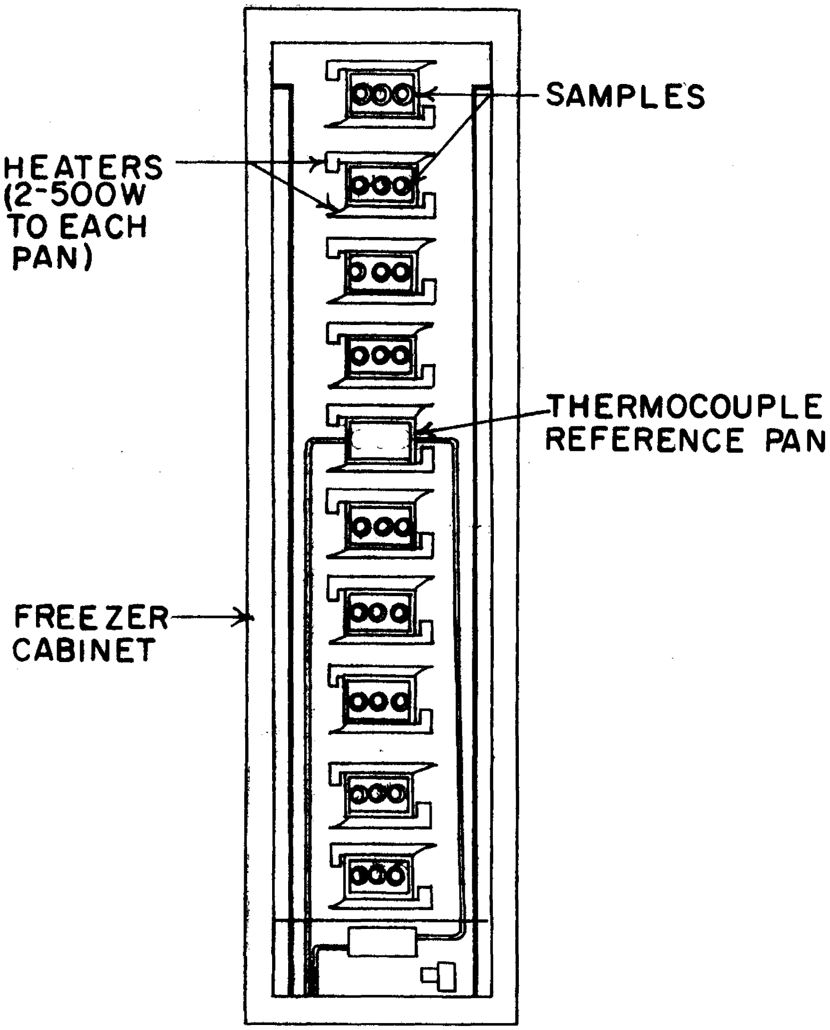

Figure D-2. Automatic freeze-thaw cabinet arrangement.

pertinent to the variables studied in the test:

(a) Properties of the Plant-Mix Friction Course Mixture Design:

(1) Type and proportions of asphalt cement, coarse aggregate, fine aggregate, and mineral filler, including maximum size and grading. Proportions of each mix component shall be reported in percent by volume of total mix.

(2) Kind and proportion of any admixture used; and

(3) Bulk specific gravity of each specimen, as determined by measured dimensions (see Proposed Revision to Method of Test to Determine Percent Air Voids in a Compacted Bituminous Paving Mixture (ASTM Designation D3203)).

(b) Characteristics of Test Specimens:

(1) Detailed description of physical appearance of each specimen before testing;

(2) Source of mix components;

(3) Location of sampled project; and

(4) Location of coring for each specimen.

(c) Results:

(1) The detailed descriptions obtained after 25 cycles and after 50 cycles, noting any damage done to the specimens, and

(2) Results of tests performed to evaluate the effects of the freezing-and-thawing test.

ALTERNATE METHOD FOR TEST SAMPLES

REF. AASHO T135

Scope

1. These specifications cover test on 4-inch diameter asphalt core samples which have been subjected to freeze and thaw as a means to aid in determining damage.

Apparatus

2. (a) Scales - with 500g capacity (± .01g)

(b) Wire Scratch Brush - A wire scratch brush made of 2 by 1/16-in. flat No. 26 gage wire bristles assembled in 50 groups of 10 bristles each and mounted to form 5 longitudinal rows and 10 transverse rows of bristles on a 7 1/2 by 2 1/2 in. hardwood block.

Procedure

After removing samples from freeze thaw and when all observations have been made, weigh and record weights of each core to nearest .1g. Hold or secure sample by any convenient means that will not in itself dause damage to the sample. Then with "Scratch Brush" apply 3 overlapping strokes to surface of core being tested. The force on the brush is to be 3 lbs. This can be achieved by adding the required weight to the brush to equal 3 lbs. The brush then only need be pushed or pulled across the core with no downward force. Record final weight and subtract from original weight for test value. See Figure D-3.

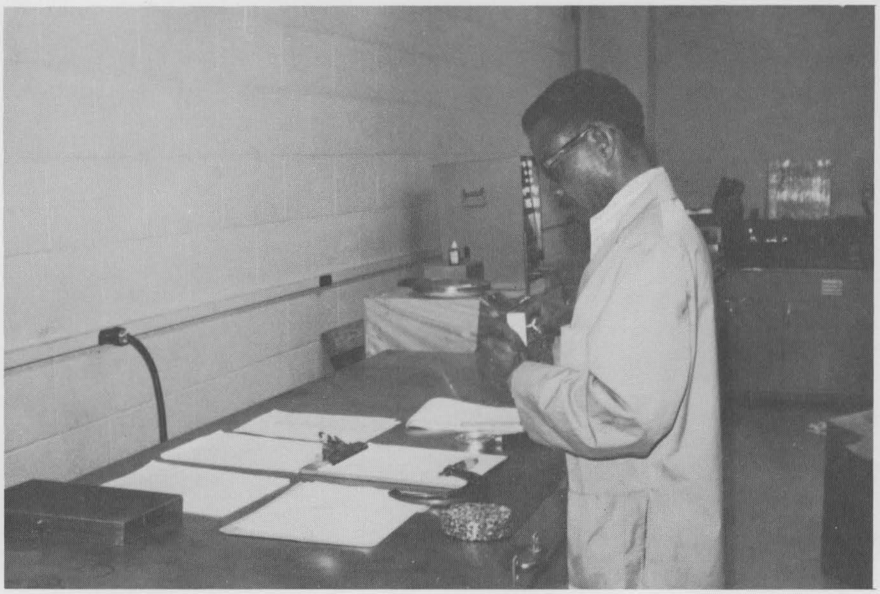

Figure D-3. Measurements and observations of samples.