NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT

# 259

# DESIGN OF EMULSIFIED ASPHALT PAVING MIXTURES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **259**

# DESIGN OF EMULSIFIED ASPHALT PAVING MIXTURES

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**The Asphalt Institute**
**College Park, Maryland**

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

PAVEMENT DESIGN AND PERFORMANCE
BITUMINOUS MATERIALS AND MIXES
(HIGHWAY TRANSPORTATION)
(AIR TRANSPORTATION)

**TRANSPORTATION RESEARCH BOARD**
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.
SEPTEMBER 1983

## NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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# FOREWORD

*By Staff*
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This report presents the results of an evaluation of laboratory mix design methods using Hveem and Marshall equipment for emulsified asphalt paving mixtures to determine if the design methods are adequate for selecting optimum asphalt emulsion and water contents for actual paving projects. It was found that neither of the methods (known as the University of Illinois method and The Asphalt Institute method) is totally satisfactory for selecting optimum asphalt and water contents and that there is a lack of compatibility between the results from the two methods. The results of a field study involving construction practices such as mixing, placement, and compaction of the emulsified asphalt mixtures are more critical than the initially selected or target asphalt emulsion contents determined from the laboratory mix design methods. Although only partially successful in terms of accomplishment of the objective of arriving at a proven laboratory mix design method, the report will be of interest and value to highway agency personnel involved in research, design, and construction of pavements using emulsified asphalts, particularly with regard to suggestions for modifying existing mix design methods.

Paving mixtures using emulsified asphalts are being used for both new construction and in maintenance and rehabilitation of existing pavements for reasons that include environmental concerns, energy conservation, and ease of construction. Questions have been raised regarding the proper use of emulsified asphalts. Of particular concern is the ability of current design methods to produce paving mixtures consisting of a variety of materials that will perform with a high degree of reliability over a range of environmental conditions. The objective of research under this project was to verify and/or modify the University of Illinois (Marshall equipment) and The Asphalt Institute (Hveem equipment) emulsified asphalt mix design methods described in Federal Highway Administration Reports No. FHWA-IP-79-1, "A Basic Asphalt Emulsion Manual," and No. FHWA-RD-78-113, "Mix Design Methods for Base and Surface Courses Using Emulsified Asphalt."

The research program planned and conducted by The Asphalt Institute involved (1) a thorough review of the two mix design methods and related literature, (2) laboratory evaluation of the methods, (3) development and laboratory evaluation of modifications to the methods, and (4) trial use of the modified mix design methods in conjunction with four paving projects using emulsified asphalts. The use of either one of the mix design methods by a highway agency is generally based on availability of Marshall or Hveem equipment.

Early in the research effort it was determined that neither method is totally satisfactory because of the length of time required and the incompatibility of results. Efforts were made to improve both methods by shortening time requirements and improving their ability to select more compatible asphalt emulsion and water contents for target mix designs. Further field evaluation of the suggested modifications to the methods is required. However, on the basis of the study of four field projects involving the use of a variety of dense-graded asphalt emulsion mixes, it appears that the laboratory mix design to determine target asphalt emulsion and water contents is not a critical factor in achieving a successful paving project. Adjustments are invariably required during construction operations to account for degree of quality control associated with such operations as aggregate feed, variable water content, proportioning of ingredients, mixing time, and timing of compaction plus climatic conditions as they develop.

As a result of this research, significant advances have been made in the state of the art for the design of mixtures and the construction of pavements using emulsified asphalts. Agencies and organizations using emulsified asphalts in pavements will certainly benefit from these advances. The need for further research and development in this field will depend on the growth of emulsified asphalt use in pavement construction and rehabilitation.

# CONTENTS

## ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 9-5 by The Asphalt Institute. The research was conducted by Principal Investigator V. P. Puzinauskas, and Co-Investigator Robert N. Jester, Senior Assistant Engineer. Laboratory technologist and technicians, C. Scott Muir, Thomas L. Norton, and William E. Morris, performed the laboratory testing.

# DESIGN OF EMULSIFIED ASPHALT PAVING MIXTURES

## SUMMARY

The primary objective of NCHRP Project 9-5 was to verify and, if needed, to modify the Asphalt Institute (Hveem equipment) and University of Illinois (Marshall equipment) emulsified asphalt paving mixture design methods presented in the Federal Highway Administration report, "A Basic Asphalt Emulsion Manual" (*1*).

This report presents the results of research carried out in two major phases: (1) laboratory evaluation of mix designs and (2) field verification of laboratory designs. The laboratory and field work were preceded by a thorough review of the two mix design methods and of other pertinent literature. The five main tasks of the project included: (1) laboratory evaluation of the methods as currently outlined in the FHWA manual; (2) if needed, modification of the design methods resulting from work in the laboratory; (3) planning and design of field projects using dense-graded emulsion mixes for base or surface courses; (4) verification of the applicability of the design methods to field conditions; and (5) analysis of data and preparation of the quarterly and final reports.

The laboratory phase of the project included evaluating and comparing The Asphalt Institute (AI) and University of Illinois (UI) procedures using aggregates and emulsions that varied widely in their properties. This involved combining at least one calcareous and one siliceous open-graded aggregate with two suitable anionic and two cationic medium-setting emulsions to determine the adequacy of the design procedure. The influence of different environmental conditions was assessed by measuring mix properties under variable testing conditions. Specimens by both methods were fabricated at different water contents and levels of compactive effort and tested after exposure to a variety of curing conditions.

In this laboratory phase, the methods were rigorously scrutinized for possible modifications and simplifications. An attempt was made to modify the various procedural elements of both methods to make them less time consuming and more convenient without sacrifice of accuracy and reliability.

The field verification phase involved evaluating the ability of the laboratory procedures to design mixtures that could be constructed satisfactorily and would perform adequately under various traffic and environmental conditions. (It should be noted that due to the relatively short duration of this research project, the pavements could be evaluated only on a short-term basis and no judgments could be made regarding long-term performance.)

*Results of Laboratory Evaluations of Design Methods*

After running mix designs according to the procedures of the reference methods for dense-graded mixtures, several major conclusions were reached as follows:

1. Both methods take a considerable length of time to complete and can present scheduling difficulties in completing all phases of the designs.
2. Neither method is totally satisfactory for establishing optimum emulsion and water contents.
3. There are considerable differences between the methods, and this incompatibility can result in dissimilar designs for the same emulsion-aggregate combination.

Because of these problems, modifications to the reference methods were investigated in an attempt to shorten them, to make them more effective in establishing optimum emulsion and water contents, and to make them more compatible with regard to level of compactive effort and curing/water exposure procedures. Also, changes in level of compactive effort were needed to produce laboratory specimens having densities and voids in closer agreement to those obtained in the field. Changes in the reference methods under investigation fell into three major categories: (1) mixture composition including selection of trial emulsion contents; (2) adjustments in levels of compactive effort for specimen fabrication; and (3) curing and water exposure procedures. Based on the results of the review of the reference methods, and on the results of the laboratory investigation of modifications to those methods, numerous changes were recommended. The mix designs run using the revised methods, however, did not result in easily identifiable "optimum" mix components for more emulsion-aggregate combinations. This indicated that the selection of optimum emulsion and water contents must be based on judgments regarding the relative importance of individual properties such as stability, density, and voids, especially with respect to those of water-exposed specimens because of the need for adequate durability.

With regard to The Asphalt Institute's design procedure for open-graded mixes, the runoff test (performed on loose mixes immediately after mixing) and washoff test (performed on compacted specimens while still in the mold after a 24-hour cure at room temperature) did not always produce definitive results for selecting optimum emulsion and water contents. Thus, they can only serve as general guidelines in the selection process. The ultimate decision will depend primarily on judgments regarding coating and workability, and on other factors such as economics and environmental conditions.

### *Results of Field Evaluation*

In support of the laboratory research on dense-graded mixes, four field projects located in Harrisonburg, Virginia; Saline County, Arkansas; Chesapeake, Virginia; and Schuyler County, New York, were studied in an attempt to determine if mixes designed in the laboratory could be effectively used in actual pavement construction. These projects involved the use of a wide variety of emulsion and aggregate types, mixing techniques, and laydown operations. The selected project locations represented a wide variation in geographic location and climate.

Three of the projects produced the successful construction of pavements. Only the Harrisonburg project could not be constructed, as planned, because of the numerous problems encountered. And yet, the laboratory designs, especially with regard to the primary criteria of adequate stability and resistance to water sensitivity, had indicated that successful pavements could be achieved with all four projects, including the one at Harrisonburg.

On the basis of the results of the field study it would appear that a precise laboratory design (even if obtainable) is not critical for achieving a successful pavement. At best, it can serve only as a general guideline for an initial job-mix formula with adjustments being made following an evaluation of mix quality including such factors as workability, coating, plasticity, and ease of compaction. Of greater importance is the degree of quality control associated with the construction operation. An accurate and uniform aggregate feed system, adequate mixing and properly timed compaction in relation to water content of the mixture are of key importance. The experience of the design and construction personnel with similar emulsion mixes may also be a determining factor in the construction of a successful project.

CHAPTER ONE

# INTRODUCTION AND RESEARCH APPROACH

## INTRODUCTION

The use of emulsified asphalts has grown continuously from the time of their inception in the late 1920s and early 1930s. This growth is evident for two major types of emulsion application, namely for intimate mixtures with mineral aggregates and also for surface spraying applications. In recent years, the rate of emulsion use has accelerated considerably. The consideration of road building costs, the greater awareness of the environmental problems, and the need for conservation of energy fuels provided an impetus for this new growth. Because of these factors, the current trends are to replace cutback asphalts with emulsified asphalt in a majority of paving applications. For the foregoing reasons, the use of emulsified asphalt paving mixtures, employing dense-graded mineral aggregates, also increased in recent years. Such mixtures are used for either surface or base courses for many types of pavements ranging from surface courses of low-volume rural roads to base courses of high-traffic highways.

Regardless of the relatively wide use of emulsion paving mixtures with dense-graded aggregates, there is no standard method for the establishment of compositional characteristics of such mixtures. Currently, more than a dozen compositional and design methods are used by different agencies and these methods vary widely in their basic approach. Ten of these design methods are described in, "A Basic Asphalt Emulsion Manual," Volume 2, prepared by The Asphalt Institute for the Federal Highway Administration (*1*). Some of these methods are rather simple, while others employ procedures and techniques that are quite involved. Because of these differences, it may be anticipated that the various methods undoubtedly will lead to differences in compositional mixture designs even when used with the same emulsion-aggregate system. The very existence of so many design methods indicates the difficulty in establishing a single method that is suitable for all emulsion-aggregate combinations.

## DESCRIPTION OF EMULSION MIXTURES AND FACTORS FOR CONSIDERATION IN MIX-DESIGN

Designing of emulsion paving mixtures presents a significant challenge for the designer because such mixtures are considerably more complex than either asphalt concrete or paving mixtures with cutback asphalt. Emulsion mixtures are three-component systems containing mineral aggregate, asphalt, and water. Asphalt concrete or cutback mixtures, on the other hand, contain aggregate and organic binder, a two-component system.

Emulsion mixtures often contain organic solvents or oils that are incorporated into the mixture with either regular medium-setting or high-float emulsions. Water in emulsion mixtures may come from three sources: water naturally occurring with the mineral aggregate, water added to the aggregate prior to the addition of emulsion, and water incorporated with the emulsion. The water incorporated with the emulsion contains soap or cationic surface active agents that decrease surface tension and improve the wetting characteristics of all water contained in the mix.

Water contents continually vary in emulsified asphalt mixtures. Initially such contents are relatively high; water is needed for uniformity of coating during mixing and for interparticle lubrication to aid compaction. After compaction, the mixture cures, which is essentially a loss of water and, if present, of organic solvent. Such curing and drying may continue for a relatively long time and it may even extend for more than one year until an equilibrium condition is reached. With gradual curing or loss of water the strength of compacted mixtures increases and reaches a certain level. Cured-out emulsified asphalt mixture may still contain a low amount of water, and it is safe to assume that the water content of the cured-out mixture also varies.

The distribution of the residual asphalt in the paving mixture depends to a considerable extent on the type of emulsified asphalt. With solventless slow-setting emulsion, regardless of whether it is cationic or anionic, it may be expected that asphalt would be distributed in globules rather than the continuous waterproofing asphalt films. Such globules, initially attached to finer aggregate particles, during the mixing process are distributed throughout the mass of the mixture. They plug up the capillary openings and voids between large particles and, thereby, waterproof the mix. To obtain more continuous asphalt films with such solventless emulsions may be prohibitive; it would require too much emulsion. On the other hand, emulsions containing solvent lead to more interconnected continuous asphalt films that act as the waterproofing barriers. However, even in these continuous film systems, the larger mineral particles often remain uncoated or are only partially coated.

Emulsions are variable chemical systems containing different chemical components designed to serve or perform effectively with a given aggregate under specific environmental conditions. When designing emulsion mixtures, it is a prerequisite that the designer be familiar with and consider the characteristics of aggregates and emulsions and their interfacial relationships. Also, laboratory design procedures should be sufficiently realistic and should reflect as closely as possible the conditions that exist during pavement construction and during the subsequent environmental exposure of the mixture and finished pavement. For instance, the laboratory mixing should result in the degree of coating achievable and expected in the field. Laboratory compaction should result in densities similar to those of the actual pavements. Also, the degree of laboratory curing should simulate the degree and rate of drying that may be expected under actual field conditions. On the other hand, the laboratory design test and conditions should expediently provide the desired information in a relatively short and convenient time period.

Because of the complexity of emulsion mixtures and because of the great number of factors influencing their behavior, the selected variable parameters should be evaluated by comparative tests. For example, some screening tests should be made to establish the suitability of a given emulsion. Also, if needed, several gradations of the available aggregate should be evaluated with the aim of finding the one that is most suitable. However, again, it must be emphasized that tests for such evaluations should be kept at a realistic level to minimize the time and cost of the laboratory design.

## RESEARCH OBJECTIVES

The overall objective of NCHRP Project 9-5 was to verify and, if needed, to modify The Asphalt Institute (AI) and the University of Illinois (UI) emulsified asphalt paving mixture design methods presented in the Federal Highway Administration report, "A Basic Asphalt Emulsion Manual" (*1*).

The plan for research was comprised of two major phases: (1) laboratory evaluation of mix designs and (2) field verification of laboratory designs. The actual laboratory or field work was preceded by a thorough review of the two mix design methods and of other pertinent literature. The five main tasks of the project included:

1. Laboratory evaluation of the two methods as currently outlined in the FHWA Manual.
2. If needed, modification of the design methods resulting from the laboratory study.
3. Planning of field projects and design of dense-graded emulsion mixes for base or surface courses.
4. Verification of the applicability of the design methods to field conditions.
5. Analysis of data and preparation of the quarterly and final reports.

Specifically included under Task 1 was a laboratory evaluation of The Asphalt Institute mix design method for open-graded mixes. This involved combining at least one calcareous and one siliceous open-graded aggregate with two suitable anionic and two cationic medium-setting emulsions to determine the adequacy of the design procedure.

The objective of the laboratory phase of the project (Tasks 1 and 2) was to evaluate in detail and compare The Asphalt Institute and University of Illinois procedures using aggregates and emulsions that varied widely in their properties. The goal of the laboratory design was to provide information that could be applied to construction operations and to the performance of paving mixtures for a range of climatic conditions and traffic loadings. Additionally, the original as-published methods were scrutinized for possible modifications and simplifications.

The objective of the field verification phase (Tasks 3 and 4) was to evaluate the ability of the laboratory procedures to provide mixtures that would perform satisfactorily under various service conditions. Field verification involved, when possible, preconstruction evaluation of materials and laboratory design of mixtures by the two methods, testing during construction, and tests after construction to verify changes in mix properties during pavement service.

## RESEARCH APPROACH

To initiate the research, the first step was to conduct a search of the literature pertaining to laboratory research and actual construction of both dense-graded and open-graded emulsified asphalt mixtures (EAMs). The intent of this review was to gain an understanding of the design details and possible difficulties involved in designing EAMs, to develop possible means for simplifying the design procedures and revising design criteria, and to obtain information on the relationships between laboratory and field mixtures that indicate the amount of variability in various properties under actual pavement service conditions.

This was followed by a thorough review of the design methods being studied in this project to ensure a complete understanding of the procedures for these methods as published in the FHWA Manual. In order to improve clarity, the methods were rewritten in outline form in a more concise and logical sequence prior to any testing in the laboratory. This review also included noting any problems with the existing methods including curing and water exposure procedures, test completion times, test scheduling limitations, and inadequacies in the design criteria for establishing optimum asphalt emulsion contents.

The next step was to design dense-graded mixes according to the reference methods using a wide range of aggregate types in combination with both anionic and cationic slow-setting emulsions. The primary aim was: (1) to develop familiarity both with the details of actually performing the designs and with the characteristic trends in specimen properties as a function of the input variables, and (2) to determine if the reference methods actually result in definitive optimum emulsion and water contents based on the design criteria.

Tests were also conducted on open-graded mixes according to The Asphalt Institute procedure using a wide variety of aggregates and medium-setting emulsions.

Following an evaluation of the results when using the reference methods, possible modifications to these methods were investigated based on this evaluation.

The laboratory procedures, including any modifications, were then used to design mixes for field projects using the actual materials from the construction sites. Where possible, the projects were constructed based on the recommendations of The Asphalt Institute with regard to target values for mixing and compaction water and emulsion contents. Samples of the mixes were obtained during construction, and field density measurements were made following early curing and, when possible, after prolonged exposure to traffic and weather. Samples were analyzed and comparisons were made to laboratory specimens to determine the applicability of the design methods to actual field conditions.

The final step was to summarize the findings and make recommendations for modifications to the reference methods. Also, suggestions were made for any additional research pertinent to the refinement of mix design methods for EAMs.

CHAPTER TWO

# FINDINGS

## LITERATURE REVIEW

### General Considerations

A search through the literature pertaining to mix designs of emulsified asphalt mixtures reveals one recurring theme—that there is no standard mix design method that has nationwide applicability for all types of emulsions and aggregates, whether it be for dense-graded or open-graded mixes. It has been noted that the development of a standardized design procedure for EAMs represents a "significant challenge to the highway industry" and that in spite of considerable research in this area, there is no consensus as to what constitutes a correct procedure (*27*). While problems have been noted with attempts to effectively characterize EAMs in the laboratory and to establish suitable design criteria for any "optimum" mix, there is an understanding that the effects of all factors affecting mixture performance must be thoroughly evaluated and understood before a universally accepted method can be developed.

It is evident that most of the design methods available today for EAMs are either simple trial-and-error processes or modifications to standard procedures that use Hveem or Marshall equipment for designing hot-mix asphalt concrete. Most of the design methods attempt to duplicate field curing which, because of variations in curing conditions throughout the nation, has resulted in the development of different types and degrees of conditioning, leading to strength values that are not comparable from one agency to the next. Also, in many instances, the mix designs are unique to a geographical area; they are geared toward emulsions that are manufactured specifically for a given aggregate and are highly dependent on the experience of the personnel performing the tests and design. In fact, many designers and users admit that their procedures do not necessarily have nationwide applicability (*12*).

In general, there are five basic items to consider in conducting a mix design on dense-graded emulsified asphalt mixtures:

1. Compatibility of emulsified asphalt and aggregate.
2. Optimum mixing water content.
3. Optimum water (or fluids) content for compaction.
4. Adequacy of strength and durability (resistance to water damage) properties.
5. Selection of optimum residual asphalt content based on established design criteria.

Although these basic items appear to be straightforward, the complexity of the three-component emulsified asphalt mixture system makes mix design quite complicated. Considerable research, especially in the last decade, has been conducted in the areas of (1) coating and mixing water content, (2) optimum fluids content at compaction, (3) level of compactive effort, (4) curing and water exposure procedures, and (5) strength testing.

### Coating and Mixing Water Content

To achieve sufficiently uniform dispersal of asphalt throughout the mix, a reasonable amount of mixing time is needed. It should be noted that good dispersion does not necessarily mean 100 percent coating. Some studies have shown no particular correlation between degree of coating and strength or fatigue life of fully cured mixes (*6, 24*). As a general guideline, it appears that 50 percent coating is selected as the acceptable minimum for base mixtures, and 75 percent is the minimum for surface courses (*6*). Coating also depends on the particular emulsion-aggregate combination being considered and on the amount of premixing water used to wet the aggregate.

The choice between cationic and anionic emulsion is a function of the coating and adhesion characteristics when combined with a given aggregate. There are experimental data that help to support the theory that cationics adhere better to most natural aggregates. This is especially true with acidic siliceous aggregates.

The amount of added mixing water needed for good dispersion is not the same for all emulsions. Cationics generally require additional mixing water in order to achieve satisfactory coating. Also, slow-setting anionic emulsions are readily dispersed by water so that the presence of larger amounts of added mixing water may enhance the dispersion during initial mixing. On the other hand, coating is not necessarily improved by the presence of excess moisture in the case of medium-setting emulsions either regular or high-float type. Such emulsions generally contain some oil distillate which facilitates mixing by decreasing viscosity of the residual asphalt, and it is possible that added water does not help to achieve optimum coating.

Different mixing times with a laboratory mechanical mixer have been selected by various research agencies. Generally, there are two approaches: (1) mixing for a fixed time for aggregate and water, then adding emulsion, and again mixing for a fixed time with the wetted aggregate; (2) mixing the ingredients until a uniformly colored mix is obtained. Mixing time depends on the characteristics of the emulsion-water-aggregate system. Excessive mixing time often may result in stripping of the asphalt from the aggregate, especially in the case of anionics (*9*). The typical mixing time is 2 minutes, but reported values have ranged from 1 minute (*5*) up to 6 minutes (*7*). It is also suggested that adding emulsion in a continual thin stream while the mixer is still running will result in better coating (*9*).

As with most other aspects of mix designs for EAMs, the mixing used in the laboratory should attempt to simulate mixing in the field. However, this is difficult to achieve and it may be expected that laboratory mixing will be more efficient. However, it has been reported, at least in one case, that better mixing was achieved in the field than in the laboratory, in spite of the much shorter field mixing time (*13*).

One way to minimize laboratory testing time is to effectively estimate a trial emulsion content for mixing that approximates the final design value. Most existing design methods for dense-graded EAMs employ the Centrifuge Kerosene Equivalent (CKE) procedure but using different multipliers (*12*). Another approach is to derive the trial emulsion content for trial mixing from the aggregate gradation by means of an empirical equation. Another and probably least complicated approach is a simple coating test on a small sample of aggregate. It is apparent that none of these procedures is totally satisfactory.

### Optimum Fluids Content at Compaction

The proper fluids content at compaction appears to be a source of confusion to many researchers. It has been established that the fluids content for maximum density is found to be from 1 to 3 percent greater than the fluids content resulting in maximum stability. Another point to note is that the optimum water content for maximum density of aggregate alone is usually greater than the optimum fluids content of the same aggregate combined with water and emulsion, and the maximum density value is often greater with the addition of emulsion. These findings are thought to be related to the presence of the emulsifiers which cause the lower surface tension of the water in the emulsion to allow the "wetter water" to penetrate and wet the aggregate better, thus making compaction more efficient (*10, 19*). Thus, obtaining densities on aggregate combined with varying percentages of water is not recommended for establishing optimum fluids content at compaction for EAMs because of the effects of other factors such as emulsion breaking, mixture stability, and trial residual asphalt content used in the mix. The question is also raised whether the optimum binder content should be based on maximum dry density or maximum stability. However, there is a moisture content for a given residual asphalt content at which both stability and density will be near maximum (*9*). This means that judgment is needed in assigning the relative importance of stability and density.

With regard to field conditions, it is generally believed that breaking of the emulsion and optimum moisture content occur at about the same time and that this breaking is the best guide for determining when to start compaction (*28*). The timing for compaction is very important; if the mix is allowed to break significantly, it will be very difficult or impossible to compact and if compaction is attempted when the mixture water content is higher than optimum, satisfactory density will not be achieved because all voids will be filled (*9*) Also, there are instances when the optimum water content for mixing of a laboratory mixture is also the optimum water content for compaction and thus no aeration prior to compaction is necessary. In the field, this would mean that compaction could commence immediately after lay-down.

In an attempt to pinpoint the most favorable combination of residual asphalt content and moisture content at compaction that maximizes dry density or stability of specimens, several researchers have adopted the factorial approach (*10, 13*), in which both the emulsion content and water content are varied as opposed to the approach of first establishing an optimum water content for a trial emulsion content and then keeping that water content constant as the emulsion content is varied. Of course, this can mean considerable increase in the number of specimens, depending on the range of contents being investigated. This also means that one property has to be given priority because the "optimum" emulsion-water content combination may vary from property to property.

### Level of Compactive Effort

Another source contributing to the variability of compositional design is the level of compactive effort used when fabricating laboratory specimens. Compaction equipment investigated has included the Marshall hammer, the Triaxial Institute kneading compactor, the kneading compaction followed by a double-plunger static load, and the vibratory air hammer (or rammer). The goal is to achieve laboratory densities that are comparable to those of emulsion pavements. A general rule is that in-field EAMs should be compacted to at least 95 percent of laboratory density (*6, 9, 16*). Of course, it is recognized that the laboratory density will depend on the level of compactive effort for a given compaction apparatus.

With the Marshall hammer, 75 blows on each specimen end are specified in several methods; however, 50-blow compaction to reduce aggregate degradation and to match the typical compactive effort for hot-mixes is also recommended. One study found that 75-blow compaction for EAMs is comparable to the field density after approximately 1 to 2 years, not after initial compaction (*9*).

Compaction with the Triaxial Institute kneading compactor by using 150 tamps at 500 psi was found to result in unduly high densities. Furthermore, such compaction tends to cause nonhomogeneity in the specimen because the tamping foot concentrates the pressure in the top portion resulting in darker and better coating in the upper half of the specimen (*22*). Other recognized disadvantages include stripping and crushing of the coarse aggregate. Several design methods, when using Hveem equipment, call for only a light kneading compaction to "level" the specimen, which is then followed by a double-plunger static load of as high as 40,000 lb. This amount of load will result in densities that are considerably higher that those resulting from 50 or 75 blows of the Marshall hammer.

Other researchers have noted the advantages of compacting EAMs with a vibratory air hammer. It can produce the necessary densities without the high contact pressures that result in aggregate degradation (*15, 19, 25*). However, vibratory compactor specimens are less stiff at early curing stages than Marshall specimens because of the reduced aggregate degradation which can lead to "tender mixes" in the laboratory. As specimens cure, stiffness increases from the presence of asphalt so that the initial effects of compaction method are negated (*15*).

### Curing and Water Exposure Procedures

Probably the most difficult part of any mix design for EAMs is establishing curing and water exposure procedures for laboratory specimens that will, in a short time, simulate environmental conditioning in the field. Methods have included air curing while still in the mold or following extrusion, oven curing both in and out of the mold, and vacuum desiccation both in and out of the mold. Water exposure procedures have included capillary soaking, total immersion, vacuum saturation of immersed specimens, and moisture-vapor susceptibility tests.

The rate of moisture loss is directly proportional to the curing time, the environmental conditions such as temperature and humidity, and the total voids in the specimen. The difficulty is in determining when curing (i.e., drying) should cease and when should the specimens be tested or exposed to water. Some researchers believe that a 3-day cure in the mold at ambient temperatures is sufficient (*7, 19*). Others have used oven curing (*13, 15, 18*) or vacuum desiccation (*4*) to accelerate the curing process. The fundamental concern is whether exposure of the specimens to a constant temperature environment, especially in the case of oven curing, results in an unrealistically rapid evaporation of water when making comparisons to what occurs in the field, especially considering mix designs for bases covered by a dense AC surface course. A too rapid evaporation may affect test properties of specimens and also distort test properties following exposure to water (*27*).

The length of water exposure procedures can vary from as little as a half-an-hour to as much as 5 days. In one study, it was found that saturation for 15 min under 15 in. (381mm) of Hg vacuum of specimens covered with at least an inch of water followed by 15 min of immersion at ambient conditions is equivalent to 1 hour of vacuum saturation at 4 in. (101.6mm) of Hg followed by 1 hour of immersion (*19*). Others have used capillary soaking in which specimens are cured in the mold and then placed in water to a depth of approximately 1 in. The specimens are allowed to soak an additional 2 or 2½ days. In certain cases, capillary soaking can be as severe as vacuum saturation. The advantages listed for capillary soaking are as follows: (1) it is a realistic representation of field conditions for a base course exposed to ground water; (2) samples are confined, this prevents their disintegration; (3) it involves the use of simple and inexpensive equipment; and (4) absorbed moisture content can be measured easily (*9*). Its main disadvantages are that because this form of conditioning takes 4 or 5 days to complete, it is difficult to reproduce; it is also suggested that capillary soaking introduces water gradients within specimens which greatly and variably affect test properties. This time problem applies as well to the moisture-vapor susceptibility test, which takes 75 hours to complete. It appears that vacuum saturation is the most convenient procedure from the viewpoint of time; however, it may be too severe with regard to the degree of saturation and water absorption by the specimens. Possible alternatives include simple immersion of extruded specimens in a water bath at room conditions for a period from 24 to 72 hours or, as was investigated by the Virginia Highway and Transportation Research Council, shortening the vacuum saturation period to 5 min and extending the subsequent immersion period to 2 hours (*18*). The Virginia study also involved the use of an accelerated curing procedure wherein specimens, while still in the mold, were kept in an oven at 140°F for 16 hours. They achieved results comparable to those when using the reference Illinois method, but with a total conditioning period of less than 24 hours instead of 7 days (*1*).

There is general agreement that because of the changes in specimen properties as a function of curing time, such properties should be evaluated at both early and long-term stages of curing. That is, the design criteria should exist for property tests at both stages of curing.

### Strength Testing

Just as there are many methods for conditioning laboratory specimens, there are also many ways to measure strength characteristics of dense-graded EAMs after conditioning. These include Marshall stability and flow; stabilometer R-value and S-value; cohesiometer C-value; indirect tensile test; diametral resilient modulus, $M_R$ and repeated-load triaxial compression test. Because most mix design methods for EAMs are modifications of the two reference methods for hot-mix asphalt concrete (Marshall and Hveem), modified Marshall stability and flow (conducted at room temperature instead of 140°F), and stabilometer and cohesiometer values are the most common strength measurements. Also, in a study at the University of Illinois (*7*), it was found that Marshall stability, diametral resilient modulus and indirect tensile strength all indicated similar trends and were found to correlate well with each other. On this basis, it appears that one strength test could be used to predict another.

Methods developed by The Asphalt Institute, Chevron, FHWA Region 10, and the University of Arizona use Hveem stabilometer and cohesiometer, while methods developed by ARMAK, the University of Illinois, the University of Mississippi, and Purdue University, utilize Marshall equipment (*1, 12*). Research at Purdue (*13*) has also focused on the calculation of Marshall stiffness ($S_M = {}^{P}\!/_{F}$, where P is the load at failure and F is the flow) and Marshall index ($I_M$ = slope of linear portion of load-deformation trace) as potential parameters for controlling mix properties. The stabilometer R-value and S-value are measures of specimen resistance to shear stress, while the cohesiometer C-value is a measure of tensile strength. These two strength parameters are also used to calculate another parameter, $R_t$-value, which is equal to the R-value plus 0.05 times the C-value. The factor of 0.05 was suggested by Hveem and Davis as being indicative of the relative strength of the cohesiometer result (*11*). Other researchers consider the C-value to be the primary strength criterion with regard to the effects of emulsion treatment, because both R- and S-values show little improvement or change after treatment with emulsion (*19*).

Strength testing of open-graded mixes is much more difficult because specimens lack sufficient cohesion for routine Marshall stability or split-tension testing (*12*). The most commonly used strength test for open-graded mixes is the diametral resilient modulus (*16*), but the repeated-load triaxial compression test is also used. The latter test is more difficult to perform than the $M_R$ test, but it allows confining pressures in excess of one atmosphere. Freezing and the use of rubber membranes are suggested to facilitate the handling of open-graded specimens.

Because strength testing results are a function of the curing and water exposure schemes developed by the various agencies, a comparison of test data is very difficult. Also, with both dense-graded and open-graded EAMs, there has been poor correlation between laboratory data and field performance results (*12*).

### Relationship Between Different Properties

The following is a discussion of general trends in EAM specimen properties as reported by various research agencies. It should be noted that in many references the indicated trends are for a limited number of emulsion-aggregate combinations (or for even just one) and, therefore, may not have general applicability.

The effect of emulsion content at early stages of curing is relatively insignificant because behavior at that time is similar to that of untreated aggregate. The emulsion has not adequately "broken" and, therefore, specimen strength is primarily dependent on interparticle contact. This "untreated aggregate" response is also evident with high water contents. When water content is low, the emulsion acts as a lubricant to overcome the interparticle friction, as shown by increases in flow or compressibility with increasing emulsion content (*13, 26*). An increase in emulsion content is also usually accompanied by decreases in dry as-cured stability, air voids, total voids, and water absorption, but increases in unit weight, voids in mineral aggregate (VMA), and percentage of retained stability after water exposure (*7, 13*).

Most researchers agree that the stability of water exposed specimens has more significance than that of cured or dry specimens. There is normally a characteristic peak in soaked stabilities indicating that there are optimum fluids contents and residual asphalt contents at which maximum stabilities are achieved (*7*). One explanation for this is that while stabilities of specimens cured at different asphalt contents are affected by the variable water, water contents of soaked specimens are essentially the same regardless of residual asphalt content. This allows selection of optimum residual asphalt content on the basis of soaked stabilities (*8*).

Specimen properties also depend on the degree and duration of curing and water exposure. One study found that specimen densities increased and immersed strength decreased with increasing vacuum (*19*). Rate of moisture loss, and thus the rate of gain in strength, is directly proportional to curing time and total voids. As the water content decreases below 1 percent, there is a significant increase in mix stability. The amount of total voids also has a bearing on the amount of water absorbed by the specimen, i.e., higher voids mean greater water absorption; and, the higher the water content, the lower is the stability (*7*).

Specimen properties also depend on the fluids content (asphalt plus water) at compaction. It affects retained moisture at time of testing, dry and wet densities, and total voids. As fluids content at compaction increases, total voids decrease (*8*). Also, there is a strong relationship between stability and density, indicating the importance of achieving good compaction (*5*).

In summary, properties such as strength, density, voids, and water absorption depend on many factors including fluids content, residual asphalt content, compactive effort, degree and duration of cure and water exposure, and type of emulsion and aggregate. The difficulty is in setting design requirements that consider all these factors and that are applicable to actual pavement design.

### Indication for Needed Research

Partially as a result of this relatively recent research, there are at least ten methods available for designing dense-graded emulsion mixes. The Asphalt Institute, Chevron, FHWA Region 10, the University of Arizona, and the U.S. Forest Service methods utilize Hveem equipment. Methods developed by ARMAK, McConnaughay, University of Illinois, University of Mississippi, and Purdue University make use of Marshall equipment. In spite of this multitude of methods, the design criteria for all of them are quite limited. In fact, four of them (ARMAK, FHWA Region 10, Arizona, and Purdue) do not have minimum strength criteria. Furthermore, the design criteria, if available, are not comparable because of the differences in curing periods and conditions (*12*).

With regard to suggestions for additional research, the overall assessment is that information on the relationship between design and construction experience with emulsion mixes is still rather limited. There is a real need for reliable, practical mix design procedures for cold emulsified asphalt mixtures, with emphasis on curing and water exposure procedures that are consistent with field conditions. Furthermore, the development of suitable design criteria for selecting optimum mix components is also needed.

Because EAMS are unique in that water is an integral part of the mix, it has been suggested by one researcher that compaction molds be modified to allow for the removal of excess water that prohibits adequate voids and densities as a result of pore water pressures built up during the compaction process (*5*). This would better simulate compaction in the field where more water may be released than in the laboratory with compaction by the Marshall hammer, kneading compactor, or double-plunger static load.

Also, the time to complete many of the existing methods is considerably longer than desirable. Thus, further research should also be directed toward minimizing laboratory testing time.

In the FHWA's state-of-the-art report, it was recommended that The Asphalt Institute method using Hveem equipment and the University of Illinois method using Marshall equipment "be further developed and/or refined as a mix design method for base and surface course using emulsified asphalt." These two methods are "among the best defined . . . are technically valid, and no theoretical basis exists for the development of faster methods" and that "additional work should also be undertaken to further develop correlations between mix parameters, such as strength, coating and stripping, and field performance" (*12*).

The purpose of NCHRP Project 9-5 was to study these two methods in an attempt to evaluate the feasibility of satisfying the recommendations of the FHWA report.

## DEFINITIONS AND CALCULATIONS

### Definitions of Terms Used in this Study

Dry bulk specific gravity, $G_d$—The ratio of the mass of a unit volume (including permeable and impermeable air voids) at a stated temperature to the mass of an equal volume of a gas-free distilled water at a stated temperature.

Dry density of paving mixture—Dry bulk specific gravity times the density of water at ambient conditions (assumed equal to 62.4 $lb/ft^3$).

Apparent specific gravity of aggregate, C—Ratio of the mass of a unit volume of the impermeable portion of the aggregate at a stated temperature to the mass of an equal volume of gas-free distilled water at a stated temperature.

Water content—Percent of water in mixture based on mass of dry aggregate.

Water content at testing, K—Percent of water in mixture, based on mass of dry aggregate, after mixture has been cured or immersed in water prior to stability testing.

Fluids content—Percent of water and asphalt in specimen, based on dry mass of aggregate.

Voids in mineral aggregate, VMA—Volume of air voids, water and asphalt, expressed as percent of total specimen volume.

Total voids, V—Volume of air voids and water, expressed as percent of total specimen volume.

Air voids—Volume of voids not filled with water or asphalt, expressed as percent of total specimen volume.

Water absorption—Mass of water picked up during water-immersion or soaking, expressed as percent of dry aggregate mass.

Retained stability—Marshall stability after water-immersion or soaking, expressed as percent of cured specimen stability.

Emulsion content—Amount of emulsion in mixture, expressed as percent based on dry aggregate mass.

Residual asphalt content, A—Asphalt residue in paving mixture, expressed as percent of dry aggregate mass. Normally calculated on the basis of emulsion composition.

### Calculations

In this study some of the compacted specimen properties defined above were calculated using the following equations:

$$G \text{ (bulk specific gravity)} = \frac{D}{F - E}$$

$$G_d \text{ (dry bulk specific gravity)} = G \times \frac{(100 + A)}{(100 + A + K)}$$

$$\text{Dry density, lb/ft}^3 = G_d \times 62.4$$

$$K \text{ (water content at testing), \%} = \frac{\text{mass of water, g}}{\text{mass of dry mixture, g}} \times (100 + A)$$

$$\text{VMA, \%} = \left[\left(\frac{100 + A + K}{G} - \frac{100}{C}\right) \div \left(\frac{100 + A + K}{G}\right)\right] \times 100$$

$$V \text{ (total voids), \%} = \left[\left(\frac{100 + A + K}{G} - \frac{100}{C} - \frac{A}{B}\right) \div \left(\frac{100 + A + K}{G}\right)\right] \times 100$$

$$\text{Air Voids, \%} = V - \left[\left(\frac{K \times 100}{L}\right) \div \left(\frac{100 + A + K}{G}\right)\right]$$

where:

D = mass of specimen in air, g;  
E = mass of specimen in water, g;  
F = mass of specimen in saturated surface-dry (SSD) condition, g;  
A = asphalt residue as percent of dry aggregate mass;  
B = specific gravity of asphalt;  
C = apparent specific gravity of aggregate; and  
L = specific gravity of water.

In addition, the strength parameter, $R_t$-value, is computed as folows:

$$R_t = R + 0.05\ C$$

where:

R = resistance R-value at 73 ± 5°F (23 ± 2.8°C); and  
C = cohesiometer C-value at 73 ± 5°F (23 ± 2.8°C).

## EVALUATION OF THE UNIVERSITY OF ILLINOIS AND THE ASPHALT INSTITUTE DESIGN METHODS FOR DENSE-GRADED MIXES

### Review and General Comparison of Two Design Methods

In the evaluation of the University of Illinois (UI) and Asphalt Institute (AI) methods, the initial step was to become thoroughly familiar with the details of the two design methods as outlined in the FHWA Manual (*1*). Detailed step-by-step test procedures for both methods were prepared, which included most of the material contained in the FHWA Manual, and presented in a more concise and logical sequence. A table comparing the separate and similar tests of both mix design methods was also prepared. The outlines of the simplified methods and the table are included in Appendix A.

The review of the two design methods brought out a number of major differences and shortcomings that in part are listed below:

1. Descriptions of both methods are lengthy and cumbersome, and the sequence of procedural steps is difficult to follow.
2. Both methods are time consuming. About 2 weeks time is required to complete either of the two methods. Additionally, design tests must be initiated on certain weekdays to avoid testing on weekends.
3. The methods differ greatly in establishing trial emulsion contents. The UI method makes use of an empirical equation based solely on aggregate gradation. This does not differentiate between types of aggregates, and it can result in negative values with dense-graded aggregates having low quantities of fines. The AI method employs the Centrifuge Kerosene Equivalent (CKE) method which takes into account the surface area and gradation of the aggregate.
4. Compaction of specimens is vastly different for the two design methods. They differ not only in the level of the compactive effort but also in the mode of compactive force.
5. Curing and water exposure procedures are different for the two design methods. Considerably more rigorous curing or drying is employed by the AI method. For water exposure, the AI method employs vacuum immersion, while the UI method uses prolonged capillary soaking of each specimen end.
6. Strength or stability determinations for the two methods are greatly different. The AI method employs triaxial confinement of specimens during testing, while the UI method uses a high rate of loading of semiconfined specimens prescribed for Marshall stability determinations.
7. The two design methods vary greatly in their mixture design criteria and in the selection of optimum binder content.

### Comparison of Individual Tests of the Two Design Methods

Both mixture design methods, after establishment of the trial emulsion content, involve three separate tests, which can be generalized as the coating, compaction, and strength tests. Results of these tests are used to establish the optimum emulsion or residual asphalt content to be used in actual pavement construction.

Detailed comparisons and discussion of the separate steps of the mix design methods follow:

### *Trial Emulsion Content*

The procedures for determining the trial emulsion content to be used for the coating and compaction tests are different for the two methods.

With the UI method, the trial residual asphalt content is computed according to the empirical equation:

$$R = 0.00138AB + 6.358 \log C - 4.655$$

where:

$A$ = percent of aggregate retained on No. 4 sieve;

$B$ = percent of aggregate passing No. 4 and retained on No. 200 sieve; and

$C$ = percent of aggregate passing No. 200 sieve.

The computed value of R is rounded to the nearest 0.5 percent and then divided by the percent residual asphalt in the emulsion to establish the trial asphalt emulsion content. This empirical equation, based solely on mineral aggregate gradation, does not differentiate between aggregates differing in angularity and surface texture. Also, for dense-graded aggregates having low quantities of fines, it may lead to negative values.

With the AI method, the trial emulsion content is based on an oil ratio determined by the Centrifuge Kerosene Equivalent (CKE) procedure. It is equal to 1.4 × CKE oil ratio, adjusted to a 60 percent asphalt residue. The CKE test takes into account surface area and texture of the aggregate as well as its gradation. However, emulsion mixtures are water containing systems and it appears that water instead of kerosene for estimating the initial trial emulsion content could be more appropriate. Thus, neither method for estimating the trial emulsion content is completely satisfactory, but it appears that the CKE approach is more realistic and, therefore, preferable.

### *Coating Test*

The objective of the coating test is to determine the minimum total water content (UI method) or fluids content (AI method) that gives the highest percent of aggregate coating. It involves mixing sample batches using the established trial emulsion content and increasing mixing water in fixed increments. An Institute laboratory study indicated that mixing water and aggregate with a mechanical mixer for approximately 30 sec and then mixing wet aggregate with emulsion for 90 sec provided optimum coating conditions for dense-graded aggregate-emulsion mixes. The coating test is rather subjective in nature. It involves visual judgment of aggregate coating by the asphalt residue and assigning to each batch of mixture the percentage of coated aggregate. This test establishes the water (or fluids) content used for mixing in the subsequent test steps of the mix design.

### *Compaction Test*

The compaction test establishes the optimum water or fluids content to be used for compaction. It should be recognized that compaction of specimens for this test and for the subsequent strength test is entirely different for the two design methods. They differ not only in the compactive effort but also in the mode of compactive force used for the fabrication of specimens.

Specimens for the UI method are compacted using 75 blows of impact force applied by the Marshall hammer. Specimens for the AI method are initially compacted by applying approximately 20 tamps of the Triaxial Institute kneading compactor tamping foot set at 250 psi, which is then followed by a 40,000-lb double-plunger static load. The trial emulsion content is used for all specimens and generally no more than four water contents are investigated in the compaction test. These include the mixing water content, established by the coating test, and lower water contents obtained by drying the mix 1, 2, or 3 percent. With the UI method, specimens are allowed to cure in the mold for one day and then are measured for Marshall stability and flow, while the AI method specimens are measured for height immediately after compaction, extruded, and weighed for calculation of density based on dimensional measurements. Thus, with the UI method, the optimum water content for compaction is based on maximum Marshall stability, while optimum fluids content for compaction with the AI method is based on maximum specimen density.

### *Strength Tests*

The strength test, the last and most important step in the laboratory mixture design, involves compaction of specimens, their curing (i.e., drying), plus water exposure for half of the specimens, followed by the strength determination.

Specimens are compacted at varying emulsion contents. For the UI method, total water content at compaction is kept constant, while for the AI method, total fluids content remains constant.

Curing and water exposure procedures of the two methods are quite different. With the UI method, compacted specimens are air-cured in the mold for 3 days before extrusion from the mold and as-cured stability and flow determinations. For water-exposure, UI method specimens, after a 3-day cure in the mold, are subjected to 2-day in-the-mold capillary soaking of each end of the specimen before testing. It may be expected that such soaking procedures will result in the development of moisture gradients within specimens which will vary with specimen density and compositional characteristics.

In the case of the AI method, specimens are cured for one day in the mold before "early cure" resistance R-value determinations. For measurements of water exposure effects, additional AI method specimens are cured for 3 days in the mold followed by 4-day-out-of-the-mold desiccation under a minimum vacuum of 750 mm Hg. After such drying, the specimens are submerged in water and saturated under a 660-mm Hg vacuum for 1 hour, which is followed by an additional 1-hour water immersion without vacuum before R-value determination.

It is safe to assume that these differences in the curing and water exposure conditions of the two design methods will lead to specimens differing widely in their physical characteristics.

Strength or stability determinations of the two design methods also differ greatly. The AI method employs a mode of triaxial specimen confinement and a relatively low rate of loading for the R-value determination which is a shear strength test. With the AI method, R-value measurements are immediately followed by the cohesiometer test for C-value determination which is a tensile strength type test.

In the case of the UI method, strength or stability determinations are accomplished by loading semiconfined specimens (of the same size as AI method specimens) at relatively high rates as prescribed for the Marshall test. Besides stability, this test provides the flow value which is a measure of specimen deformation prior to failure. Another significant difference in the strength tests of the two design methods is that for the R-value measurements of the AI method, specimens are loaded parallel to the axis of compaction and C-values are measured by applying tensile forces perpendicular to the axis of compaction. On the other hand, Marshall stability and flow values of the UI method are measured by applying compressive forces perpendicular to the axis of compaction. These modes of loading undoubtedly lead to substantial variances in measured strength characteristics.

### *Mixture Design Criteria*

The two design methods vary greatly in their mixture design criteria which utilize laboratory test data in the selection of the optimum emulsion content (i.e., optimum residual asphalt content) to be used for field mixtures. These criteria are summarized in tabular form in Appendix B.

The AI method differentiates between criteria for base or temporary surface courses and criteria for permanent surface pavements. The UI method, however, has a single set of criteria for emulsion mixtures for base courses alone. Also, the UI method criteria, besides containing stability and coating limits, also include requirements for percentages of total voids, stability loss and absorbed water during soaking. On the other hand, the AI method, though having the same coating criteria, relies solely on strength parameters such as R- or S-values and cohesiometer C-value. Because of these basic differences, direct comparisons concerning the selectivity or utility of the two sets of criteria are nearly impossible.

## Laboratory Evaluations of Design Methods

### *General*

Comprehensive testing to evaluate experimentally all phases of the two design methods was undertaken. The purpose of these tests was to compare the individual design steps and complete design procedures for different aggregates and emulsions. Another aim of this testing program was to develop a thorough familiarization by laboratory personnel with all testing steps used in both the University of Illinois and Asphalt Institute design procedures. The testing procedures described in, "A Basic Asphalt Emulsion Manual" (*1*), were followed. All property tests on emulsions and aggregates were conducted according to the methods contained in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, Part II, The American Association of State Highway and Transportation Officials, or *Annual Book of ASTM Standards*, Part 15, American Society for Testing and Materials.

### *Materials*

*Emulsion.* Two types of emulsions were used in these tests. The first received was SS-1h. The second, designated as AE-BM, was SS-1 type emulsion modified to suit mixtures with crusher-run limestone containing relatively high amounts of fines (passing U.S. Standard Sieve No. 200). The AE-BM emulsion contained a moderate amount of oil distillate. Properties of both emulsions are given in Table 1. Generally, both emul-

**Table 1. Properties of asphalt emulsions.**

| EMULSION GRADE | CSS-1h | AE-BM[a] |
|---|---|---|
| TESTS ON EMULSION | | |
| Viscosity, Saybolt Furol at 77°F (25°C), sec | 30.7 | 93.8 |
| Settlement, 5-day, % | 2.79 | ---- |
| Storage Stability Test, 24 hour, % | ---- | 0.2 |
| Cement Mixing Test, % | 0.2 | 2.4 |
| Particle Charge Test | Positive | ---- |
| Sieve Test, % | 0.03 | 0.09 |
| Distillation: | | |
| Residue, % | 66.8 | 61.6 |
| Oil Distillate, % | 0.5 | 2.1 |
| Water, % | 32.7 | 36.3 |
| TESTS ON DISTILLATION RESIDUE | | |
| Penetration, 77°F (25°C), 100g, 5 sec | 91 | 132 |
| Ductility, 77°F (25°C), 5 cm/min, cm | 150+ | 150+ |
| Specific Gravity | 1.025 | 1.032 |
| Solubility in Trichloroethylene, % | 99.70 | 98.99 |
| Viscosity, 140°F (60°C), Poises | 1692 | 1144 |
| Viscosity, 275°F (135°C), cSt | 374 | 521 |
| Ash Content, % | 0.33 | 1.04 |

[a] Modified SS-1 emulsion.

sions meet the requirements in AASHTO or ASTM specifications for cationic or anionic emulsified asphalts.

*Mineral Aggregates.* Four different aggregates were used in this first laboratory testing phase. Two of these aggregates were limestones, one obtained from Rockville, Maryland, and the other from Harrisonburg, Virginia. The Maryland limestone was considerably finer than the Virginia limestone. The two other aggregates were highly siliceous materials originating in the vicinity of College Park, Maryland. One of these materials consisted of natural rounded gravel and sand and the other was crushed gravel and sand. The coarse fraction of the crushed Maryland gravel was prepared by laboratory crushing of larger particles of natural gravel. Limestone filler (passing U.S. Standard Sieve No. 200) was used for both siliceous aggregates.

The more important properties of the four aggregates are given in Table 2 and gradations are shown in Figure 1. It should be noted that the gradations of the four aggregates represent coarse, medium, and fine gradations. However, all these aggregate gradations lie within a wide range of gradations designated as "dense-graded" in "A Basic Asphalt Emulsion Manual" (*2*). This range is represented by the solid lines in Figure 1.

### *Test Data and Discussion of Standard Design Procedures*

*Data Description.* To evaluate the reference design procedures, six sets of laboratory designs were conducted for each design method. In the case of the SS-1h emulsion, mixes with all four mineral aggregates were prepared. With the AE-BM emulsion, however, laboratory mixtures were prepared only with the two calcareous aggregates. Thus, a total of 12 laboratory designs were made for the evaluation and comparison of the procedures of both design methods. Test data for the UI method are summarized in Table 3 and illustrated in Figures 2 through 7. Test data for the AI method are shown in Table 4 and Figures 8 through 13.

The data in the first four columns of Tables 3 and 4 provide compositional characteristics for each mixture which include emulsion and residual asphalt contents, fluids content (i.e., asphalt plus water) and water content at compaction as established by the compaction test.

Beside compositional characteristics, the tables include for each mixture the values of dry density, voids in mineral aggre-

**Table 2. Properties of mineral aggregates.**

| | MINERAL AGGREGATE | | | |
|---|---|---|---|---|
| | VIRGINIA LIMESTONE | NATURAL MARYLAND GRAVEL AND SAND | CRUSHED MARYLAND GRAVEL AND SAND | MARYLAND LIMESTONE |
| | GRADATION | | | |
| | COARSE | MIDDLE | FINE | MIDDLE |
| U.S. STANDARD SIEVE | PERCENT PASSING | | | |
| 3/4 in. | 92.1 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 74.5 | 94.3 | 100.0 | 84.9 |
| 3/8 in. | 60.2 | 82.8 | 95.0 | 70.1 |
| No. 4 | 36.2 | 53.7 | 77.0 | 50.7 |
| No. 8 | 24.3 | 39.8 | 63.0 | 39.5 |
| No. 16 | 13.9 | 24.3 | 50.0 | 27.2 |
| No. 30 | 8.3 | 17.1 | 35.0 | 19.0 |
| No. 50 | 5.1 | 12.0 | 23.4 | 13.4 |
| No. 100 | 3.4 | 7.5 | 13.1 | 9.3 |
| No. 200 | 2.3 | 5.1 | 9.2 | 6.9 |
| SPECIFIC GRAVITY | | | | |
| Bulk | 2.686 | 2.608 | 2.624 | 2.714 |
| Bulk (SSD) | 2.704 | 2.624 | 2.631 | 2.723 |
| Apparent | 2.736 | 2.650 | 2.656 | 2.738 |
| WATER ABSORPTION, % | 0.68 | 0.60 | 0.56 | 0.33 |
| UNIT WEIGHT, lb/cu ft | 129.6 | 128.2 | 122.2 | 122.3 |
| SAND EQUIVALENT | 67 | 58 | 84 | 76 |
| LOS ANGELES ABRASION, % | 18.9 | 22.5 | 28.4 | 31.5 |
| SOLUBILITY IN HCL, % | | | | |
| Passing No. 4 Sieve | 89.8 | ---- | ---- | 80.5 |
| Retained on No. 4 Sieve | 91.1 | ---- | ---- | 73.5 |
| CENTRIFUGE KEROSENE EQUIVALENT | | | | |
| CKE, % | 3.1 | 4.2 | 3.8 | 5.3 |
| Surface Capacity, % | 2.5 | 1.7 | 2.7 | 2.4 |
| Oil Ratio, % | 3.0 | 4.4 | 5.5 | 5.0 |

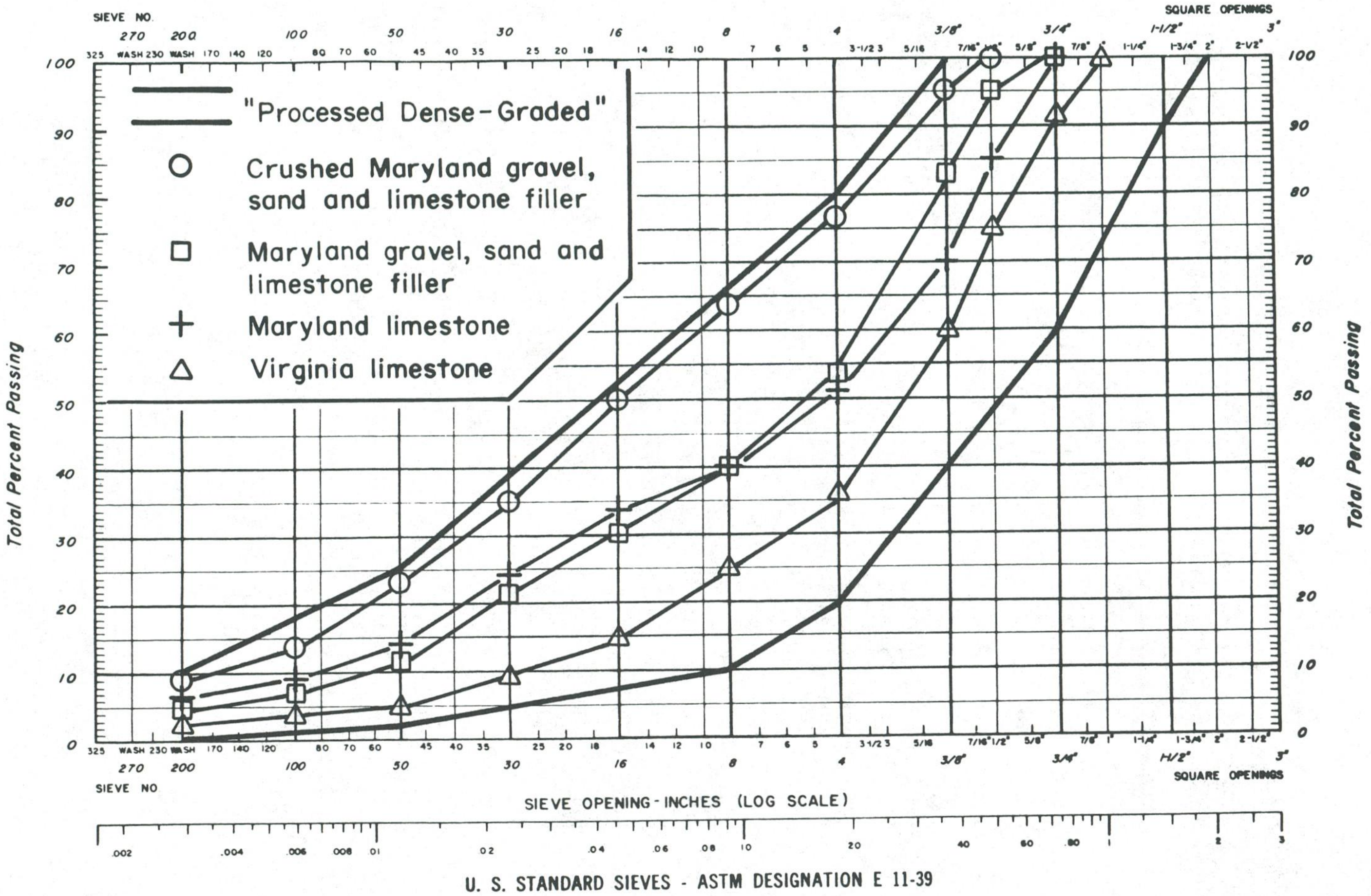

*Figure 1. Gradation of mineral aggregates.*

gate (VMA), total voids, air voids, and water content at testing. Additionally, for UI method specimens, Marshall stabilities of cured and soaked specimens plus retained stability and water absorption are provided in Table 3. In Table 4, dealing with the AI method, $R_t$ and C-values are shown for early cure and vacuum-saturated specimens. Because the UI method specifies Marshall stability testing at room temperature, only R-value and C-value determinations at room temperature were made on AI method specimens in order to make reasonable comparisons between the two methods. Additionally, the table includes water absorption values for the vacuum-saturated specimens.

As specified by the UI method, all mixtures were prepared at five different emulsion contents. The middle asphalt content is established by empirical formula and it is the same as that used for the coating and compaction tests. The other four asphalt contents vary above and below the middle value by fixed increments. For the AI method (Table 4) only three residual asphalt contents are specified. These contents are arrived at by multiplying the CKE oil ratio by arbitrary factors of 1.1, 1.4, and 1.7.

*Trial Binder Contents.* The data in Tables 3 and 4 (first and second columns) indicate that the ranges of emulsion or residual asphalt contents selected for trial by the two methods vary substantially. Residual asphalt contents selected for evaluation by the CKE oil ratio method (AI method) appear to be higher than asphalt contents established by the use of the empirical equation (UI method). Also, it appears that the trial asphalt contents established by the CKE method correlate better with the fineness of the four aggregates as represented by Figure 1.

Additionally, the CKE oil ratio method leads to a considerably narrower range of asphalt contents selected for evaluation than does the use of the UI method's empirical equation. These differences point towards the need for improvement of the method to be used for selection of the trial asphalt contents for evaluation. A possible compromise for both methods would be to use, for example, 1.4 times the CKE oil ratio. The advantage of such an approach is that it considers surface area and surface texture as well as gradation of aggregate. This value could be considered as the middle trial content. Four additional contents spaced in equal increments above and below this value could be selected for trials. Such an approach, it appears, would combine both the initial accuracy of the AI method and the flexibility of the UI method.

*Comparison of Specimen Properties Prepared by Two Design Methods.* The data in the summary Tables 3 and 4 and in Figures 2 through 13 indicate major differences in physical properties of specimens fabricated by the two reference design methods. For example, comparing properties for a given emulsion-aggregate combination reveals that specimens at comparable residual asphalt contents compacted by AI design procedures are invariably denser than specimens compacted by UI procedures, and the differences range from about 2 to more than 10 lb/cu ft. It is apparent that these density differences tend to correlate with the Los Angeles abrasion test results for individual aggre-

**Table 3. Design of emulsion paving mixtures by the University of Illinois method.**

| | MIXTURE COMPOSITION | | | | PROPERTIES OF CURED SPECIMENS | | | | | | PROPERTIES OF SOAKED SPECIMENS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGGREGATE/EMULSION | EMUL. CONT. % | RESID. ASPH. % | FLUID CONT. % | WATER CONT. % | DRY DENSITY lb/ft$^3$ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | MARSHALL STAB. lb | DRY DENSITY lb/ft$^3$ | VMA | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | MARSHALL STAB. lb. | RET. STAB. % | WATER ABSORPT. % |
| VIRGINIA | 2.3 | 1.5 | 6.3 | 4.8 | 147.0 | 15.2 | 11.7 | 10.7 | 0.4 | 4835 | 146.4 | 15.6 | 12.1 | 6.9 | 2.3 | 2394 | 49.5 | 1.9 |
| LIMESTONE | 3.0 | 2.0 | 6.8 | 4.8 | 147.3 | 15.4 | 10.9 | 9.7 | 0.5 | 4690 | 146.5 | 15.9 | 11.4 | 6.3 | 2.2 | 2853 | 60.8 | 1.7 |
| (Coarse Gradation) | 3.8 | 2.5 | 7.3 | 4.8 | 147.0 | 16.0 | 10.4 | 9.2 | 0.5 | 4045 | 144.8 | 17.3 | 11.7 | 6.5 | 2.3 | 1981 | 49.0 | 1.8 |
| | 4.5 | 3.0 | 7.8 | 4.8 | 145.4 | 17.3 | 10.7 | 8.9 | 0.8 | 3490 | 144.8 | 17.7 | 11.0 | 5.6 | 2.4 | 2071 | 59.3 | 1.6 |
| EMULSION: CSS-1h | 5.3 | 3.5 | 8.3 | 4.8 | 144.9 | 18.0 | 10.3 | 9.0 | 0.6 | 3265 | 144.0 | 18.5 | 10.9 | 5.1 | 2.6 | 1841 | 56.4 | 2.0 |
| MARYLAND GRAVEL, SAND | 2.3 | 1.5 | 4.8 | 3.3 | 143.1 | 14.7 | 11.4 | 10.4 | 0.4 | 2460 | 142.1 | 15.3 | 12.0 | 3.7 | 3.8 | 920 | 37.4 | 3.4 |
| AND LIMESTONE FILLER | 3.0 | 2.0 | 5.3 | 3.3 | 141.7 | 16.0 | 11.6 | 10.6 | 0.5 | 2040 | 140.8 | 16.6 | 12.2 | 3.5 | 3.9 | 1050 | 51.5 | 3.4 |
| (Middle Gradation) | 3.8 | 2.5 | 5.8 | 3.3 | 141.3 | 16.7 | 11.3 | 10.2 | 0.5 | 1745 | 140.1 | 17.3 | 12.0 | 4.0 | 3.7 | 1115 | 63.9 | 3.2 |
| | 4.5 | 3.0 | 6.3 | 3.3 | 140.0 | 17.8 | 11.4 | 10.2 | 0.5 | 1255 | 137.0 | 19.6 | 13.3 | 5.0 | 3.9 | 870 | 69.3 | 3.4 |
| EMULSION: CSS-1h | 5.3 | 3.5 | 6.8 | 3.3 | 139.3 | 18.6 | 11.2 | 9.7 | 0.7 | 1115 | 136.3 | 20.4 | 13.1 | 5.4 | 3.7 | 625 | 56.1 | 3.0 |
| CRUSHED MARYLAND GRAVEL, | 3.7 | 2.5 | 7.2 | 4.7 | 133.6 | 21.4 | 16.3 | 15.4 | 0.4 | 2202 | 133.8 | 21.2 | 16.1 | 5.9 | 4.9 | 1082 | 49.1 | 4.5 |
| SAND AND LIMESTONE FILLER | 4.5 | 3.0 | 7.7 | 4.7 | 132.8 | 22.2 | 16.2 | 15.1 | 0.5 | 2159 | 133.4 | 21.9 | 15.8 | 6.0 | 4.7 | 1163 | 53.9 | 4.2 |
| (Fine Gradation) | 5.2 | 3.5 | 8.2 | 4.7 | 133.1 | 22.4 | 15.4 | 14.2 | 0.6 | 1993 | 133.0 | 22.4 | 15.4 | 5.9 | 4.6 | 1175 | 59.0 | 4.0 |
| | 6.0 | 4.0 | 8.7 | 4.7 | 132.4 | 23.2 | 15.2 | 14.2 | 0.5 | 1884 | 132.5 | 23.1 | 15.2 | 6.0 | 4.5 | 1119 | 59.4 | 4.0 |
| EMULSION: CSS-1h | 6.7 | 4.5 | 9.2 | 4.7 | 131.9 | 23.8 | 15.0 | 13.7 | 0.6 | 1462 | 131.9 | 23.8 | 15.0 | 6.5 | 4.2 | 1042 | 71.3 | 3.6 |
| MARYLAND | 4.1 | 2.5 | 8.1 | 5.6 | 144.8 | 17.3 | 11.9 | 10.4 | 0.6 | 2137 | 145.5 | 16.9 | 11.4 | 4.4 | 3.1 | 1595 | 74.6 | 2.5 |
| LIMESTONE | 4.9 | 3.0 | 8.6 | 5.6 | 143.6 | 18.4 | 11.9 | 10.1 | 0.8 | 1623 | 144.5 | 17.9 | 11.4 | 4.7 | 3.0 | 1303 | 80.3 | 2.2 |
| (Middle Gradation) | 5.7 | 3.5 | 9.1 | 5.6 | 142.9 | 19.2 | 11.7 | 9.9 | 0.8 | 1316 | 143.3 | 19.0 | 11.5 | 4.0 | 3.4 | 959 | 72.9 | 2.6 |
| | 6.5 | 4.0 | 9.6 | 5.6 | 141.7 | 20.3 | 11.8 | 9.8 | 0.9 | 1272 | 142.6 | 19.8 | 11.3 | 4.1 | 3.3 | 918 | 72.2 | 2.4 |
| EMULSION: AE-BM | 7.3 | 4.5 | 10.1 | 5.6 | 139.2 | 22.1 | 12.8 | 10.6 | 1.0 | 956 | 140.6 | 21.2 | 11.8 | 4.2 | 3.5 | 745 | 77.9 | 2.5 |
| VIRGINIA | 2.5 | 1.5 | 5.3 | 3.8 | 144.5 | 16.7 | 13.3 | 12.2 | 0.5 | 2737 | 143.8 | 17.0 | 13.7 | 8.7 | 2.2 | 1801 | 65.8 | 1.7 |
| LIMESTONE | 3.3 | 2.0 | 5.9 | 3.8 | 141.8 | 18.6 | 14.2 | 13.1 | 0.5 | 2303 | 143.2 | 17.8 | 13.4 | 7.4 | 2.7 | 1239 | 53.8 | 2.2 |
| (Coarse Gradation) | 4.1 | 2.5 | 6.5 | 3.8 | 142.2 | 18.8 | 13.3 | 12.1 | 0.5 | 2176 | 142.7 | 18.5 | 13.0 | 6.9 | 2.7 | 1461 | 67.1 | 2.2 |
| | 4.9 | 3.0 | 6.9 | 3.8 | 142.5 | 19.0 | 12.5 | 10.5 | 0.9 | 1872 | 140.4 | 20.2 | 13.8 | 5.8 | 3.7 | 847 | 45.2 | 2.8 |
| EMULSION: AE-BM | 5.7 | 3.5 | 7.4 | 3.8 | 143.2 | 19.0 | 11.4 | 9.3 | 0.9 | 1352 | 141.1 | 20.1 | 12.7 | 5.3 | 3.4 | 1269 | 93.9 | 2.4 |
| MARYLAND | 3.7 | 2.5 | 8.1 | 5.6 | 144.0 | 17.8 | 12.3 | 11.2 | 0.5 | 4578 | 143.3 | 18.2 | 12.7 | 4.2 | 3.8 | 2051 | 44.8 | 3.3 |
| LIMESTONE | 4.5 | 3.0 | 8.6 | 5.6 | 143.4 | 18.5 | 12.0 | 10.9 | 0.5 | 3601 | 142.4 | 19.1 | 12.6 | 4.5 | 3.7 | 1943 | 54.0 | 3.2 |
| (Middle Gradation) | 5.2 | 3.5 | 9.2 | 5.6 | 142.0 | 19.7 | 12.2 | 10.9 | 0.6 | 3004 | 140.4 | 20.6 | 13.2 | 5.4 | 3.6 | 1655 | 55.1 | 3.0 |
| | 6.0 | 4.0 | 9.7 | 5.6 | 141.3 | 20.4 | 11.9 | 10.4 | 0.7 | 2488 | 140.5 | 20.9 | 12.5 | 5.4 | 3.3 | 1466 | 58.9 | 2.6 |
| EMULSION: CSS-1h | 6.7 | 4.5 | 10.2 | 5.6 | 140.5 | 21.3 | 11.9 | 10.3 | 0.8 | 2521 | 137.7 | 22.9 | 13.6 | 5.4 | 3.9 | 1183 | 46.9 | 3.1 |

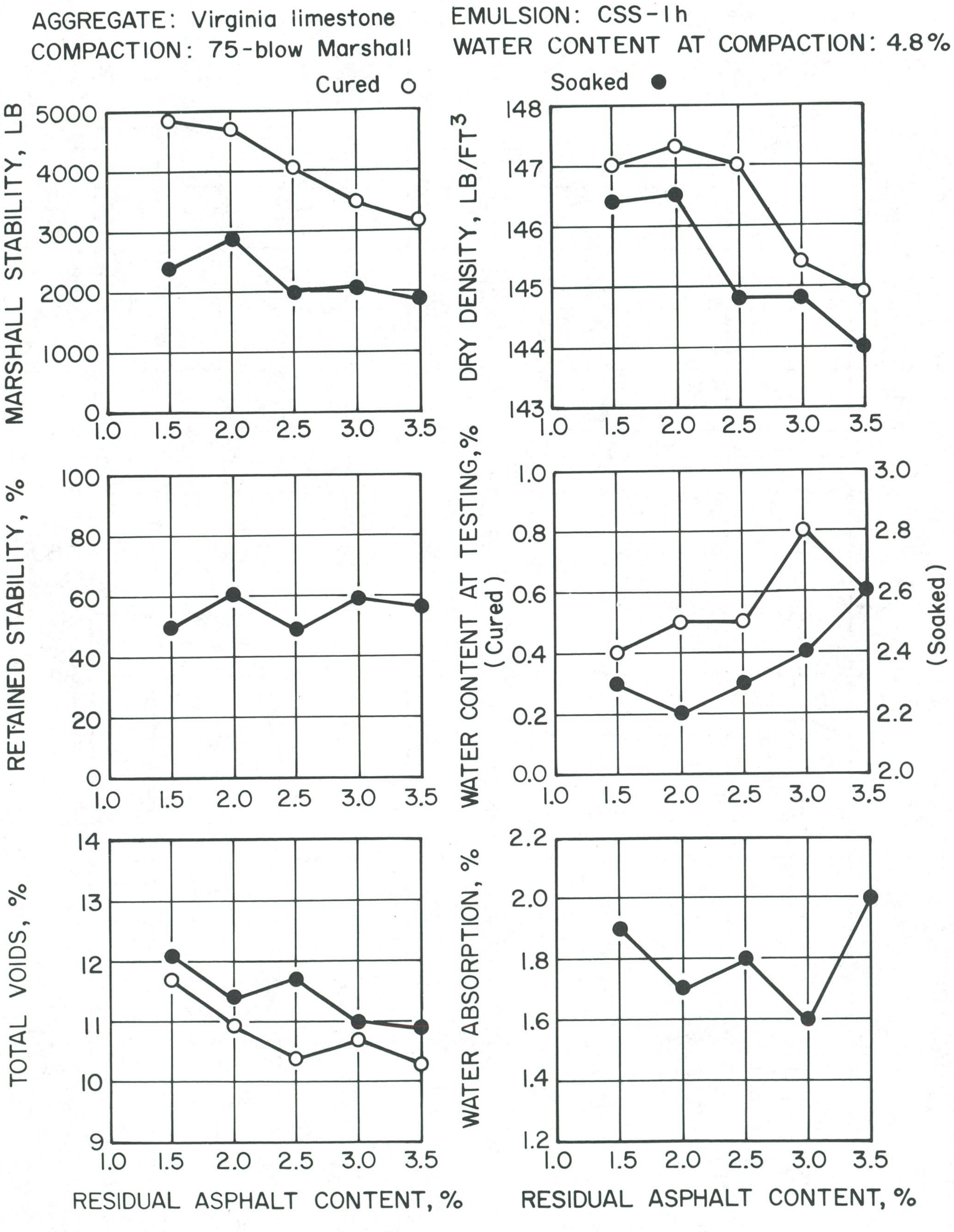

*Figure 2. Design of emulsion paving mixtures by University of Illinois method.*

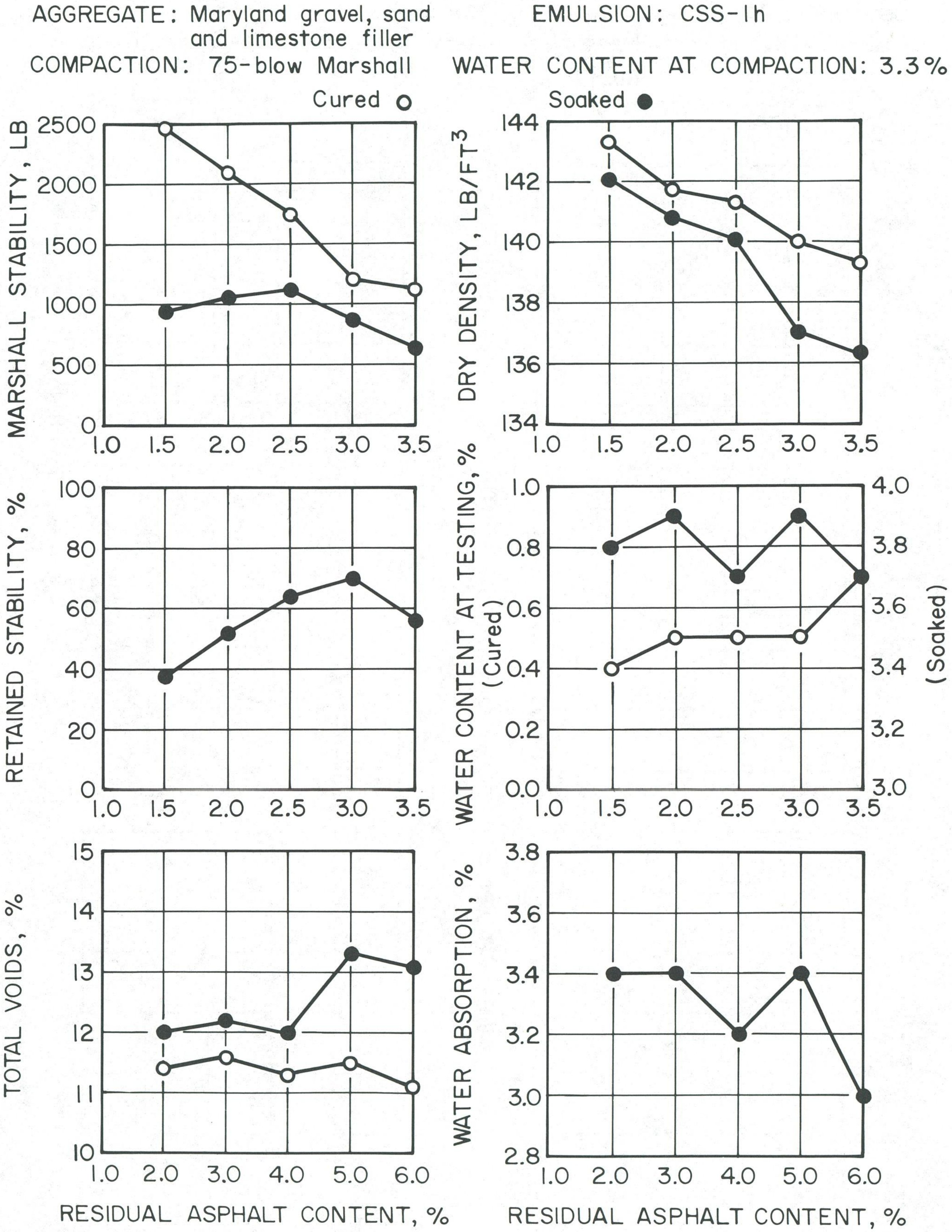

*Figure 3. Design of emulsion paving mixtures by University of Illinois method.*

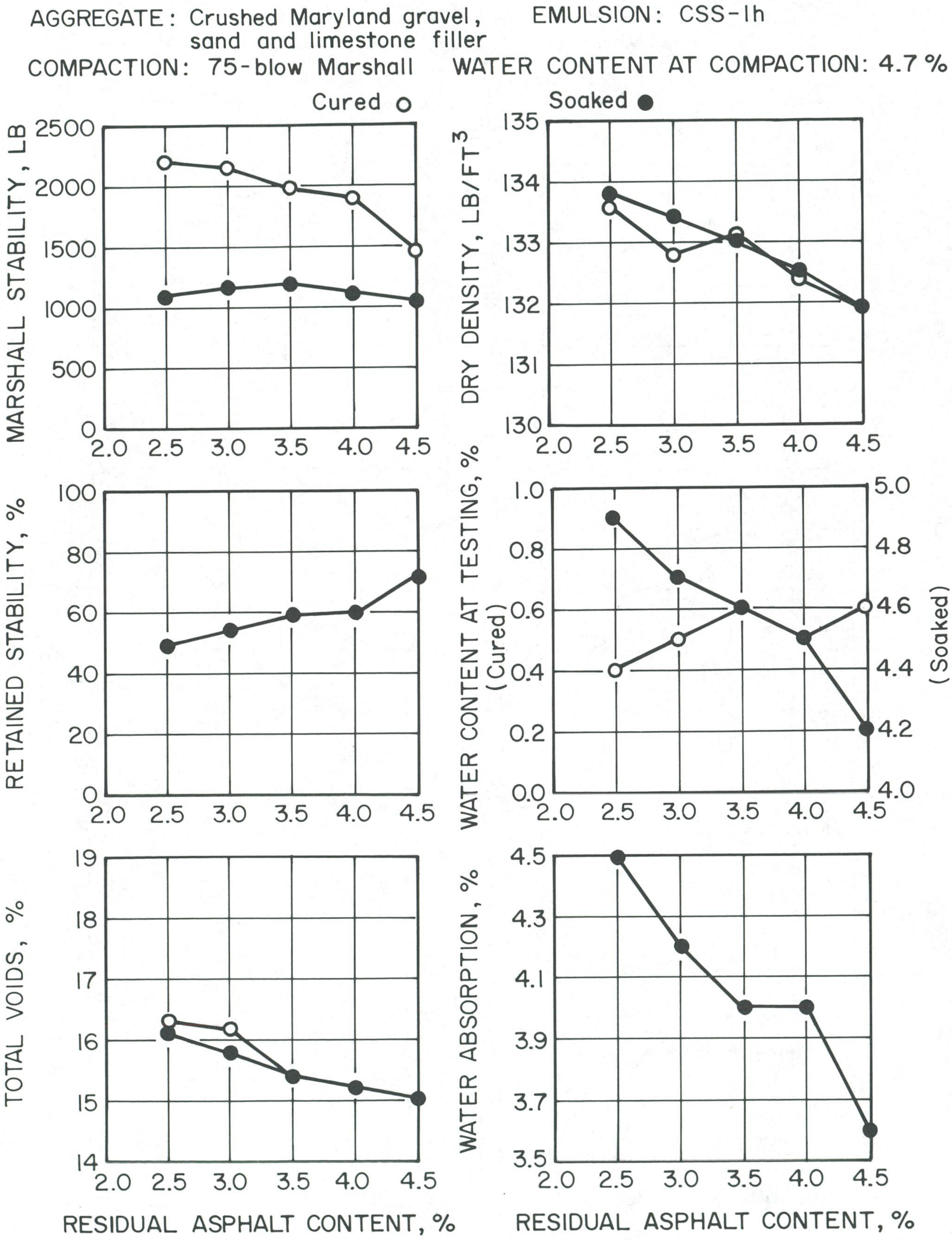

*Figure 4. Design of emulsion paving mixtures by University of Illinois method.*

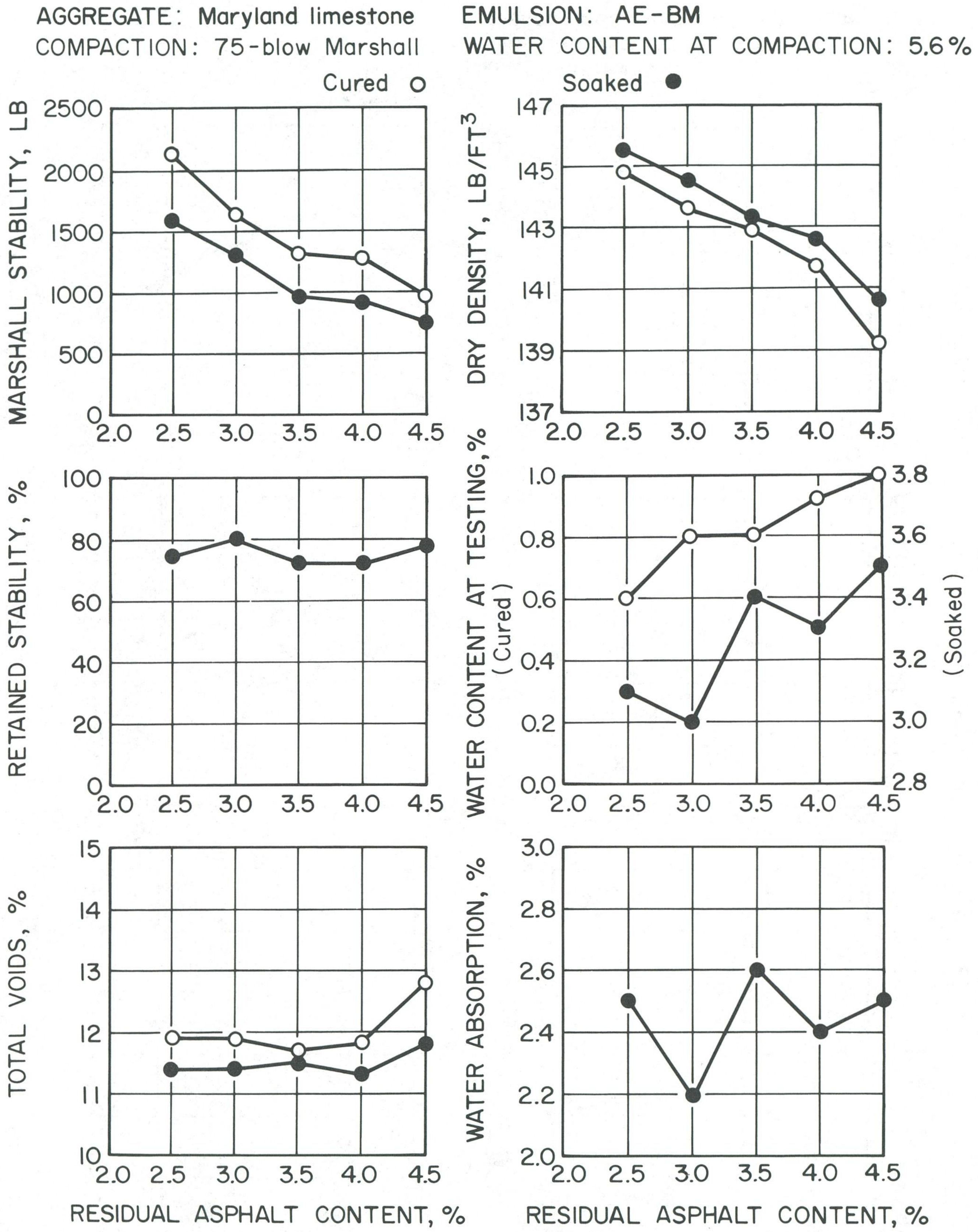

*Figure 5. Design of emulsion paving mixtures by University of Illinois method.*

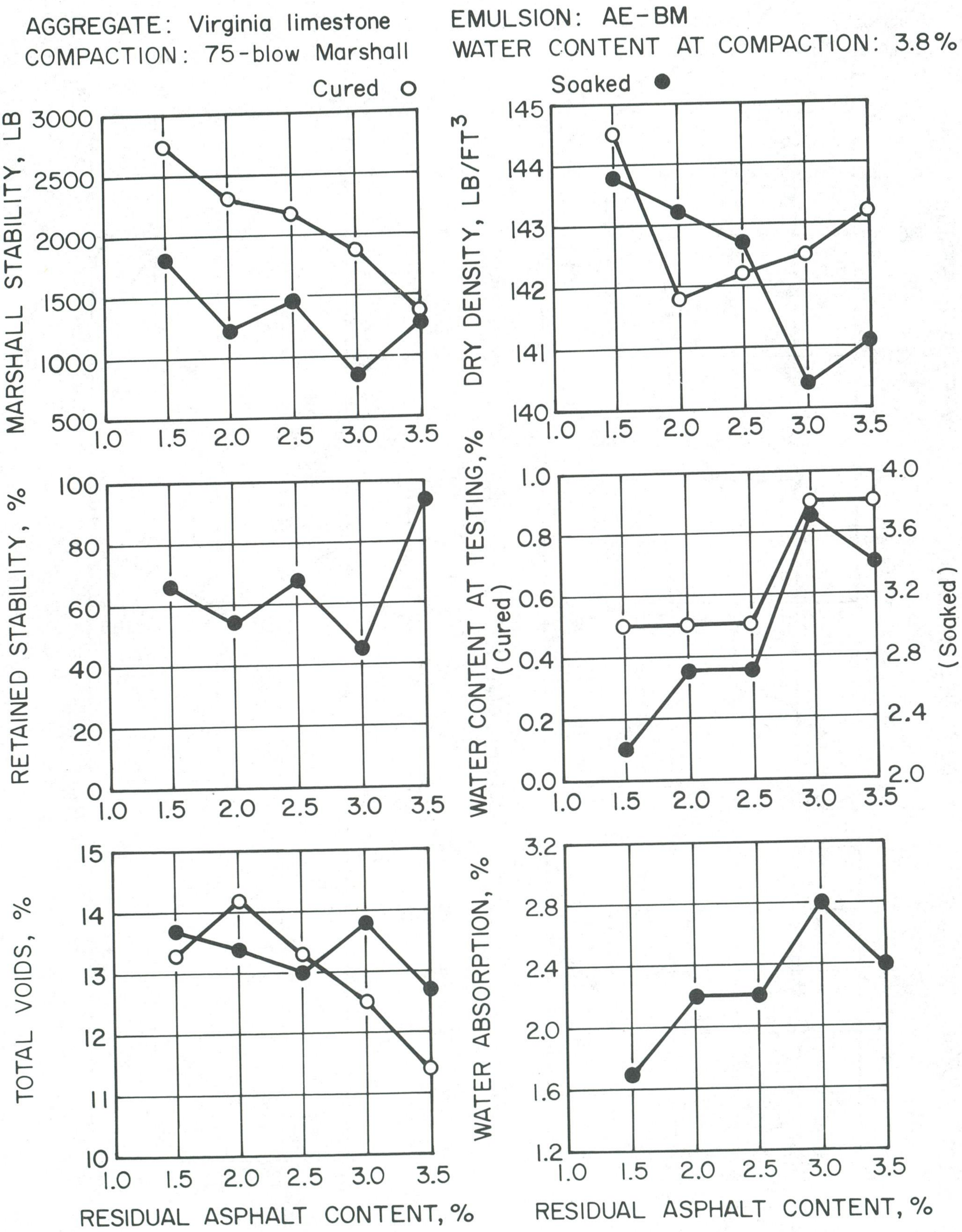

*Figure 6. Design of emulsion paving mixtures by University of Illinois method.*

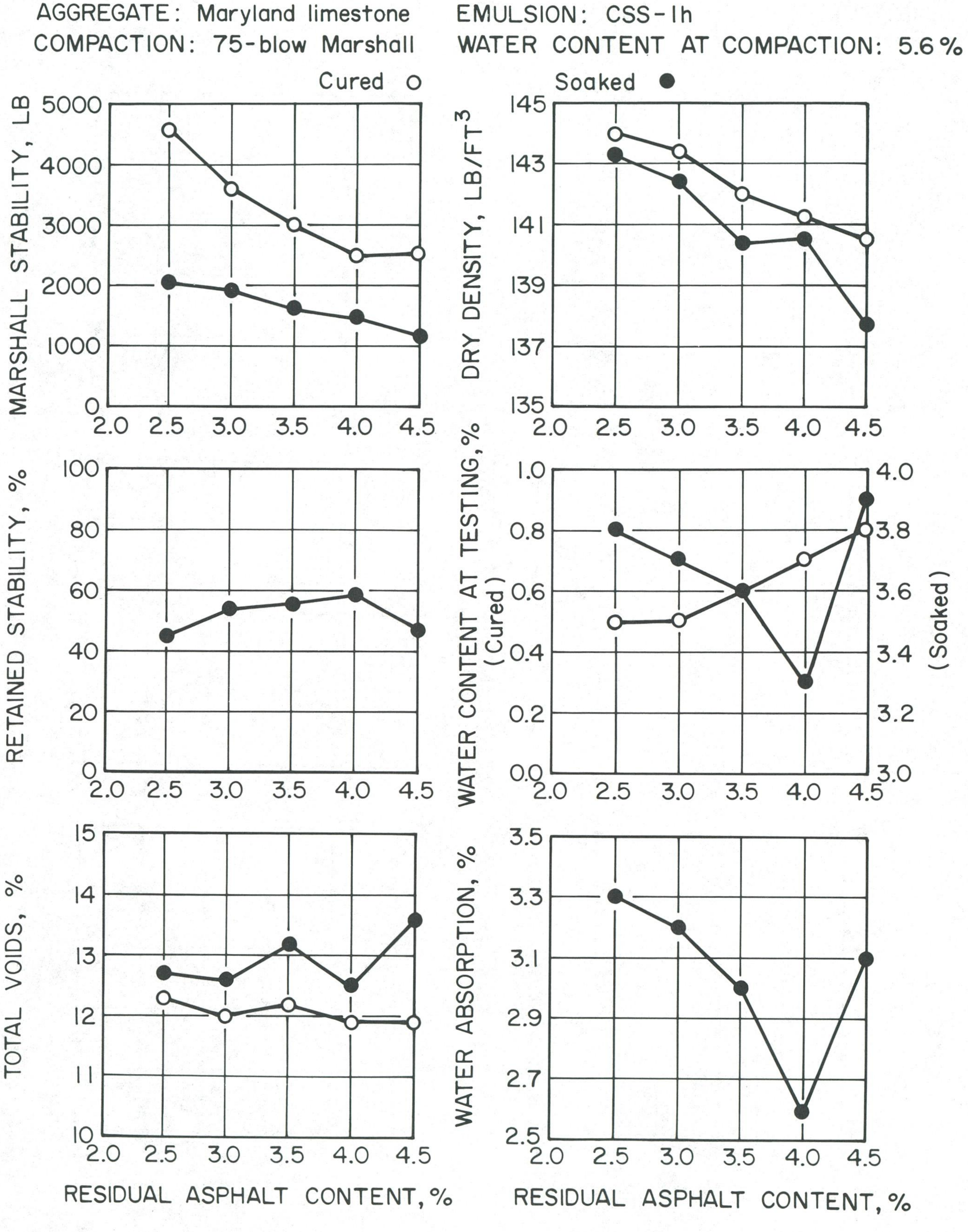

*Figure 7. Design of emulsion paving mixtures by University of Illinois method.*

Table 4. Design of emulsion paving mixtures by the Asphalt Institute method.

|  | MIXTURE COMPOSITION |  |  |  | PROPERTIES OF EARLY CURE SPECIMENS |  |  |  |  |  |  | PROPERTIES OF VACUUM SATURATED SPECIMENS |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGGREGATE/EMULSION | EMUL. CONT. % | RESID. ASPH. % | FLUID CONT. % | WATER CONT. % | DRY DENSITY lb/ft$^3$ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | $R_t$ VALUE | C VALUE | DRY DENSITY lb/ft$^3$ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | $R_t$ VALUE | C VALUE | WATER ABSORPT. % |
| VIRGINIA LIMESTONE<br>(Coarse Gradation)<br>EMULSION: CSS-1h | 3.0 | 2.0 | 5.3 | 3.3 | 147.1 | 15.5 | 11.0 | 8.9 | 0.9 | 94.8 | 137 | 148.2 | 14.9 | 10.4 | 1.2 | 4.0 | 101.8 | 236 | 3.7 |
|  | 3.8 | 2.5 | 5.3 | 2.8 | 147.5 | 15.7 | 10.1 | 8.7 | 0.6 | 96.8 | 164 | 148.9 | 14.9 | 9.2 | 0.9 | 3.6 | 103.5 | 267 | 3.3 |
|  | 4.6 | 3.1 | 5.3 | 2.3 | 147.8 | 16.0 | 9.1 | 7.6 | 0.7 | 99.6 | 248 | 147.9 | 16.0 | 9.1 | 1.5 | 3.3 | 99.4 | 246 | 2.8 |
| MARYLAND GRAVEL, SAND<br>AND LIMESTONE FILLER<br>(Middle Gradation)<br>EMULSION:CSS-1h | 4.3 | 2.9 | 5.6 | 2.7 | 142.5 | 16.2 | 9.9 | 8.6 | 0.6 | 81.7 | 76 | 142.6 | 16.2 | 9.9 | 1.9 | 3.6 | 88.8 | 159 | 3.4 |
|  | 5.5 | 3.7 | 5.6 | 1.9 | 143.4 | 16.4 | 8.4 | 7.1 | 0.6 | 86.2 | 141 | 141.5 | 17.5 | 9.6 | 2.7 | 3.2 | 84.5 | 183 | 3.0 |
|  | 6.7 | 4.5 | 5.6 | 1.1 | 143.3 | 17.1 | 7.4 | 6.8 | 0.3 | 83.1 | 164 | 142.3 | 17.6 | 8.1 | 2.5 | 2.5 | 86.1 | 227 | 2.2 |
| CRUSHED MARYLAND GRAVEL,<br>SAND AND LIMESTONE FILLER<br>(Fine Gradation)<br>EMULSION: CSS-1h | 5.4 | 3.6 | 6.9 | 3.3 | 137.8 | 19.8 | 12.2 | 10.4 | 0.9 | 92.7 | 188 | 138.1 | 19.6 | 12.0 | 1.3 | 5.0 | 92.8 | 225 | 4.9 |
|  | 6.9 | 4.6 | 6.9 | 2.3 | 139.2 | 19.7 | 10.1 | 8.6 | 0.7 | 94.5 | 208 | 137.8 | 20.5 | 11.0 | 1.4 | 4.5 | 95.4 | 216 | 4.4 |
|  | 8.4 | 5.6 | 6.9 | 1.3 | 139.2 | 20.5 | 8.9 | 7.5 | 0.7 | 94.0 | 204 | 136.2 | 22.2 | 10.9 | 1.8 | 4.4 | 78.1 | 229 | 4.2 |
| MARYLAND LIMESTONE<br>(Middle Gradation)<br>EMULSION: AE-BM | 5.5 | 3.4 | 5.9 | 2.5 | 151.5 | 14.2 | 6.6 | 5.0 | 0.7 | 109.5 | 397 | 152.9 | 13.4 | 5.7 | 0.6 | 2.1 | 109.7 | 413 | 1.8 |
|  | 6.8 | 4.2 | 5.9 | 1.7 | 151.6 | 14.9 | 5.4 | 3.9 | 0.6 | 99.8 | 282 | 151.8 | 14.8 | 5.3 | 0.7 | 1.9 | 102.4 | 281 | 1.6 |
|  | 8.4 | 5.2 | 5.9 | 0.7 | 150.8 | 16.1 | 4.5 | 3.4 | 0.5 | 98.4 | 237 | 149.2 | 17.0 | 5.5 | 1.5 | 1.8 | 85.6 | 189 | 1.4 |
| VIRGINIA LIMESTONE<br>(Coarse Gradation)<br>EMULSION: AE-BM | 3.0 | 1.8 | 5.3 | 3.5 | 147.3 | 15.3 | 11.2 | 9.0 | 1.0 | 92.5 | 116 | 148.5 | 14.6 | 10.5 | 1.2 | 4.0 | 97.2 | 152 | 3.6 |
|  | 3.8 | 2.3 | 5.3 | 3.0 | 147.8 | 15.4 | 10.2 | 8.1 | 0.9 | 94.2 | 154 | 149.0 | 14.7 | 9.4 | 1.0 | 3.6 | 99.8 | 223 | 3.3 |
|  | 4.6 | 2.8 | 5.3 | 2.5 | 148.6 | 15.3 | 9.0 | 6.7 | 1.0 | 100.6 | 243 | 149.1 | 15.1 | 8.7 | 1.0 | 3.3 | 99.7 | 229 | 2.8 |
| MARYLAND LIMESTONE<br>(Middle Gradation)<br>EMULSION: CSS-1h | 5.5 | 3.7 | 5.9 | 2.2 | 150.9 | 14.8 | 6.4 | 5.1 | 0.6 | 108.0 | 352 | 149.8 | 15.4 | 7.1 | 1.3 | 2.5 | 93.9 | 222 | 2.3 |
|  | 6.8 | 4.6 | 5.9 | 1.3 | 150.1 | 16.0 | 5.7 | 4.3 | 0.6 | 93.6 | 179 | 148.9 | 16.6 | 6.5 | 1.4 | 2.2 | 91.6 | 171 | 1.8 |
|  | 8.4 | 5.7 | 5.9 | 0.2 | 148.6 | 17.7 | 5.2 | 4.8 | 0.2 | 97.5 | 238 | 141.6 | 21.5 | 9.7 | 4.3 | 2.5 | 70.0 | 93 | 2.1 |

gates as shown in Table 2. Differences in dry densities of specimens compacted by the two methods appear to increase with the higher abrasion losses for a given aggregate. This, in turn, suggests a considerable, as well as differential, crushing of softer aggregates during the highly variable compaction processes employed by the two design methods.

Differences in specimen densities lead to differences in other related properties that are listed in Tables 3 and 4. As expected, lower densities lead to higher voids contents regardless of whether such voids are expressed as VMA, total voids, or air voids. Thus, AI method specimens contain considerably less voids than comparable UI method specimens. It is also interesting to note that at comparable residual asphalt contents, regardless of the lower voids for the AI method specimens, the water absorption values for these specimens are roughly the same or even higher than for higher void UI method specimens. This behavior is difficult to explain. However, again, the differences may be caused by excessive cracking of aggregate particles during the AI double-plunger compaction process. Such cracking and subsequent stratification of particles provide permeable pathways for water to migrate into the interior of the specimen. Additionally, this water intrusion process may be facilitated by the application of vacuum during immersion of the AI method specimens. Vacuum tends to separate fractured aggregate faces that provide the pathways for capillary water migration. In the case of the UI specimens, it was evident that separate soaking of each specimen end introduced variable water content gradients within the compacted specimens which undoubtedly contributed to the differences in water absorption.

A comparison of Figures 2 through 7 with Figures 8 through 13 indicates considerable scatter in the test data points for both methods. It also appears that such scatter is more pronounced for mixtures containing larger maximum particle size aggregates. The figures indicate that peak or optimum values are either nonexistent or difficult to establish on the basis of the tests of either of the two methods. Scatter in data points and a lack of peak values contribute to this difficulty in establishing the recommended asphalt content to be used with a given mixture by either method. Unfortunately, review of studies dealing with both methods does not provide sufficient information on actual data points for the individual specimens or experiments. Thus, it is difficult to judge whether the scatter and inaccuracies in the test results generally are applicable to these two design methods or only reflect specifically on the lack of precision for the tests in this study.

*Effectiveness of Design Criteria.* The data in the summary Tables 3 and 4 show that, in most cases, it is difficult or nearly impossible to establish an optimum emulsion content based on the criteria of the reference methods (see Appendix B). For instance, the primary criterion of the UI method for selecting the optimum emulsion content is maximum soaked stability. The results show that, in many instances, there is no definitive peak in the soaked stability or that the soaked stability increases with decreasing residual asphalt content, which is the usual pattern for stabilities of specimens tested "dry." The UI method also specifies limits on total voids of from 2 to 8 percent when computing voids using bulk specific gravity of the aggregate. However, using the procedure for calculating voids specified in the reference method, the total voids for virtually every mix exceeded the 8 percent limit. An additional problem with using bulk specific gravity in the calculation of voids is that such calculations may lead to negative values for the air voids of soaked specimens. This erroneous calculation is because the UI method equations do not consider the effects of absorption, but do call for the use of aggregate bulk specific gravity (which includes permeable voids) and not apparent specific gravity (which excludes permeable voids). Thus, it is possible for the sum of the individually computed volumes of aggregate, asphalt, and water to be greater than the total specimen volume and this leads to computed air voids with negative values. By using apparent specific gravity, the volume assigned to the aggregate is reduced and computed air voids are all positive values. The voids in Tables 3 and 4 were computed using apparent specific gravities as recommended in the AI method.

With regard to other criteria of the UI method, no problems were encountered in meeting the minimum stability requirement of 500 lb (2224 N) or the minimum aggregate coating of 50 percent. The 4 percent maximum absorption requirement was a problem with only one emulsion-aggregate combination, and the maximum "soaked" stability corresponded with less than 50 percent retained stability (or greater than 50 percent loss in stability) in only one instance. Thus, the usefulness of most of the UI method criteria is questionable.

With the AI method, virtually every specimen tested met the criteria for a dense-graded base course or temporary wearing surface; namely, a minimum $R_t$-value of 70 and a minimum cohesiometer C-value of 50 for "early cure" specimens, and an R-value of 78 and a C-value of 100 for vacuum-saturated specimens (see Appendix B). Based on these laboratory results, the lowest trial emulsion content would be selected as the design value in almost every case. There is a definite need to consider other properties besides strength characteristics if the AI method is to be effective. For example, in many instances the emulsion content giving the maximum $R_t$-value does not result in maximum density. This is also true with the UI method, i.e., the maximum soaked stability often does not match up with other optimum specimen properties. In summary, the criteria of the reference methods are either overly restrictive (UI method) or insufficiently selective (AI method), and in some cases there is no definitive optimum when considering all specimen properties. This points to the need for considering other properties besides strength when selecting an "optimum" mix.

*Summary.* This investigation of the two reference mix-design methods led to two major conclusions: (1) that neither method is satisfactory for establishing optimum emulsion and water contents for dense-graded emulsion mixes; and (2) that there are considerable differences between the methods that can result in dissimilar designs for the same emulsion-aggregate combination. Because of these problems, the decision was made in the early stages of the project to thoroughly evaluate modifications to the reference methods and then apply the results of that evaluation to mixes from actual field projects.

## EVALUATION OF THE ASPHALT INSTITUTE DESIGN METHOD FOR OPEN-GRADED MIXES

Open-graded emulsified asphalt mixes (EAMs) are mixtures of open-graded aggregates and medium-setting emulsions that are characterized by a high (20 to 30 percent) void content and less than 10 percent of the aggregate passing the No. 10 sieve. Generally, high consistency cationic emulsions, namely CMS-2 or CMS-2h, are preferred in order to minimize runoff and washoff, especially in cooler weather and to provide greater film

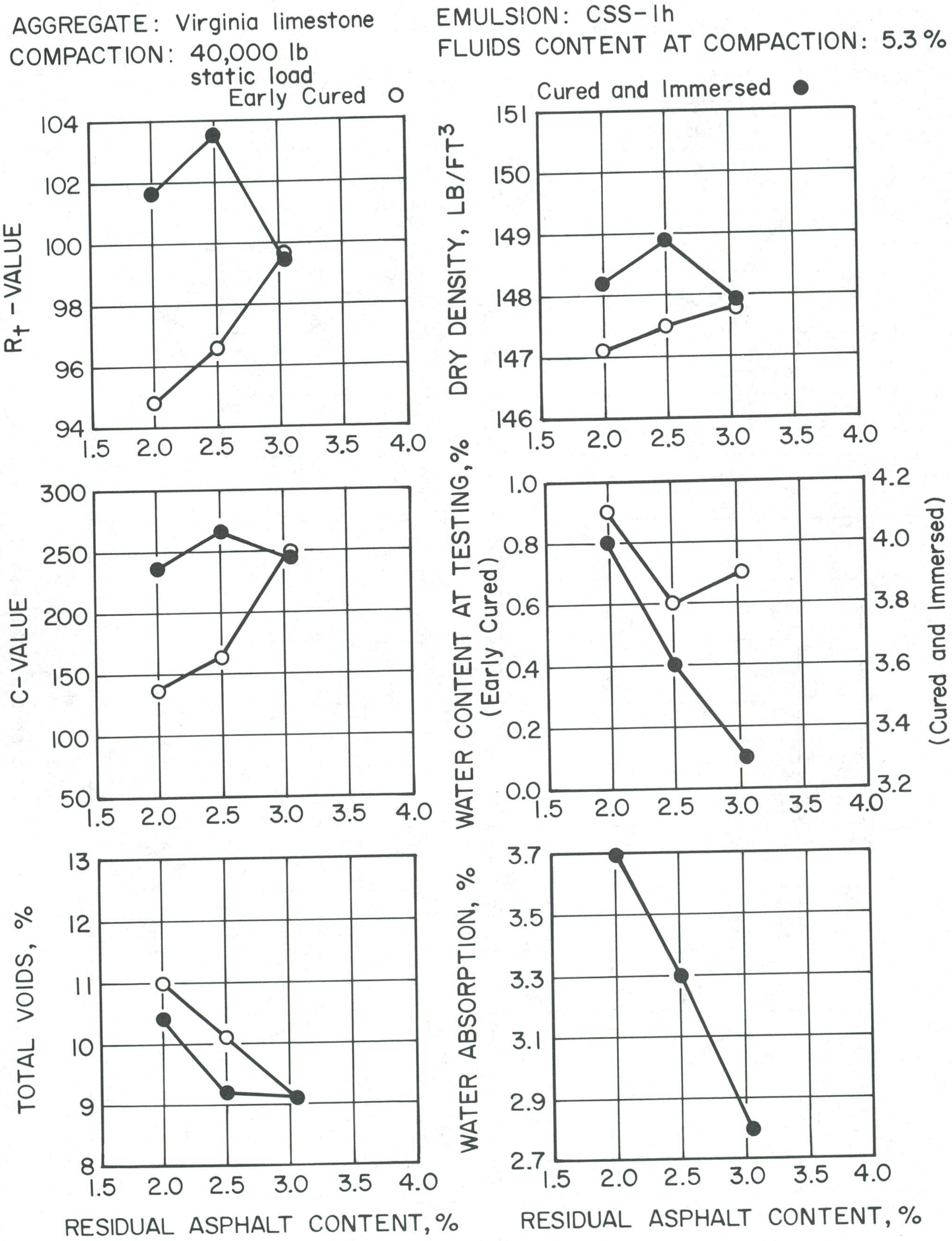

*Figure 8. Design of emulsion paving mixtures by the Asphalt Institute method.*

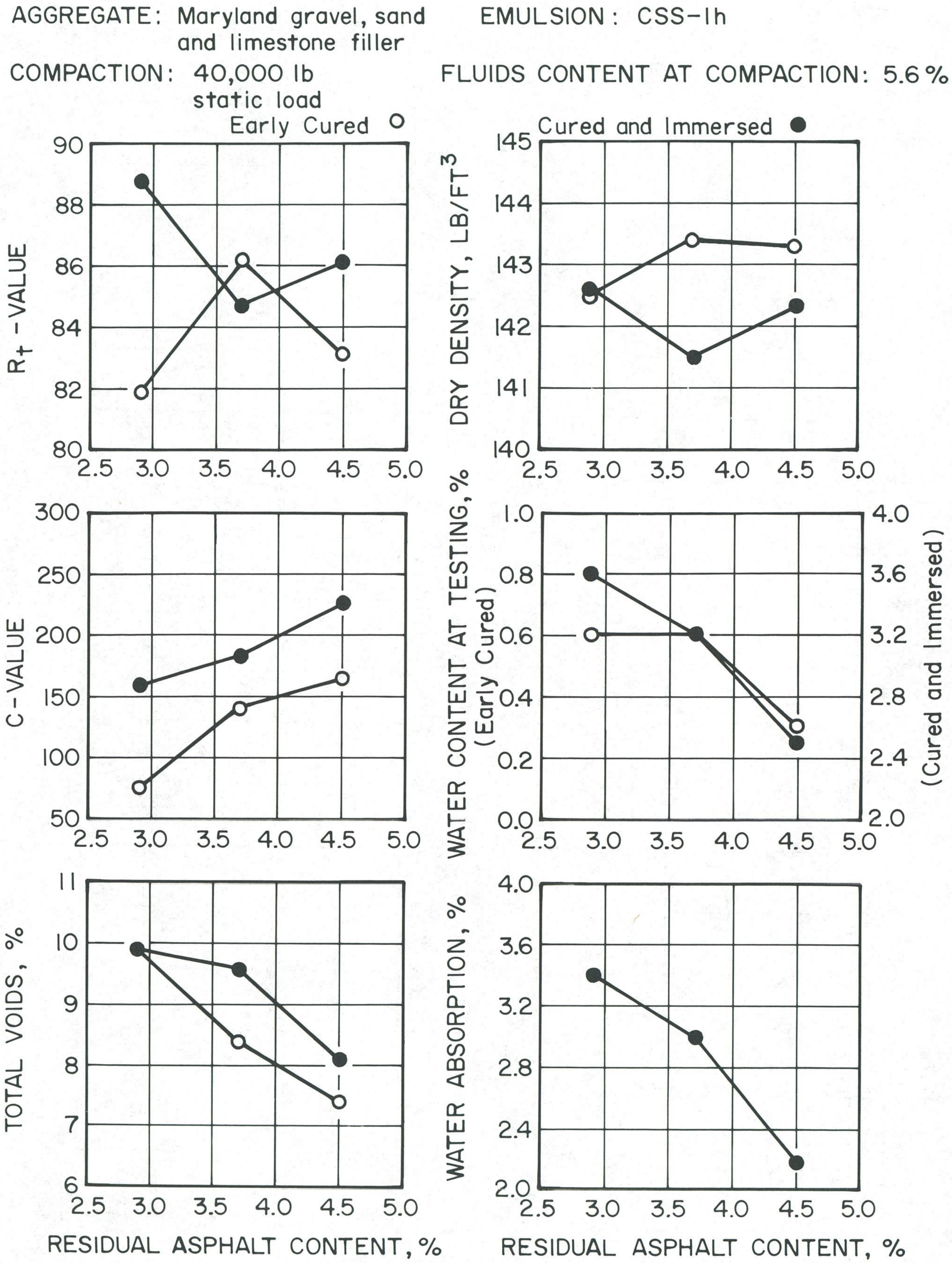

*Figure 9. Design of emulsion paving mixtures by the Asphalt Institute method.*

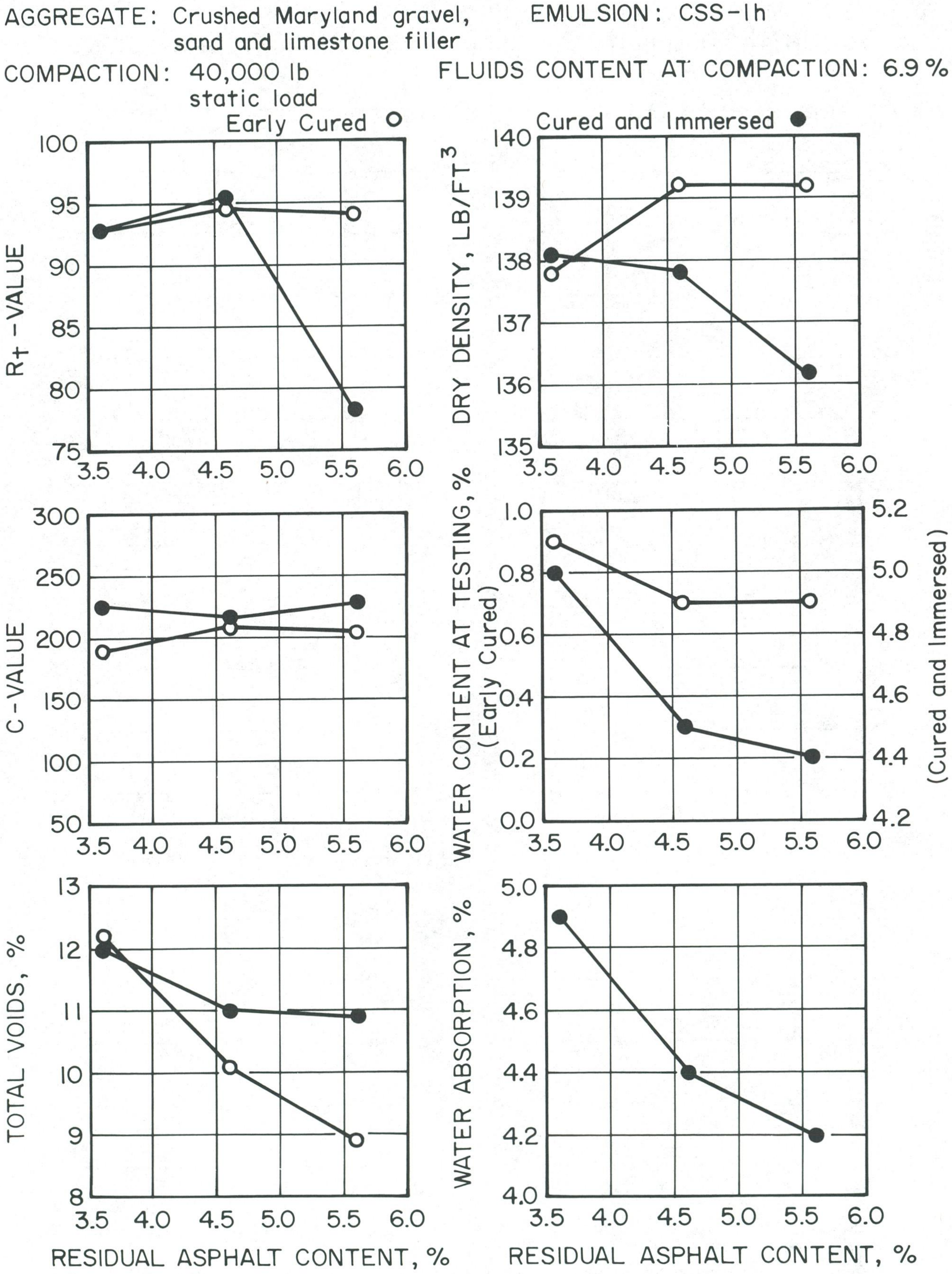

*Figure 10. Design of emulsion paving mixtures by the Asphalt Institute method.*

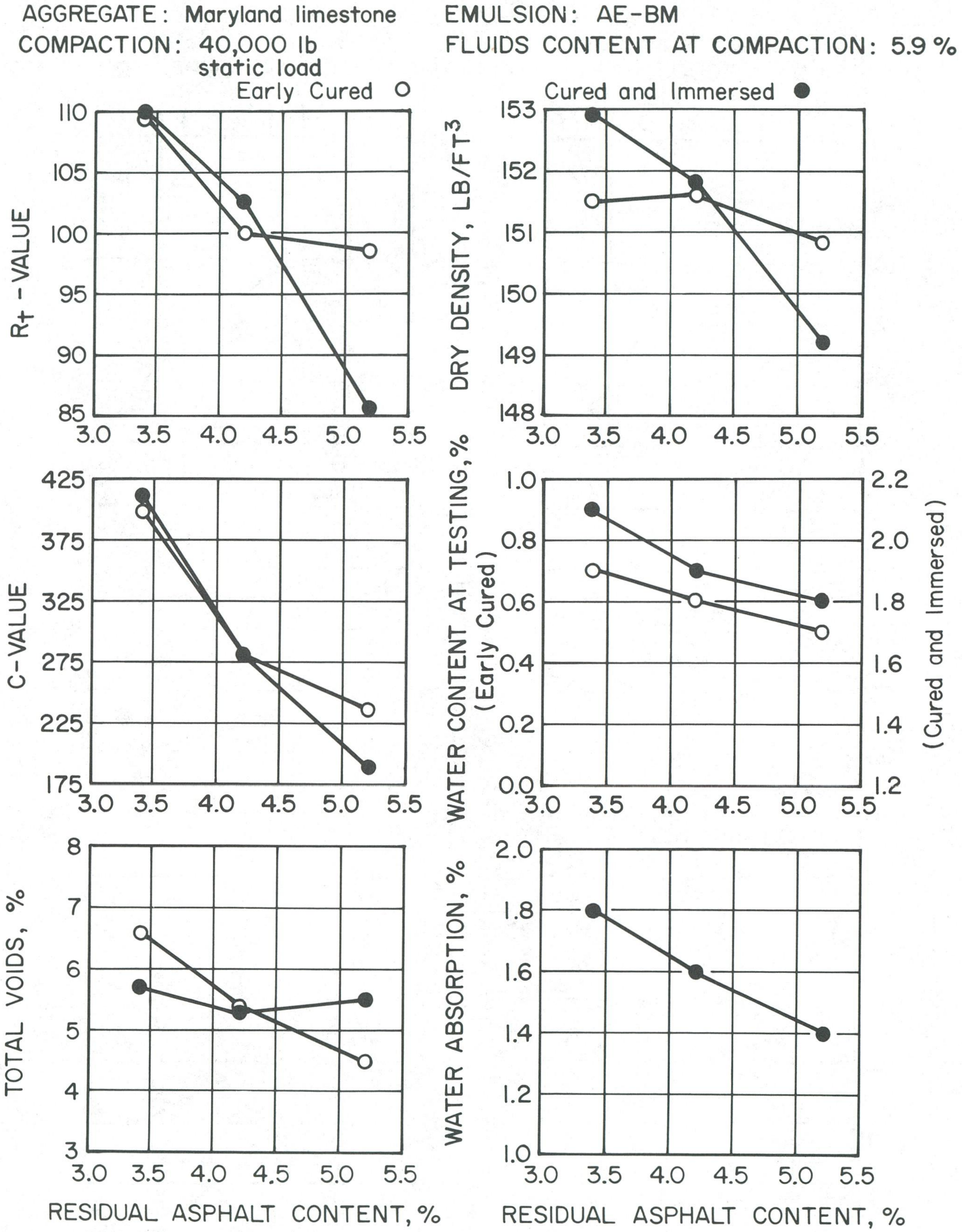

*Figure 11. Design of emulsion paving mixtures by the Asphalt Institute method.*

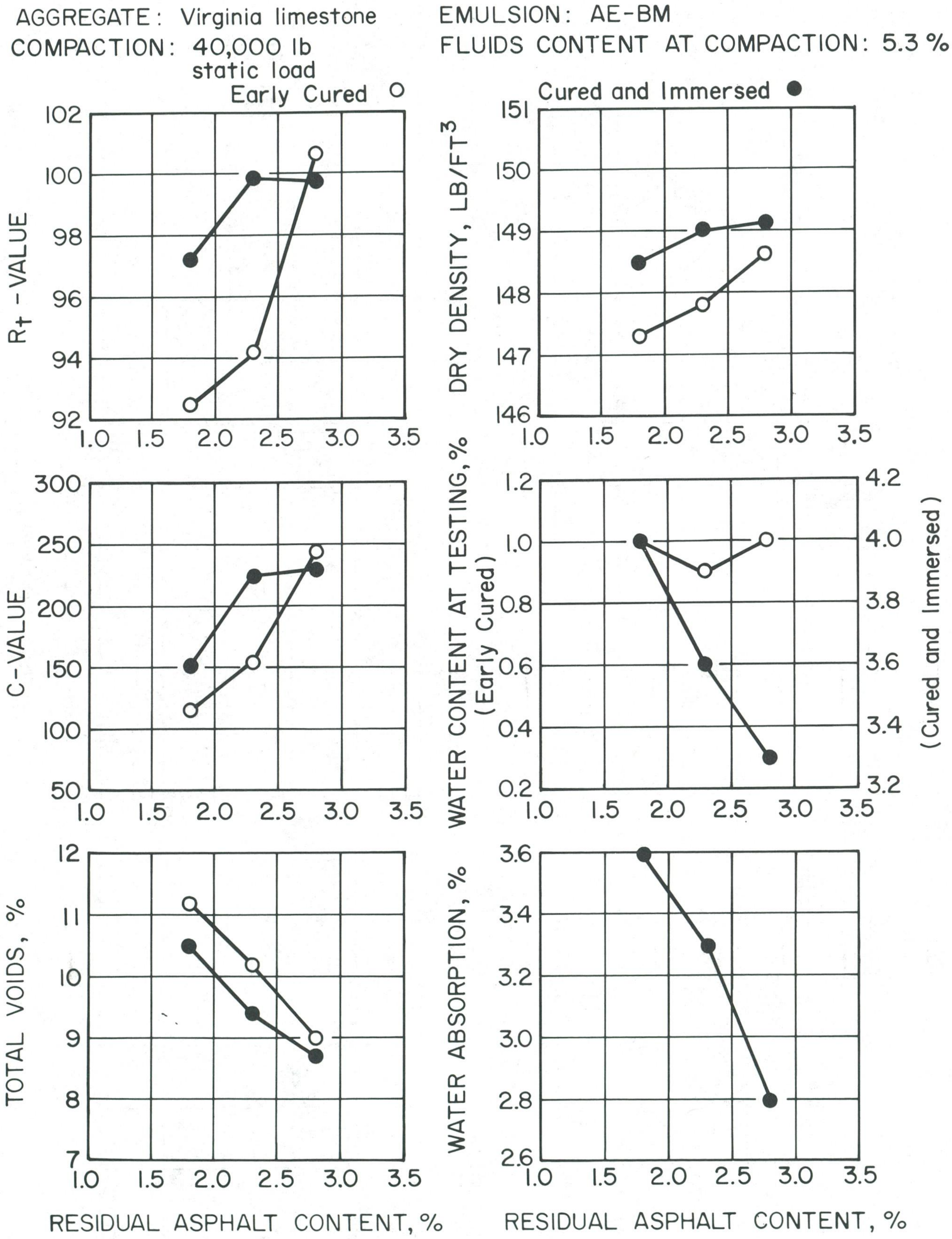

*Figure 12. Design of emulsion paving mixtures by the Asphalt Institute method.*

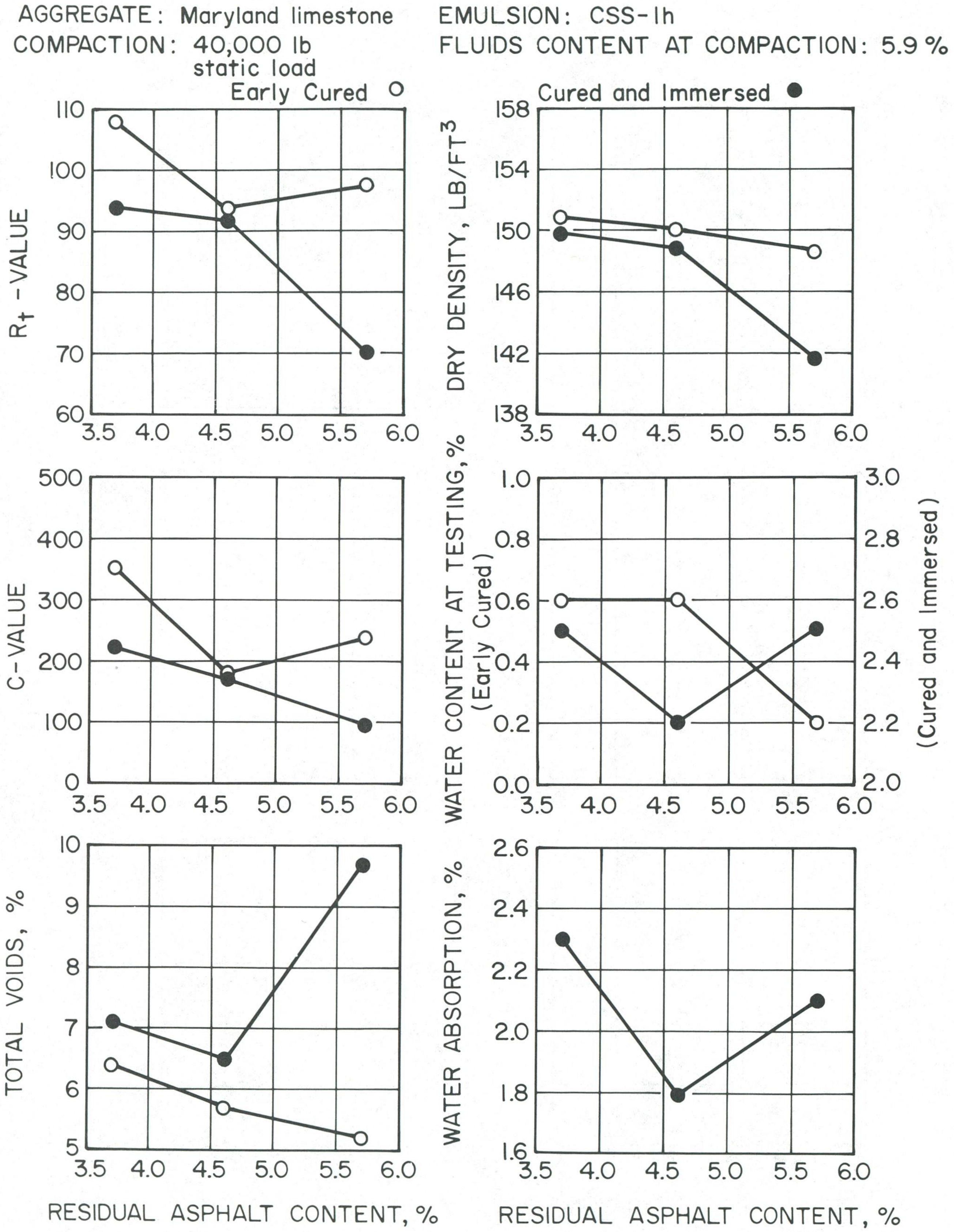

*Figure 13. Design of emulsion paving mixtures by the Asphalt Institute method.*

thickness and durability (*16*). It should be noted, however, that MS-2 and MS-2h emulsions may work better than cationics with some aggregates (*24*).

In comparison with the dense-graded mixes, curing of open-graded EAMs is much faster and more complete due to the high porosity or high voids content. Because of this, such mixtures develop early field stability, resist rutting and are suitable for carrying heavy truck traffic due to their high flexibility resulting in resistance to fatigue and reflection-type cracking. The high void content also allows for rapid draining of surface runoff which minimizes hydroplaning, reduces stripping problems, eliminates road spray, and provides good frictional properties. Furthermore, the thick asphalt film tends to maintain workability of the mix, which is advantageous when hauling the mix to paving sites in remote areas such as forest roads (*17*). It is also suggested that this type of mix may be more economical than a dense-graded mix because the cost per ton (with its relatively low emulsion content) is less and the volume per ton is greater due to the high void content in the finished pavement (*24*).

There are, however, problems associated with using open-grade emulsion mixes. The low stiffness and tensile strength mean that higher stresses are transmitted to the underlying layers that must therefore be of greater structural thickness than that for dense-graded pavements (*15*). The free-draining nature of open-graded EAMs can result in a weakened subgrade if no impermeable dense-graded layer is placed below the open-graded surface course. The high friction quality can also cause excessive tire wear (*17*). If excess fines are accidentally introduced into the mix, the emulsion will tend to break faster than expected, which can cause problems with mixing, laydown, and compaction. Also, excessive fines will reduce the void content and slow the curing of the lower portions of the lift (*24*).

Open-graded mixes can be used for a variety of pavements ranging from single lane roads with low traffic volumes to multiple lane roads carrying large volumes of heavy traffic. Success has been achieved with average daily traffic volumes of 500, with 25 to 30 percent logging trucks averaging 100,000 lb with a maximum of 200,000 lb. Open-graded mixes can be cold-mixed, placed and compacted using conventional equipment and construction procedures (*24*). As with dense-graded mixes, 2-in. lifts are recommended. During the normal summer paving season, open-graded mixes will break very quickly, and damage from rainfall is unlikely after only 2 or 3 hours depending on temperature and drying conditions (*28*). When curing conditions are favorable, the compacted mix can be opened to heavy truck traffic within 45 min to 1 hour or to "controlled" traffic immediately (*16*). Pavement performance will generally depend on curing conditions, quality and gradation of aggregate, grade of emulsion, quality control of construction, and amount of traffic. There have been failures on some of the pavements in Region 6 of the U.S. Forest Service, but the causes of these failures have not always been precisely determined even though the emulsion mix is often blamed (*15*). Factors that have contributed to reported failures include: (1) poor (or no) mix design; (2) poor construction practices and quality control; and (3) inadequate structural design (*16*).

There is no standard mix design procedure for open-graded emulsion mixes, and no strength criteria are specified because of the insufficient tensile strength of the specimens for routine Marshall stability or split-tension testing. Acceptability of the mix is usually based on coating, runoff, washoff, workability, and film thickness (*12*).

There has been little research on open-graded emulsion mixes, and development of standard laboratory curing procedures has been lacking (*28*). Design methods have been developed by Chevron, Region 6 of the U.S. Forest Service, Region 10 of FHWA, and The Asphalt Institute, but none contain strength criteria (*16*). A typical "optimum" emulsion content is simply "all the emulsion that the aggregate will hold," i.e., that content where any additional emulsion drains from the mix (so-called runoff test) (*24*). Susceptibility to damage by rainfall can be measured by a "washoff" test on compacted specimens, but the primary criteria for selecting emulsion and water contents, as previously mentioned, are usually workability, coating percentage, and film thicknesses (*16*), which obviously involve considerable engineering judgment.

### Review and Laboratory Evaluation of The Asphalt Institute Method for Open-Graded Mixes

An outline of The Asphalt Institute method is included in Appendix C. The method basically involves selecting trial emulsion contents based on the gradation of the aggregate, preparing trial batches with varying emulsion and water contents, judging the mixes for coating and workability, and conducting the runoff and washoff tests on loose and compacted mixes, respectively. The objective of the mix design is to determine the maximum emulsified asphalt content that can be used within the range of emulsion contents recommended for a given aggregate gradation that meets the design requirements.

A review of the reference method indicated certain important limitations of the design procedure. The use of the 40,000-lb double-plunger static load for compaction leads to excessive aggregate degradation. The use of subjective criteria, such as coating and workability, provides only limited information for determining optimum emulsion and water contents. The only tests covered by the actual design criteria are the runoff test, which is performed on loose mixes immediately after mixing, and the washoff test, which is performed on compacted specimens while still in the mold after a 24-hour cure at room temperature. (Both runoff and washoff are determined on the basis of the mass of oven-dried residue expressed as percent of aggregate mass in the specimen.)

Table 5 shows recommended aggregate properties and emulsion grades and contents for open-graded emulsion mixes (*2*). Five combinations of aggregate and emulsion were tested using four different medium-setting emulsions and three different aggregates. Four of the combinations involved aggregate having gradations meeting the recommendation for a "medium" open-graded base course, and the fifth involved aggregate with a gradation for a "fine" open-graded surface course. Table 6 gives the gradations and specific gravities for the three aggregate types and four gradations used in this task. The emulsions combined with these aggregates were CMS-2 from the Chesapeake, Virginia, field project; MS-2M from the Arkansas field project; CMS-1 supplied by Hy-Way Asphalt, Inc., of Salina, Kansas; and MS-2Gh supplied by Cortland Asphalt Products Corporation of New York. Properties of these emulsions are summarized in Table 7.

The results of the testing for this task of the project are given in Table 8. The first series of specimens tested in the laboratory

Table 5. Aggregates for open-graded emulsion mixes.

| Sieve Size | Base | | Surface |
|---|---|---|---|
| | Coarse | Medium | Fine |
| 1-1/2 in. (38.1mm) | 100 | | |
| 1 in. (25.0mm) | 95-100 | 100 | |
| 3/4 in. (19.0mm) | | 90-100 | |
| 1/2 in. (12.5mm) | 25-60 | | 100 |
| 3/8 in. ( 9.5mm) | | 20-55 | 85-100 |
| No. 4 (4.75mm) | 0-10 | 0-10 | |
| No. 8 (2.36mm) | 0-5 | 0-5 | 0-10 |
| No. 16 (1.18mm) | | | 0-5 |
| No. 200 (75μm) | 0-2 | 0-2 | 0-2 |
| Los Angeles Abrasion loss @ 500 Rev. (ASTM C 131) | 40 max | 40 max | 40 max |
| Percent Crushed Faces | 65 min | 65 min | 65 min |
| Emulsified Asphalt Grades | MS-2, MS-2h, HFMS-2, HFMS-2h, CMS-2 or CMS-2h | | |

| Aggregate Gradation | Emulsion Content Range (%) |
|---|---|
| Coarse | 4.5 - 6.5 |
| Medium | 5.0 - 7.0 |
| Fine | 6.0 - 8.0 |

involved the use of MS-2Gh with crushed Maryland gravel and sand. Water (if any) was added to the aggregate and this was followed by 30 sec of mixing using a mechanical mixer. The required amount of emulsion was added which was then followed by an additional 30 sec of mixing. Specimens for the washoff test were compacted as specified in the reference method—approximately 20 tamps at 250 psi of the Triaxial Institute kneading compactor followed by a 40,000-lb double-plunger static load. Two emulsion contents, 5.0 and 6.0 percent, were investigated with added mixing water contents ranging from 0 to 3 percent in increments of 1 percent. For both emulsion contents, there was an abrupt change in the amount of runoff when comparing mixes with 1 and 2 percent added mixing water. The runoff values for 5 percent emulsion content were 0.08 percent with 1 percent water and 0.70 percent with 2 percent water, while for 6 percent emulsion content the values were 0.02 and 0.97 percent. The criterion of 0.5 percent maximum was exceeded in both cases with the addition of 2 percent water. However, for compacted specimens there was virtually no washoff regardless of mixing water content. All specimens easily met the limiting criterion of 0.5 percent. As expected, there was considerable aggregate degradation resulting from the 40,000-lb double-plunger static load, and voids and densities were comparable to those of dense-graded mixes. Because of the absence of noticeable washoff and the excessive crushing of the aggregate during compaction, the decision was made to reduce the level of compactive effort in an attempt to obtain more definitive test results and to reduce the amount of aggregate degradation.

For the next two series of specimens using CMS-2 with Virginia granite and MS-2M with Maryland limestone (both aggregates having a gradation for a "medium" base course), all mixes were subjected to the same runoff test, but the level of compactive effort for washoff test specimens was reduced from the normal 40,000-lb double-plunger static load (following 20 tamps at 250 psi of the kneading compactor) to 10,000, 5,000, and 2,500 lb. Again, two emulsion contents, 5.0 and 6.0 percent, were investigated with increasing added water contents in increments of 1 percent.

As indicated in Table 8, with CMS-2 mixes, there was very little runoff with only slightly higher values with 6 percent emulsion content than with 5 percent. Also, in spite of the reduced compaction loads, there was virtually no washoff in all cases. This was probably the result of two factors: (1) good adhesion of the asphalt to the aggregate, and (2) exudation of fluids during compaction (especially with the kneading compactor), resulting in the loss of potential washoff material.

With MS-2M mixes, there were very definitive results with the runoff test, i.e., an abrupt increase in runoff with the addition of 1 percent more added water. Also, there was a noticeable difference in washoff test results between mixes with 5 percent emulsion content and those with 6 percent, although there were few differences when the water content was varied for a given emulsion content. The reduction in compactive effort from 10,000 to 5,000 lb resulted in considerably higher washoff values with 6 percent emulsion, but a further reduction to 2,500 lb reduced those values considerably indicating that this load was inadequate for proper compaction because of loss of fluids.

The data from the first 3 series of specimens indicated that the results of the washoff test are not a function of the level of compactive effort; instead, they are more a function of the emulsion-aggregate combination being investigated. Based on this judgment, the decision was made to select 10,000 lb as appropriate for compacting open-graded emulsion mixes in the laboratory.

**Table 6. Properties of mineral aggregate used for open-graded mixes.**

| MINERAL AGGREGATE | CRUSHED MD. GRAVEL SAND AND LIMESTONE FILLER | VIRGINIA GRANITE | MARYLAND LIMESTONE | VIRGINIA GRANITE |
|---|---|---|---|---|
| GRADATION OF AGGREGATE | MEDIUM | MEDIUM | MEDIUM | FINE |
| U.S. STANDARD SIEVE | | | | |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 62.0 | 70.0 | 62.0 | 100.0 |
| 3/8 in. | 37.5 | 40.0 | 37.5 | 90.0 |
| No. 4 | 5.0 | 7.0 | 5.0 | 50.0 |
| No. 8 | 2.5 | 4.0 | 2.5 | 6.0 |
| No. 16 | 2.2 | 2.6 | 1.8 | 5.0 |
| No. 30 | 2.0 | 2.1 | 1.3 | 3.1 |
| No. 50 | 1.8 | 1.6 | 0.9 | 1.4 |
| No. 100 | 1.4 | 0.9 | 0.6 | 0.6 |
| No. 200 | 1.2 | 0.5 | 0.4 | 0.3 |
| SPECIFIC GRAVITY | | | | |
| Bulk | 2.591 | 2.646 | 2.704 | 2.654 |
| Bulk (SSD) | 2.610 | 2.675 | 2.716 | 2.713 |
| Apparent | 2.640 | 2.705 | 2.737 | 2.713 |

**Table 7. Properties of asphalt emulsions used for open-graded mixes.**

| EMULSION GRADE | MS-2Gh | CMS-2 | MS-2M | CMS-1 |
|---|---|---|---|---|
| TESTS ON EMULSIONS | | | | |
| Viscosity, Saybolt Furol @ 77°F (25°C), sec | --- | --- | 80.4 | --- |
| Viscosity, Saybolt Furol @ 122°F (50°C), sec | --- | 206.5 | --- | 118.6 |
| Storage Stability Test, 24hr., % | --- | 0.3 | 0.4 | 0.2 |
| Cement Mixing Test, % | --- | --- | --- | --- |
| Particle Charge Test | --- | Positive | --- | Positive |
| Sieve Test, % | --- | 0.03 | 0.02 | 0.01 |
| Distallation: | | | | |
| Residue, % | 68.8 | 65.6 | 66.9 | 67.1 |
| Oil Distillate, % | 8.2 | 5.7 | 2.3 | 3.5 |
| Water, % | 23.0 | 28.7 | 30.8 | 29.4 |
| TESTS ON RESIDUE: | | | | |
| Penetration, 77° (25°C),100g,5 sec | 66 | 155 | 122 | 360+ |
| Ductility, 77°F (25°C),5cm/min, cm | --- | 95.8 | 150+ | --- |
| Specific Gravity | --- | 1.015 | 1.028 | 0.989 |
| Solubility in Trichloroethylene, % | --- | 99.58 | 99.70 | 99.75 |
| Viscosity, 140°F (60°C), poises | --- | 751 | 1016 | --- |
| Viscosity, 275°F (135°C), cSt | --- | 253 | 414 | 57 |
| Ash Content, % | ___ | 0.16 | 0.13 | --- |

This load was used for the final two series of specimens using CMS-1 with Maryland limestone and with Virginia granite. For both combinations, the washoff test results were inconclusive as shown by the low percentages for all emulsion and water contents. With regard to runoff test results, there was a considerable increase in runoff with increasing water contents when using 6 percent emulsion and Virginia granite having a "fine" gradation for a surface course. This was not the case with Maryland limestone ("medium" gradation) as the aggregate. There was virtually no runoff with 6 percent emulsion. This situation, where the only variables were aggregate type and gradation, clearly shows the importance of material characteristics relative to test results for open-graded emulsion mixes.

## MODIFICATIONS TO THE DESIGN METHODS FOR DENSE-GRADED MIXES

As a result of the evaluation of the University of Illinois and The Asphalt Institute mix-design methods, several major conclusions were reached as follows:

1. Both methods require too much time to complete and can present scheduling difficulties in completing different phases of the design tests.
2. Neither method is totally satisfactory for establishing optimum emulsion and water contents.
3. There are considerable differences between the methods,

**Table 8. Open-graded mix designs.**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A. Emulsion: MS2G-H | | | | | | | | |
| Aggregate: Crushed Maryland Gravel, Sand and Limestone Filler | | | | | | | | |
| Gradation: "Medium" Base Course | | | | | | | | |
| Emulsion Content (%) | 5.00 | 5.00 | 5.00 | 5.00 | 6.00 | 6.00 | 6.00 | 6.00 |
| Total Water Content (%) | 1.19 | 2.19 | 3.19 | 4.19 | 1.42 | 2.42 | 3.42 | 4.42 |
| (1) Run-Off (%)<br>(Loose Mix) | 0.00 | 0.02 | 0.97 | 1.21 | 0.00 | 0.08 | 0.70 | 0.89 |
| (2) Wash-Off (%) | | | | | | | | |
| (a) 40,000 lb | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 |
| B. Emulsion: CMS-2 | | | | | | | | |
| Aggregate: Virginia Granite | | | | | | | | |
| Gradation: "Medium" Base Course | | | | | | | | |
| Emulsion Content (%) | 5.00 | 5.00 | 5.00 | | 6.00 | 6.00 | 6.00 | |
| Total Water Content (%) | 2.48 | 3.48 | 4.48 | | 2.76 | 3.76 | 4.76 | |
| (1) Run-Off (%)<br>(Loose Mix) | 0.00 | 0.01 | 0.02 | | 0.03 | 0.18 | 0.06 | |
| (2) Wash-Off (%)<br>Compactive Effort: | | | | | | | | |
| (a) 10,000 lb | 0.05 | 0.05 | 0.00 | | 0.00 | 0.01 | 0.01 | |
| (b) 5,000 lb | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| (c) 2,500 lb | 0.00 | 0.00 | 0.02 | | 0.00 | 0.00 | 0.00 | |
| C. Emulsion: MS-2M | | | | | | | | |
| Aggregate: Maryland Limestone | | | | | | | | |
| Gradation: "Medium" Base Course | | | | | | | | |
| Emulsion Content (%) | 5.00 | 5.00 | 5.00 | | 6.00 | 6.00 | 6.00 | |
| Total Water Content (%) | 1.58 | 2.58 | 3.58 | | 1.89 | 3.89 | 3.89 | |
| (1) Run-Off (%)<br>(Loose Mix) | 0.09 | 0.23 | 1.89 | | 0.00 | 1.18 | 2.95 | |
| (2) Wash-Off (%)<br>Compactive Effort: | | | | | | | | |
| (a) 10,000 lb | 0.02 | 0.02 | 0.02 | | 0.26 | 0.25 | 0.22 | |
| (b) 5,000 lb | 0.02 | 0.02 | 0.03 | | 0.54 | 0.56 | 0.54 | |
| (c) 2,500 lb | 0.03 | 0.04 | * | | 0.02 | 0.02 | * | |
| D. Emulsion: CMS-1 | | | | | | | | |
| Aggregate: Maryland Limestone | | | | | | | | |
| Gradation: "Medium" Base Course | | | | | | | | |
| Emulsion Content (%) | 5.00 | 5.00 | 5.00 | | 6.00 | 6.00 | 6.00 | |
| Total Water Content (%) | 1.51 | 2.51 | 3.51 | | 1.80 | 2.80 | 3.80 | |
| (1) Run-Off (%)<br>(Loose Mix) | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.01 | |
| (2) Wash-Off (%)<br>Compactive Effort: | | | | | | | | |
| (a) 10,000 lb | 0.00 | 0.00 | 0.00 | | 0.05 | 0.01 | 0.00 | |
| E. Emulsion: CMS-1 | | | | | | | | |
| Aggregate: Virginia Granite | | | | | | | | |
| Gradation: "Fine" Surface Course | | | | | | | | |
| Emulsion Content (%) | 5.00 | 5.00 | 5.00 | | 6.00 | 6.00 | 6.00 | |
| Total Water Content (%) | 1.51 | 2.51 | 3.51 | | 1.80 | 2.80 | 3.80 | |
| (1) Run-Off (%)<br>(Loose Mix) | 0.01 | 0.04 | 0.06 | | 0.00 | 0.25 | 0.30 | |
| (2) Wash-Off (%)<br>Compactive Effort: | | | | | | | | |
| (a) 10,000 lb | 0.02 | 0.00 | 0.00 | | 0.02 | 0.02 | 0.00 | |

*Mixtures broke apart after compaction.

and this incompatibility can result in dissimilar designs for the same emulsion-aggregate combination.

Because of these problems, modifications to the reference methods were investigated in an attempt to shorten them, to make them more effective in establishing optimum emulsion and water contents, and to make them more compatible with regard to level of compactive effort, curing and water exposure procedures. Changes in the reference methods under investigation fell into three major categories:

1. Trial mixture composition including selection of emulsion, water and fluids contents.
2. Curing and water exposure procedures.
3. Level of compactive effort for specimen fabrication.

## Evaluation of Trial Mixture Composition Procedures

As noted earlier, the two methods differ greatly in the procedure for determining the trial emulsion content. The UI method makes use of an empirical equation derived using multiple linear stepwise regression techniques. The gradations of nine aggregates consisting of a variety of pit run gravel and crushed limestone from Illinois were correlated with residual asphalt contents giving peak soaked Marshall stabilities (*9*). Unfortunately, because of the broad limits for dense-graded aggregates, it is possible for the residual asphalt content calculated from this equation to have a negative value when the percent of material passing the No. 200 sieve is small. Thus, the utility of this equation is limited and questionable.

The AI method specifies the use of the CKE method which was developed for the Hveem design method when using asphalt cement or cutback asphalt (*22, 23*). It has been adapted for use with emulsified asphalts. A question remains as to its accuracy due to the presence of water in the more complex EAM system. Because water is added to the aggregate prior to the adding of emulsion, the absorptivity of the aggregate would be different from the absorptivity when using asphalt cement or cutback asphalt. In spite of this, it appears that use of the CKE method may be a more reasonable approach because both gradation and surface characteristics of the aggregate are taken into consideration and the method can be applied to all dense-graded aggregates.

Another difference between the two reference methods is that for the strength test phase, the UI method specifies constant water content as residual asphalt content is varied, while the AI method specifies constant fluids content which necessitates that total water content be reduced as residual asphalt is increased. Thus, in order to maintain constant fluids content for all emulsion contents, a disproportionate amount of water is often needed for the lower emulsion content mixes. Also, by keeping the water content constant for all mixes, the only variable is residual asphalt content. On the other hand, with constant fluids content, both asphalt content and water content are variables. Therefore, in order to make the strength test phase of the mix design effective in establishing optimum emulsion content, it is recommended that water content be kept constant during this last phase of testing.

### Modifications to Curing and Water Exposure Procedures

Both reference design methods require a lengthy 7-day cure and water exposure, although the conditions for the treatment of specimens is entirely different for the two methods. The "ultimate cure" specimen of the AI method is kept in the mold at room conditions for 3 days, vacuum desiccated for an additional 4 days, and then subjected to 1 hour of vacuum saturation followed by 1 hour total immersion at room temperature. This extreme conditioning contrasts sharply with the 3 days drying in the mold followed by 2 days of capillary soak of each end of partially immersed specimens of the UI method. It would be desirable to shorten the curing period and yet still achieve water contents in the range between those of vacuum desiccated AI method specimens and 3-day-in-the-mold UI specimens.

To shorten the design procedure, alternative shorter methods for specimen curing were investigated. The goal was to find a curing procedure that results in a reasonably well "cured out" specimen in a short time but at a rate consistent with field conditions.

#### *Modified Drying Conditions (Reference AI Method Compaction)*

Serial series of specimens were prepared using CSS-1h and Virginia limestone to study the effects of specimen conditioning. Three emulsion contents (3.0, 3.8, and 4.6 percent) were used and the specimens were compacted using the 40,000-lb double-plunger static load of the reference AI method. Fluids content at compaction was held constant at 5.3 percent. In addition to the curing procedure of the AI method, additional specimens were subjected to one of the following drying conditions:

1. Immediate extrusion after compaction, air curing for approximately 1 day, followed by vacuum desiccation for approximately 3 days (see Figure 14).
2. One day in mold at room temperature, extrusion, air curing for approximately 4 days (see Figure 15).
3. Kept in mold and placed immediately into oven at 100°F, oven cured for approximately 1 day, extrusion, vacuum desiccation for approximately 4 days (see Figure 16).
4. One day in mold at room temperature, extrusion, placed in oven at 120°F, oven cured for approximately 4 days (see Figure 17).
5. One day in mold at room temperature, extrusion, air curing at room temperature for one day, oven curing at 120°F for one day (see Figure 18).

Drying graphs plotting water content against curing time were developed for these five modified curing conditions through periodic weighing of specimens. As the curves in Figures 14 through 18 indicate, the major portion of the water loss occurs during the first two days regardless of emulsion or water content for all five conditions. This indicates that a two-day cure period is adequate.

Procedures for water exposure for these specimens included the AI method's 2-hour vacuum saturation for all curing conditions plus a simple 24-hour immersion at room temperature for additional specimens subjected to curing conditions 2, 4, and 5. In addition, another series of specimens were kept in the mold for 1 day at room temperature, extruded, and air cured for approximately 9 days (condition no. 6). They were then subjected to the capillary soak of the UI method. However, half of the specimens were soaked on one end only for the entire 4 days, while the other half were inverted after 2 days as specified in the UI method. All specimens subjected to either the AI method curing-water exposure procedures or one of the other six conditioning procedures described above were then tested for strength, density, and voids analysis. The results of these tests are summarized in Table 9.

The various curing conditions resulted in only minor differences with regard to density and voids, but strength properties tended to increase with the use of oven-curing; this was especially true for the soaked specimens. Table 9 indicates there was considerably greater water absorption with the two-hour vacuum saturation procedure than with either the 24-hour immersion or with the capillary soaking. Also, there was virtually no difference in specimen properties when comparing capillary soaking on one end with specimens soaked on both ends.

#### *Modified Drying Conditions (UI Method (Marshall) Compaction)*

To further investigate the effects of specimen conditioning, additional specimens were prepared using CSS-1h and Maryland limestone. In this case, compaction was achieved by either 50

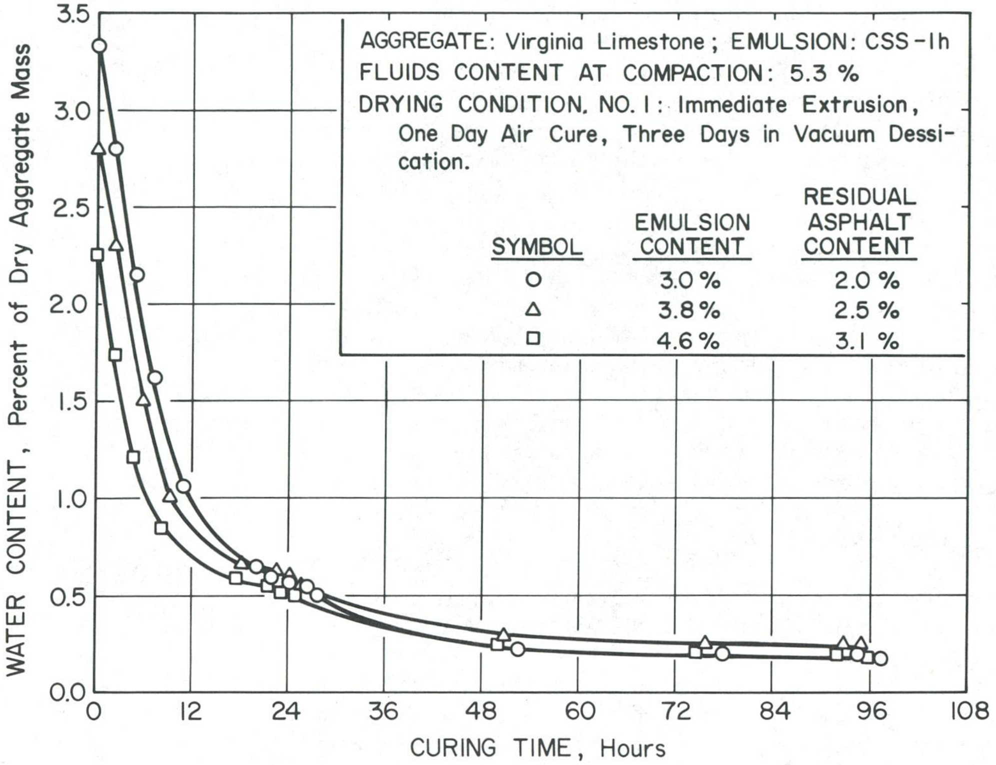

*Figure 14. Effect of emulsion and water contents on drying of dense-graded emulsion mixes (drying condition No. 1).*

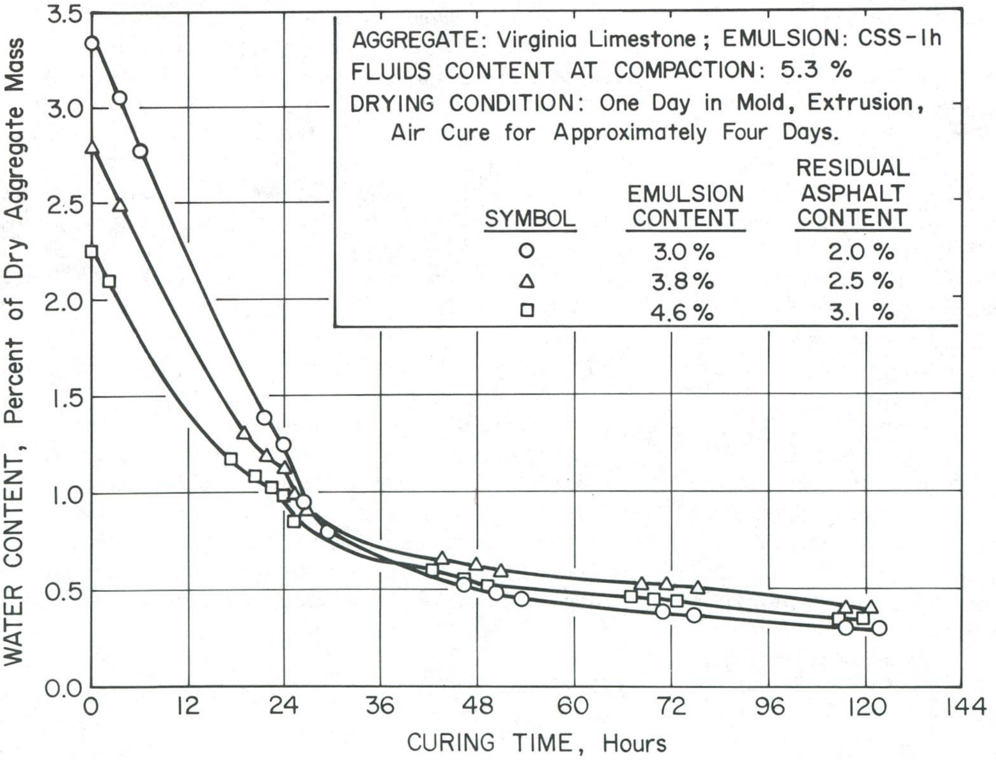

*Figure 15. Effect of emulsion and water contents on drying of dense-graded emulsion mixes (drying condition No. 2).*

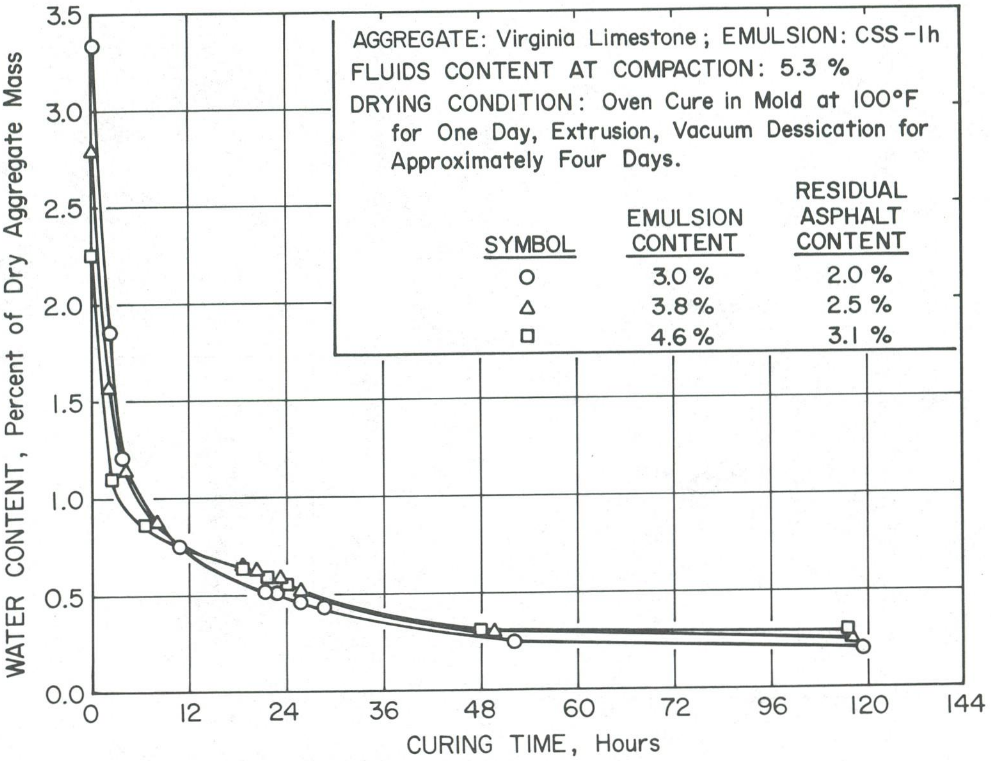

*Figure 16. Effect of emulsion and water contents on drying of dense-graded emulsion mixes (drying condition No. 3).*

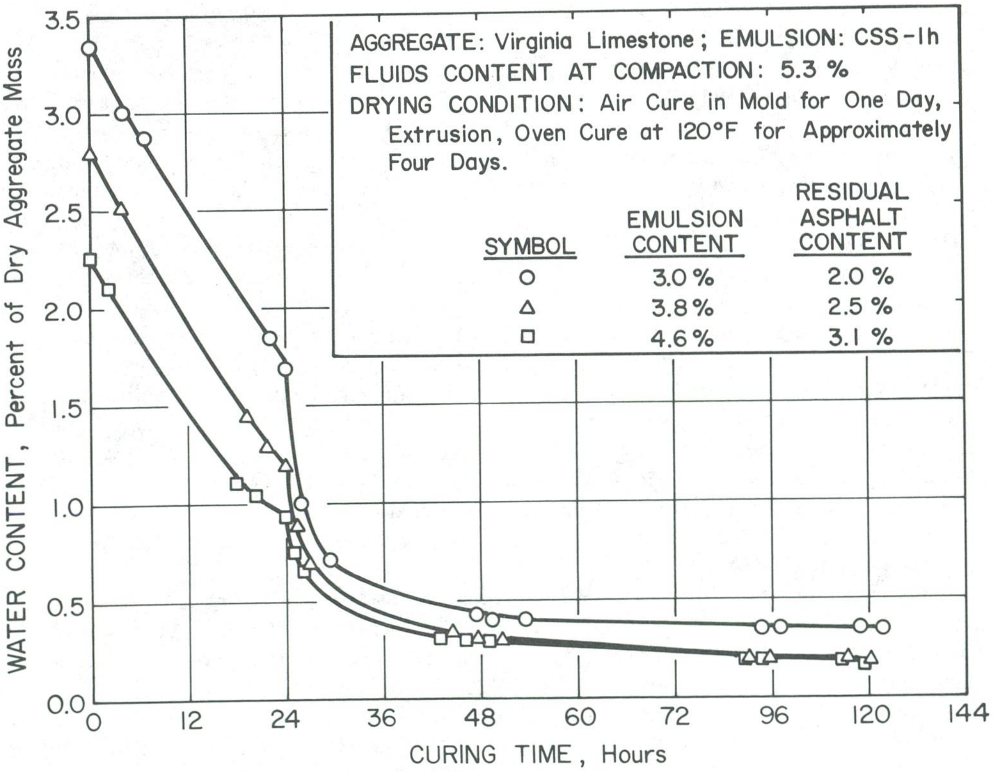

*Figure 17. Effect of emulsion and water contents on drying of dense-graded emulsion mixes (drying condition No. 4).*

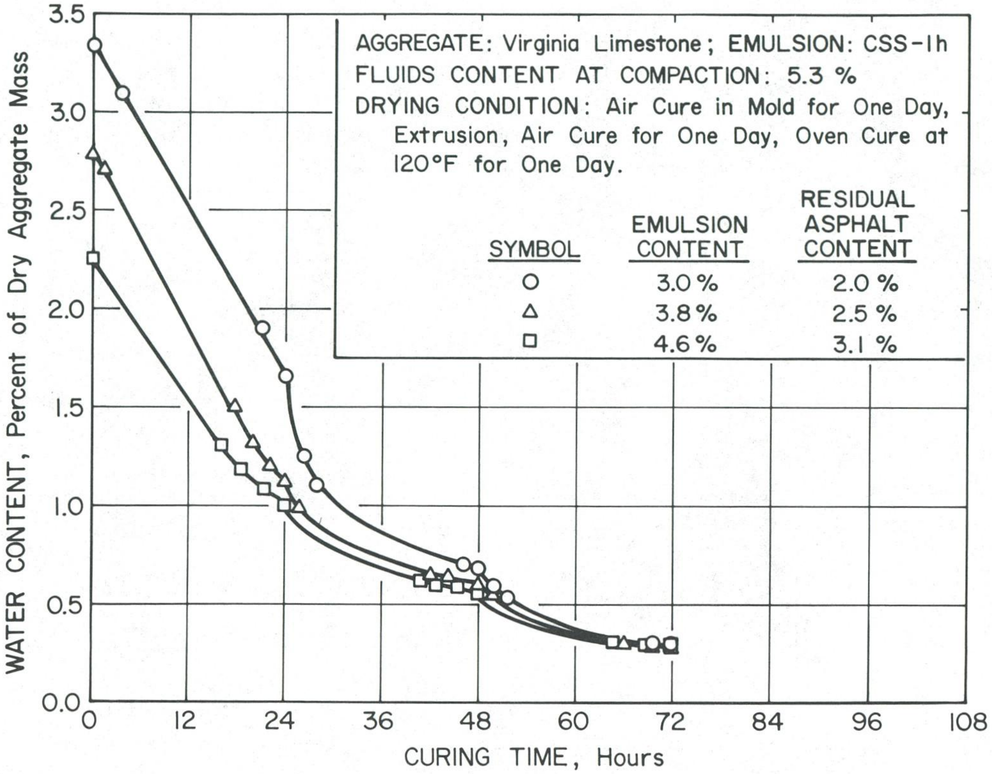

*Figure 18. Effect of emulsion and water contents on drying of dense-graded emulsion mixes (drying condition No. 5).*

or 75 blows of the Marshall hammer and water content at compaction was held constant at 5.6 percent. Specimens containing three residual asphalt contents (3.0, 3.5, and 4.0 percent) were kept in the mold for 1 day at room temperature (to allow for the development of initial cohesiveness), extruded, and subjected to one of the following conditions:

1. One day air cure at room temperature.
2. Two days air cure at room temperature.
3. One day in the oven at 100°F.
4. One day in the oven at 120°F.
5. Two days in the oven at 120°F.

An additional series was prepared according to the UI method (75-blow compaction and 3 days in the mold at room temperature) as a control. While the water exposure procedure for the control specimens was 4-day capillary soaking (2 days on each end), the other specimens were subjected to the 2-hour vacuum saturation procedure of the AI Method, though additional specimens kept in the oven at 120°F for 1 day were subjected to a 24-hour immersion at room conditions or 1-hour dry vacuum plus 24-hour immersion.

Summaries of the data resulting from these modified curing-water exposure procedures are given in Tables 10 (75-blow compaction) and 11 (50-blow compaction). Comparisons of the data show that specimens kept in the oven at 100°F for 1 day had reasonably comparable properties to those of the control specimens. Water contents at testing of the oven-cured specimens were somewhat less (0.27-0.36 percent vs. 0.54-0.60 percent), but other properties such as dry density, VMA, and total voids were in close agreement. There was especially close agreement for specimens exposed to water though the oven-cured specimens were subjected to the 2-hour AI method vacuum-saturation procedure while the control specimens underwent the 4-day capillary soak of the UI method. Water absorption ranged from 4.12 to 4.33 percent for the vacuum-saturated specimens, while those of the capillary-soaked specimens ranged from 1.83 to 2.91 percent. Thus, by adopting the 2-day cure (1 day in mold at room temperature plus 1 day in oven at 100°F) and the 2-hour AI method immersion procedure, both design methods can have their "ultimate" treatment periods shortened from 7 to 2 days, while the specimens are subjected to satisfactory extremes in drying and water exposure conditions. Oven-curing at 100°F is recommended because it simulates actual pavement conditions during the construction season more accurately than does vacuum desiccation at toom temperature. Furthermore, the relatively low oven temperature is recommended because higher temperatures can result in excessive water vapor pressures within the specimens leading to their premature deterioration.

### Modifications to Level of Compactive Effort

It was noted earlier that the compaction procedures of the reference methods produce specimens having significant differences in property values such as density and voids. The objective of this testing phase was to determine if comparable compactive efforts using the two types of equipment (Marshall hammer, and Triaxial Institute kneading compactor followed by double-plunger static load) could be established that would be applicable in general to all emulsion-aggregate combinations. Various levels of compactive effort were used to fabricate specimens that were then subjected to the 2-day curing and water exposure procedure

**Table 9. Effect of curing and water exposure conditions on properties of Hveem specimens.**

MINERAL AGGREGATE: Virginia Limestone

EMULSION: CSS-1h

COMPACTION: 40,000 lb. Double-Plunger Static Load

FLUIDS CONTENT AT COMPACTION: 5.31 Percent

| Air Cure and Water Exposure Conditions* | AI |  | Cure | Water | Cure | Water | Water | Cure | Water | Cure | Water | Water | Cure | Water | Water | Cure (6) |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Early Cure | Ult. Cure | (1) | (1) | (2) | (1) | (2) | (3) | (1) | (4) | (1) | (2) | (5) | (1) | (2) | Water (3) | Water (4) |
| A. Emulsion Content: 3.0 Percent, Residual Asphalt Content: 2.0 Percent |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| R-Value | 88.0 | 90.0 | 93.0 | 91.7 | 91.1 | 89.8 | 87.9 | 91.2 | 90.6 | 92.7 | 90.2 | 91.9 | 91.1 | 91.4 | 92.4 | 91.1 | 89.8 |
| C-Value | 137 | 236 | 361 | 221 | 464 | 217 | 179 | 409 | 276 | 492 | 348 | 341 | 408 | 352 | 285 | 234 | 236 |
| $R_t$-Value | 94.8 | 101.8 | 111.1 | 102.8 | 114.3 | 100.7 | 96.9 | 111.7 | 104.4 | 117.3 | 107.6 | 109.0 | 111.5 | 109.0 | 106.7 | 102.8 | 101.6 |
| Water Content at Testing,% | 1.17 | 4.40 | 0.26 | 4.10 | 0.25 | 4.51 | 3.45 | 0.52 | 3.96 | 0.07 | 4.26 | 2.40 | 0.21 | 4.07 | 2.49 | 2.14 | 2.37 |
| Water Absorption,% | --- | 4.13 | --- | 3.69 | --- | 4.13 | 2.78 | --- | 3.57 | --- | 3.99 | 2.24 | --- | 3.69 | 2.15 | 1.91 | 2.17 |
| Dry Density, lb/ft$^3$ | 146.8 | 147.6 | 147.0 | 148.0 | 146.6 | 147.5 | 146.5 | 146.2 | 148.9 | 147.9 | 147.9 | 148.1 | 147.0 | 148.6 | 147.8 | --- | --- |
| VMA, % | 15.70 | 15.23 | 15.56 | 15.00 | 15.80 | 15.30 | 15.90 | 16.03 | 14.48 | 15.05 | 15.06 | 14.94 | 15.59 | 14.90 | 15.09 | --- | --- |
| Total Voids, % | 11.25 | 10.75 | 11.09 | 10.51 | 11.35 | 10.82 | 11.45 | 11.59 | 9.96 | 10.56 | 10.57 | 10.45 | 11.13 | 10.41 | 10.60 | --- | --- |
| Air Voids, % | 8.55 | 0.57 | 10.50 | 0.98 | 10.78 | 0.36 | 3.51 | 10.39 | 0.69 | 10.40 | 0.67 | 4.88 | 10.64 | 0.94 | 4.82 | --- | --- |
| B. Emulsion Content: 3.8 Percent, Residual Asphalt Content: 2.5 Percent |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| R-Value | 88.5 | 90.1 | 92.3 | 87.7 | 92.3 | 88.5 | 90.2 | 91.6 | 89.8 | 92.2 | 90.2 | 89.9 | 88.2 | 90.8 | 90.0 | 88.1 | 88.7 |
| C-Value | 164 | 267 | 389 | 158 | 545 | 201 | 230 | 371 | 299 | 402 | 392 | 394 | 350 | 312 | 291 | 229 | 236 |
| $R_t$-Value | 96.8 | 103.5 | 111.8 | 95.6 | 119.6 | 98.6 | 101.7 | 110.2 | 104.8 | 112.3 | 109.8 | 109.6 | 105.7 | 106.4 | 104.6 | 99.6 | 100.5 |
| Water Content at Testing,% | 0.94 | 3.84 | 0.23 | 3.84 | 0.34 | 4.22 | 3.01 | 0.26 | 3.46 | 0.16 | 4.08 | 2.52 | 0.15 | 4.07 | 2.68 | 2.14 | 2.38 |
| Water Absorption, % | --- | 3.60 | --- | 3.42 | --- | 3.63 | 2.66 | --- | 3.08 | --- | 3.81 | 2.31 | --- | 3.78 | 1.67 | 1.97 | 2.16 |
| Dry Density, lb/ft$^3$ | 147.0 | 148.6 | 147.5 | 147.6 | 148.0 | 147.3 | 147.6 | 146.8 | 149.7 | 148.3 | 147.8 | 148.4 | 146.9 | 147.7 | 148.7 | --- | --- |
| VMA, % | 16.03 | 15.11 | 15.77 | 15.70 | 15.43 | 15.87 | 15.70 | 16.15 | 14.47 | 15.28 | 15.59 | 15.24 | 16.09 | 15.61 | 15.05 | --- | --- |
| Total Voids, % | 10.38 | 9.40 | 10.10 | 10.03 | 9.74 | 10.21 | 10.03 | 10.51 | 8.72 | 9.58 | 9.91 | 9.53 | 10.45 | 9.93 | 9.34 | --- | --- |
| Air Voids, % | 8.22 | 0.49 | 9.57 | 1.18 | 8.95 | 0.50 | 3.09 | 9.90 | 0.63 | 9.21 | 0.48 | 3.69 | 10.11 | 0.54 | 3.12 | --- | --- |
| C. Emulsion Content: 4.6 Percent, Residual Asphalt Content: 3.1 Percent |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| R-Value | 87.2 | 87.0 | 92.1 | 87.2 | 90.0 | 85.1 | 87.9 | 91.7 | 90.3 | 92.3 | 91.9 | 90.6 | 88.8 | 89.3 | 87.1 | 89.5 | 90.3 |
| C-Value | 248 | 246 | 375 | 208 | 370 | 206 | 210 | 444 | 263 | 515 | 392 | 395 | 546 | 381 | 271 | 267 | 257 |
| $R_t$-Value | 99.6 | 99.4 | 110.9 | 97.6 | 108.5 | 95.4 | 98.4 | 113.9 | 103.5 | 118.1 | 111.5 | 110.4 | 116.1 | 108.4 | 100.7 | 102.9 | 103.2 |
| Water Content at Testing,% | 0.97 | 3.86 | 0.31 | 3.47 | 0.36 | 3.83 | 2.83 | 0.66 | 3.29 | 0.13 | 3.65 | 2.50 | 0.21 | 3.75 | 2.58 | 2.34 | 2.29 |
| Water Absorption, % | --- | 3.33 | --- | 2.96 | --- | 3.44 | 2.47 | --- | 2.84 | --- | 3.41 | 2.26 | --- | 3.40 | 2.18 | 2.14 | 2.09 |
| Dry Density, lb/ft$^3$ | 147.4 | 147.1 | 147.0 | 147.3 | 146.4 | 147.5 | 145.9 | 147.1 | 148.8 | 148.1 | 148.0 | 146.9 | 148.2 | 147.7 | 147.7 | --- | --- |
| VMA, % | 16.23 | 16.39 | 16.45 | 16.25 | 16.81 | 16.15 | 17.09 | 16.41 | 15.42 | 15.81 | 15.88 | 16.52 | 15.77 | 16.06 | 16.06 | --- | --- |
| Total Voids, % | 9.39 | 9.55 | 9.62 | 9.41 | 10.01 | 9.31 | 10.32 | 9.59 | 8.52 | 8.93 | 9.01 | 9.70 | 8.89 | 9.20 | 9.21 | --- | --- |
| Air Voids, % | 7.17 | 0.72 | 8.92 | 1.45 | 9.19 | 0.53 | 3.91 | 8.08 | 0.90 | 8.63 | 0.60 | 4.00 | 8.41 | 0.60 | 3.29 | --- | --- |

*Air Curing Procedure

Early Cure -One day in mold.

Ult. Cure -Three days in mold, extrusion, four day vacuum dessication (followed by one hour vacuum saturation, one hour immersion).

(1) Immediate extrusion, one day room cure, three day vacuum dessication.
(2) One day in mold, extrusion, four day room cure.
(3) One day in mold in oven at 100°F, extrusion, four day vacuum dessication.
(4) One day in mold, extrusion, four days in oven at 120°F.
(5) One day in mold, extrusion, one day room cure, one day in oven at 120°F.
(6) One day in mold, extrusion, nine day room cure.

*Water Exposure Procedure

(1) One-hour vacuum saturation, one-hour immersion.
(2) One-day immersion.
(3) Four-day capillary soak on one end only.
(4) Four-day capillary soak on both ends (UI method).

**Table 10. Effect of curing and water exposure conditions on properties of Marshall specimens (75 blows).**

MINERAL AGGREGATE: Maryland Limestone

EMULSION: CSS-1h

COMPACTION: 75 Blows Marshall Hammer

WATER CONTENT AT COMPACTION: 5.6 Percent

| Air Cure and Water Exposure Conditions* | Cure (1) | Water (1) | Cure (2) | Water (2) | Cure (3) | Water (2) | Cure (4) | Water (2) | Cure (5) | Water (2) | Water (3) | Water (4) | Cure (6) | Water (2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A. Emulsion Content: 4.5 Percent, Residual Asphalt Content: 3.0 Percent | | | | | | | | | | | | | |
| R-Value | 79.8 | 75.0 | 82.2 | 78.0 | 82.8 | 62.0 | 79.0 | 71.5 | 77.3 | 76.7 | 85.2 | 83.3 | 81.8 | 79.2 |
| C-Value | 174 | 86 | 169 | 87 | 262 | 101 | 238 | 114 | 170 | 122 | 119 | 150 | 247 | 134 |
| $R_t$-Value | 88.5 | 79.3 | 90.7 | 82.4 | 95.9 | 67.1 | 90.9 | 77.2 | 85.8 | 82.8 | 91.2 | 90.8 | 94.2 | 85.9 |
| Marshall Stability,** lb | 2548 | 1202 | 2578 | 1340 | 4122 | 1517 | 4161 | 1744 | 4138 | 2122 | 2222 | 2009 | 4425 | 2218 |
| Water Content at Testing,% | 0.54 | 3.44 | 0.46 | 4.36 | 0.27 | 4.88 | 0.27 | 4.84 | 0.17 | 4.67 | 4.43 | 3.54 | 0.08 | 4.20 |
| Water Absorption, % | --- | 2.91 | --- | 3.81 | --- | 4.40 | --- | 4.32 | --- | 4.42 | 4.31 | 3.43 | --- | 3.98 |
| Dry Density, lb/ft$^3$ | 142.1 | 140.2 | 143.6 | 143.4 | 141.3 | 143.0 | 140.8 | 142.8 | 142.1 | 143.8 | 144.5 | 142.4 | 143.5 | 143.4 |
| VMA, % | 19.22 | 20.36 | 18.42 | 18.53 | 19.69 | 18.71 | 20.00 | 19.10 | 19.25 | 18.25 | 17.86 | 19.06 | 18.44 | 18.47 |
| Total Voids, % | 12.75 | 13.98 | 11.88 | 12.00 | 13.25 | 12.20 | 13.59 | 12.31 | 12.78 | 11.70 | 11.28 | 12.57 | 11.90 | 11.93 |
| Air Voids, % | 11.56 | 6.47 | 10.86 | 2.27 | 12.65 | 1.35 | 13.01 | 1.55 | 12.41 | 1.25 | 1.32 | 4.73 | 11.72 | 2.56 |
| | B. Emulsion Content: 5.2 Percent, Residual Asphalt Content: 3.5 Percent | | | | | | | | | | | | | |
| R-Value | 79.7 | 76.1 | 76.8 | 75.3 | 80.0 | 69.8 | 76.7 | 66.0 | 76.3 | 79.1 | 81.8 | 79.4 | 81.5 | 82.5 |
| C-Value | 124 | 85 | 129 | 56 | 207 | 75 | 152 | 83 | 168 | 104 | 110 | 127 | 230 | 134 |
| $R_t$-Value | 85.9 | 80.4 | 83.3 | 78.1 | 90.4 | 73.6 | 84.3 | 70.2 | 84.7 | 84.3 | 87.3 | 85.8 | 93.0 | 89.2 |
| Marshall Stability,** lb | 1402 | 1484 | 1558 | 1238 | 4065 | 1654 | 3518 | 1539 | 3591 | 1558 | 1904 | 1853 | 3666 | 2223 |
| Water Content at Testing,% | 0.59 | 2.81 | 0.52 | 4.06 | 0.75 | 4.66 | 0.34 | 4.66 | 0.26 | 4.76 | 4.45 | 3.08 | 0.11 | 4.19 |
| Water Absorption, % | --- | 2.22 | --- | 3.46 | --- | 4.20 | --- | 4.27 | --- | 4.44 | 4.36 | 2.78 | --- | 4.02 |
| Dry Density, lb/ft$^3$ | 142.3 | 141.5 | 142.2 | 142.6 | 141.0 | 141.3 | 141.0 | 142.4 | 141.1 | 141.9 | 143.7 | 142.0 | 142.5 | 144.2 |
| VMA, % | 19.51 | 20.02 | 19.59 | 19.36 | 20.26 | 20.12 | 20.27 | 19.45 | 20.21 | 19.74 | 18.73 | 19.67 | 19.41 | 18.44 |
| Total Voids, % | 11.98 | 12.54 | 12.08 | 11.82 | 12.81 | 12.64 | 12.81 | 11.93 | 12.75 | 12.24 | 11.14 | 12.16 | 11.88 | 10.81 |
| Air Voids, % | 10.69 | 6.40 | 10.94 | 2.85 | 11.18 | 2.44 | 12.06 | 1.66 | 12.17 | 1.78 | 1.24 | 5.39 | 11.65 | 1.45 |
| | C. Emulsion Content: 6.0 Percent, Residual Asphalt Content: 4.0 Percent | | | | | | | | | | | | | |
| R-Value | 80.4 | 71.5 | 75.0 | 76.0 | 79.2 | 76.0 | 74.0 | 71.8 | 76.4 | 79.3 | 75.6 | 78.2 | 77.4 | 81.9 |
| C-Value | 188 | 101 | 132 | 79 | 168 | 82 | 139 | 92 | 149 | 114 | 142 | 128 | 209 | 158 |
| $R_t$-Value | 89.8 | 76.6 | 81.6 | 80.0 | 87.6 | 80.1 | 81.0 | 76.4 | 83.9 | 85.0 | 82.7 | 84.6 | 87.9 | 89.8 |
| Marshall Stability,** lb | 1906 | 1169 | 2087 | 1241 | 2873 | 1580 | 2370 | 1266 | 2284 | 1785 | 1853 | 2081 | 3494 | 2194 |
| Water Content at Testing,% | 0.60 | 2.43 | 0.51 | 3.90 | 0.41 | 4.32 | 0.35 | 4.64 | 0.15 | 4.60 | 4.18 | 2.38 | 0.10 | 4.16 |
| Water Absorption, % | --- | 1.83 | --- | 3.07 | --- | 3.83 | --- | 4.12 | --- | 4.32 | 4.06 | 2.11 | --- | 4.05 |
| Dry Density, lb/ft$^3$ | 143.1 | 141.0 | 141.5 | 141.4 | 141.6 | 142.1 | 140.8 | 141.1 | 140.8 | 142.0 | 143.8 | 142.5 | 140.5 | 143.2 |
| VMA, % | 19.48 | 20.63 | 20.36 | 20.42 | 20.28 | 19.98 | 20.76 | 20.59 | 20.78 | 20.10 | 19.07 | 19.80 | 20.92 | 19.40 |
| Total Voids, % | 10.88 | 12.15 | 11.85 | 11.92 | 11.77 | 11.43 | 12.30 | 12.11 | 12.32 | 11.56 | 10.42 | 11.23 | 12.47 | 10.78 |
| Air Voids, % | 9.56 | 6.87 | 10.73 | 3.43 | 10.87 | 1.98 | 11.53 | 2.02 | 12.00 | 1.49 | 1.17 | 6.01 | 12.26 | 1.60 |

*Air Curing Procedures
(1) Three days in mold, (Univ. of Ill. method).
(2) One day in mold, extrusion, one day room cure.
(3) One day in mold, extrusion, two day room cure.
(4) One day in mold, extrusion, one day in oven at 100°F.
(5) One day in mold, extrusion, one day in oven at 120°F.
(6) One day in mold, extrusion, two days in oven at 120°F.

*Water Exposure Procedures
(1) = Four-day capillary soak (Univ. of Ill. method).
(2) = One-hour vacuum saturation, one hour immersion.
(3) = One-hour dry vacuum, one day immersion.
(4) = One-day immersion. (All specimens exposed to water were air-cured according to preceding conditions).

**Marshall Stability measured after determination of R-Value and C-Value.

**Table 11. Effect of curing and water exposure conditions on properties of Marshall specimens (50 blows).**

MINERAL AGGREGATE: Maryland Limestone EMULSION: CSS-1h

COMPACTION: 50 Blows Marshall Hammer WATER CONTENT AT COMPACTION: 5.6 Percent

| Air Cure and Water Exposure Conditions | Cure (2) | Water (2) | Cure (3) | Water (2) | Cure (4) | Water (2) |
|---|---|---|---|---|---|---|
| A. Emulsion Content: 4.5 Percent, Residual Asphalt Content: 3.0 Percent | | | | | | |
| R-Value | 78.1 | 72.1 | 85.5 | 82.1 | 82.4 | 81.3 |
| C-Value | 219 | 91 | 254 | 120 | 199 | 141 |
| $R_t$-Value | 89.1 | 76.6 | 98.2 | 88.1 | 92.4 | 88.4 |
| Marshall Stability,** lb | 3227 | 593 | 4438 | 1769 | 3670 | 1619 |
| Water Content at Testing,% | 0.65 | 4.52 | 0.26 | 4.79 | 0.26 | 4.94 |
| Water Absorption, % | ---- | 3.48 | ---- | 4.45 | ---- | 4.33 |
| Dry Density, lb/ft$^3$ | 142.2 | 140.2 | 143.3 | 143.2 | 141.6 | 141.5 |
| VMA, % | 19.20 | 20.38 | 18.58 | 18.61 | 19.50 | 19.57 |
| Total Voids, % | 12.73 | 13.99 | 12.06 | 12.09 | 13.09 | 13.13 |
| Air Voids, % | 11.29 | 4.14 | 11.47 | 1.42 | 12.51 | 2.25 |
| B. Emulsion Content: 5.2 Percent, Residual Asphalt Content: 3.5 Percent | | | | | | |
| R-Value | 75.6 | 67.5 | 83.2 | 75.1 | 81.2 | 76.5 |
| C-Value | 100 | 88 | 159 | 171 | 159 | 108 |
| $R_t$-Value | 80.6 | 71.9 | 91.2 | 83.7 | 89.2 | 81.9 |
| Marshall Stability,** lb | 1568 | 733 | 3685 | 1463 | 2885 | 1770 |
| Water Content at Testing,% | 0.54 | 4.69 | 0.34 | 4.76 | 0.31 | 4.65 |
| Water Absorption, % | ---- | 3.58 | ---- | 4.41 | ---- | 4.24 |
| Dry Density, lb/ft$^3$ | 142.2 | 140.2 | 141.2 | 141.8 | 141.5 | 142.1 |
| VMA, % | 19.57 | 20.70 | 20.15 | 19.84 | 19.96 | 19.66 |
| Total Voids, % | 12.05 | 13.29 | 12.69 | 12.35 | 12.47 | 12.15 |
| Air Voids, % | 10.87 | 3.11 | 11.96 | 1.91 | 11.80 | 1.93 |
| C. Emulsion Content: 6.0 Percent, Residual Asphalt Content: 4.0 Percent | | | | | | |
| R-Value | 77.0 | 78.0 | 78.6 | 68.7 | 75.7 | 72.3 |
| C-Value | 160 | 94 | 178 | 105 | 171 | 125 |
| $R_t$-Value | 85.0 | 82.7 | 87.5 | 74.0 | 84.3 | 78.6 |
| Marshall Stability,** lb | 1811 | 897 | 2900 | 1572 | 2270 | 1678 |
| Water Content at Testing,% | 0.60 | 4.37 | 0.47 | 4.88 | 0.36 | 4.66 |
| Water Absorption, % | ---- | 3.11 | ---- | 4.48 | ---- | 4.26 |
| Dry Density, lb/ft$^3$ | 140.8 | 140.8 | 140.1 | 140.6 | 138.2 | 141.1 |
| VMA, % | 20.77 | 20.73 | 21.16 | 20.84 | 22.20 | 20.58 |
| Total Voids, % | 12.31 | 12.26 | 12.74 | 12.38 | 13.89 | 12.09 |
| Air Voids, % | 11.02 | 2.78 | 11.73 | 1.79 | 13.11 | 1.95 |

*Air Curing Procedures
(2) One day in mold, extrusion, one-day room cure.
(3) One day in mold, extrusion, two-days' room cure.
(4) One day in mold, extrusion, one-day in oven at 100°F.

*Water Exposure Procedures
(2) = One-hour vacuum saturation, one hour immersion. (All specimens exposed to water were air-cured according to preceding conditions.)

**Marshall Stability measured after determination of R-Value and C-Value.

recommended above. In this case, CSS-1h and Maryland limestone were mixed with 2.6 percent total moisture and CSS-1h and crushed Maryland gravel (with sand and limestone dust-filler) were mixed with 4.7 percent total moisture. Residual asphalt contents of 3.0, 3.5, and 4.0 percent were included for each compactive effort. Comparisons therefore involved one set of mixes with a "middle" dense-graded limestone at a relatively low mixing water content and another set with a "fine" dense-graded crushed gravel-sand at a higher mixing water content.

The limestone mixes were subjected to 50 and 75 blows of the Marshall hammer and double-plunger static loads of 5,000, 10,000, 20,000 and 40,000 lb (following 20 tamps at 250 psi of the Triaxial Institute kneading compactor). The gravel mixes were compacted by all of the above except for the 40,000-lb load. For each compactive effort and residual asphalt content, four specimens were prepared—two cured and two vacuum saturated, with one of the cured and one of the vacuum saturated being tested for R-value and C-value, and the other two being tested for Marshall stability and flow.

The results of this investigation are given in Tables 12 and 13. With the limestone mixes (Table 12) the effect of level of compactive effort is more evident than with the gravel mixes (Table 13). The general trend for the limestone mixes is close agreement in property values for specimens compacted by 75 blows and the 5,000-lb static load, though R-values are considerably greater for the 75-blow specimens. For the gravel mixes, there is close agreement between 75-blow and 10,000-lb specimens. A reduction of the static load of the AI method from 40,000 to 10,000 lb would lead to better agreement in densities between the two design methods and would reduce the amount of aggregate degradation during compaction.

Table 12. Effect of compactive effort and emulsion content on properties of compacted specimens (limestone).

MINERAL AGGREGATE: Maryland Limestone EMULSION: CSS-1h WATER CONTENT AT COMPACTION: 2.6 percent

| COMPACTIVE EFFORT | MARSHALL HAMMER | | | | DOUBLE-PLUNGER STATIC LOAD | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50 Blows | | 75 Blows | | 5,000 lb | | 10,000 lb | | 20,000 lb | | 40,000 lb | |
| CURING CONDITIONS: | Cure | Water | Cure | Water | Cure | Water | Cure | Water | Cure | Water | Cure | Water |
| | A. Emulsion Content: 4.5 Percent, Residual Asphalt Content: 3.0 Percent | | | | | | | | | | | |
| R-Value | 84.5 | ---- | 90.0 | 87.8 | 86.5 | 77.2 | 87.1 | 78.4 | 89.7 | 82.3 | 93.4 | 88.9 |
| C-Value | 59 | ---- | 187 | 131 | 157 | 116 | 172 | 98 | 275 | 110 | 514 | 206 |
| $R_t$-Value | 87.5 | ---- | 99.4 | 94.4 | 94.4 | 83.0 | 95.7 | 83.3 | 103.5 | 87.8 | 119.1 | 99.2 |
| Marshall Stability, lb | 1278 | 710 | 1783 | 588 | 1719 | 1030 | 2035 | 1302 | 4009 | 2172 | 5908 | 3934 |
| Retained Marshall Stability, % | ---- | 55.6 | ---- | 33.0 | ---- | 59.9 | ---- | 64.0 | ---- | 54.2 | ---- | 66.6 |
| Water Content at Testing,% | 0.12 | 6.34 | 0.16 | 5.12 | 0.23 | 5.29 | 0.31 | 5.12 | 0.26 | 4.13 | 0.30 | 3.04 |
| Water Absorption, % | ---- | 6.22 | ---- | 4.95 | ---- | 50.6 | ---- | 4.82 | ---- | 3.87 | ---- | 2.43 |
| Dry Density, lb/ft$^3$ | 140.2 | 137.5 | 142.0 | 140.8 | 142.1 | 140.7 | 144.4 | 141.7 | 147.8 | 145.8 | 150.6 | 150.0 |
| VMA, % | 20.34 | 21.87 | 19.32 | 20.01 | 19.23 | 20.04 | 17.94 | 19.47 | 16.03 | 17.19 | 14.40 | 14.79 |
| Total Voids, % | 13.96 | 15.61 | 12.85 | 13.60 | 12.76 | 13.63 | 11.37 | 13.02 | 9.30 | 10.55 | 7.54 | 7.96 |
| Air Voids, % | 13.70 | 2.04 | 12.49 | 2.39 | 12.25 | 2.04 | 10.68 | 1.73 | 8.71 | 1.19 | 6.83 | 0.87 |
| | B. Emulsion Content: 5.2 Percent, Residual Asphalt Content: 3.5 Percent | | | | | | | | | | | |
| R-Value | 77.5 | 72.2 | 90.5 | 88.5 | 83.1 | 80.5 | 86.2 | 80.6 | 90.2 | 83.5 | 92.7 | 91.2 |
| C-Value | 131 | 73 | 207 | 146 | 157 | 102 | 184 | 106 | 322 | 132 | 361 | 218 |
| $R_t$-Value | 84.01 | 75.9 | 100.9 | 95.8 | 91.0 | 85.6 | 95.4 | 85.9 | 106.3 | 90.1 | 110.8 | 102.1 |
| Marshall Stability, lb | 1268 | 746 | 1872 | 872 | 1878 | 1210 | 1948 | 1673 | 3833 | 2578 | 5606 | 3749 |
| Retained Marshall Stability, % | ---- | 58.8 | ---- | 46.6 | ---- | 64.4 | ---- | 85.9 | ---- | 67.3 | ---- | 66.9 |
| Water Content at Testing,% | 0.13 | 5.30 | 0.18 | 5.29 | 0.20 | 5.29 | 0.30 | 4.68 | 0.34 | 3.47 | 0.21 | 2.85 |
| Water Absorption, % | ---- | 5.17 | ---- | 5.12 | ---- | 5.09 | ---- | 4.38 | ---- | 3.12 | ---- | 2.44 |
| Dry Density, lb/ft$^3$ | 140.1 | 138.6 | 141.3 | 140.3 | 141.3 | 139.6 | 144.3 | 142.0 | 147.8 | 147.0 | 150.4 | 149.9 |
| VMA, % | 20.81 | 21.62 | 20.07 | 20.70 | 20.09 | 21.07 | 18.37 | 19.72 | 16.43 | 16.93 | 14.92 | 15.21 |
| Total Voids, % | 13.40 | 14.29 | 12.59 | 13.29 | 12.62 | 13.69 | 10.74 | 12.21 | 8.61 | 9.16 | 6.97 | 7.28 |
| Air Voids, % | 13.12 | 2.91 | 12.21 | 1.80 | 12.18 | 2.26 | 10.07 | 1.92 | 7.84 | 1.28 | 6.47 | 0.66 |
| | C. Emulsion Content: 6.0 Percent, Residual Asphalt Content: 4.0 Percent | | | | | | | | | | | |
| R-Value | 77.5 | 75.2 | 88.2 | 83.0 | 84.0 | 78.2 | 87.3 | 75.0 | 89.3 | 80.4 | 93.3 | 90.3 |
| C-Value | 78 | 81 | 184 | 141 | 190 | 103 | 198 | 69 | 249 | 113 | 340 | 237 |
| $R_t$-Value | 81.4 | 79.3 | 97.4 | 90.1 | 93.5 | 83.4 | 97.2 | 78.5 | 101.8 | 86.1 | 110.3 | 102.2 |
| Marshall Stability, lb | 1303 | 632 | 1639 | 745 | 2228 | 1308 | 2187 | 1537 | 3832 | 2900 | 5578 | 3405 |
| Retained Marshall Stability, % | ---- | 48.5 | ---- | 45.5 | ---- | 58.7 | ---- | 70.3 | ---- | 75.7 | ---- | 61.0 |
| Water Content at Testing,% | 0.17 | 5.44 | 0.17 | 5.06 | 0.28 | 4.99 | 0.29 | 4.26 | 0.26 | 3.35 | 0.23 | 2.56 |
| Water Absorption, % | ---- | 5.26 | ---- | 4.88 | ---- | 4.71 | ---- | 3.97 | ---- | 3.09 | ---- | 2.17 |
| Dry Density, lb/ft$^3$ | 138.7 | 136.1 | 140.7 | 139.5 | 141.9 | 139.5 | 144.7 | 142.3 | 147.9 | 146.9 | 150.3 | 150.1 |
| VMA, % | 21.92 | 23.41 | 20.80 | 21.50 | 20.14 | 21.52 | 18.58 | 19.87 | 16.77 | 17.32 | 15.38 | 15.55 |
| Total Voids, % | 13.58 | 15.23 | 12.34 | 13.11 | 11.61 | 13.13 | 9.88 | 11.31 | 7.87 | 8.49 | 6.34 | 6.52 |
| Air Voids, % | 13.21 | 3.82 | 12.22 | 2.24 | 11.00 | 2.42 | 9.24 | 1.97 | 7.28 | 0.91 | 5.80 | 0.60 |

Curing Conditions: Cure -- One day in mold, extrusion, one day in oven at 100°F.
Water -- Identical cure as above followed by one-hour vacuum saturation, one-hour immersion.

The data in Tables 12 and 13 were used to investigate relationships among several of the specimen properties for both emulsion-aggregate combinations. The relationships are shown graphically in Figures 19 through 26. The data in these two tables were also used to develop the following values of correlation coefficient, r:

| | Cured Specimens | Immersed Specimens | All Specimens |
|---|---|---|---|
| A. CSS-lh and Maryland Limestone | | | |
| 1. Marshall stability vs. dry density | 0.94 | 0.95 | 0.92 |
| 2. R-value vs. dry density | 0.74 | 0.74 | 0.71 |
| 3. Marshall stability vs. R-value | 0.68 | 0.53 | 0.66 |
| 4. Total voids vs. dry density | −0.94 | −0.96 | −0.95 |
| B. CSS-lh and Crushed Maryland Gravel and Sand | | | |
| 1. Marshall stability vs. dry density | 0.84 | 0.90 | 0.75 |
| 2. R-value vs. dry density | 0.66 | 0.75 | 0.54 |
| 3. Marshall stability vs. R-value | 0.50 | 0.55 | 0.61 |
| 4. Total voids vs. dry density | −0.74 | −0.80 | −0.77 |

As these numbers indicate, there is very good correlation between Marshall stability and dry density with the limestone mixes, but less so with the gravel mixes. On the other hand, R-value correlates poorly with dry density in both cases, which again, points out the fundamental differences between the two stability tests, as does the poor correlation between Marshall stability and R-value for both mix types. With regard to total voids vs. dry density, there is very good correlation for the limestone mixes, but a poor relationship for the gravel mixes.

To summarize, the results of these tests indicate the difficulty of developing compatible design methods when using Marshall and Hveem equipment, and also emphasize the importance of aggregate type on specimen properties of EAMs.

### Effect of Compaction on Degradation of Mineral Aggregates

The effects that differences in type and intensity of compactive effort can impart on specimen properties are also indicated by

Table 13. Effect of compactive effort and emulsion content on properties of compacted specimens (gravel/sand).

MINERAL AGGREGATE: Crushed MD Gravel and Sand EMULSION: CSS-1h WATER CONTENT AT COMPACTION: 4.7 percent

| COMPACTIVE EFFORT | MARSHALL HAMMER | | | | DOUBLE-PLUNGER STATIC LOAD | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 Blows | | 75 Blows | | 5,000 lb | | 10,000 lb | | 20,000 lb | |
| CURING CONDITIONS: | Cure | Water | Cure | Water | Cure | Water | Cure | Water | Cure | Water |
| | A. Emulsion Content: 4.5 Percent, Residual Asphalt Content: 3.0 Percent | | | | | | | | | |
| R-Value | 85.0 | 86.2 | 86.5 | 78.8 | 82.5 | 80.5 | 83.8 | 82.5 | 86.0 | 84.0 |
| C-Value | 251 | 187 | 304 | 166 | 197 | 146 | 194 | 163 | 244 | 185 |
| $R_t$-Value | 97.6 | 95.6 | 101.7 | 87.1 | 92.4 | 87.8 | 93.5 | 90.7 | 98.2 | 93.3 |
| Marshall Stability, lb | 2935 | 1287 | 3148 | 1907 | 2114 | 1388 | 2785 | 1807 | 3685 | 2302 |
| Retained Marshall Stability, % | ---- | 43.9 | ---- | 60.6 | ---- | 65.7 | ---- | 64.9 | ---- | 62.5 |
| Water Content at Testing,% | 0.28 | 7.72 | 0.33 | 7.13 | 0.51 | 7.90 | 0.45 | 7.38 | 0.39 | 6.56 |
| Water Absorption, % | ---- | 7.41 | ---- | 6.67 | ---- | 7.41 | ---- | 6.75 | ---- | 6.06 |
| Dry Density, lb/ft$^3$ | 132.4 | 131.7 | 133.1 | 133.5 | 130.6 | 131.2 | 131.9 | 132.3 | 134.0 | 134.7 |
| VMA, % | 22.46 | 22.87 | 22.03 | 21.81 | 23.47 | 23.14 | 22.70 | 22.50 | 21.45 | 21.13 |
| Total Voids, % | 16.43 | 16.88 | 15.96 | 15.73 | 17.52 | 17.16 | 16.69 | 16.48 | 15.34 | 15.00 |
| Air Voids, % | 15.86 | 1.08 | 15.27 | 0.93 | 16.48 | 1.03 | 15.76 | 1.29 | 14.53 | 1.27 |
| | B. Emulsion Content: 5.2 Percent, Residual Asphalt Content: 3.5 Percent | | | | | | | | | |
| R-Value | 87.4 | 78.0 | 86.8 | 82.5 | 82.4 | 78.6 | 84.5 | 83.0 | 84.0 | 83.3 |
| C-Value | 248 | 156 | 259 | 187 | 215 | 139 | 223 | 155 | 258 | 164 |
| $R_t$-Value | 99.8 | 85.8 | 99.8 | 91.9 | 93.2 | 85.6 | 95.7 | 90.8 | 96.9 | 91.5 |
| Marshall Stability, lb | 1902 | 1594 | 2665 | 1934 | 1946 | 1389 | 2689 | 1938 | 3574 | 2387 |
| Retained Marshall Stability, % | ---- | 83.8 | ---- | 72.6 | ---- | 71.4 | ---- | 72.1 | ---- | 66.8 |
| Water Content at Testing,% | 0.41 | 7.27 | 0.40 | 6.95 | 0.41 | 7.51 | 0.45 | 7.08 | 0.48 | 6.11 |
| Water Absorption, % | ---- | 6.82 | ---- | 6.52 | ---- | 6.99 | ---- | 6.49 | ---- | 5.57 |
| Dry Density, lb/ft$^3$ | 130.3 | 131.7 | 132.7 | 133.2 | 131.4 | 131.8 | 132.4 | 132.7 | 134.8 | 135.3 |
| VMA, % | 24.05 | 23.22 | 22.67 | 22.35 | 23.40 | 23.18 | 22.78 | 22.68 | 21.39 | 21.10 |
| Total Voids, % | 17.17 | 16.26 | 15.65 | 15.31 | 16.45 | 16.21 | 15.78 | 15.66 | 14.26 | 13.94 |
| Air Voids, % | 16.34 | 1.43 | 14.83 | 0.97 | 15.62 | 0.89 | 14.85 | 1.12 | 13.25 | 1.14 |
| | C. Emulsion Content: 6.0 Percent, Residual Asphalt Content: 4.0 Percent | | | | | | | | | |
| R-Value | 85.1 | 77.0 | 83.0 | 80.9 | 80.6 | 79.5 | 81.6 | 80.8 | 86.2 | 84.0 |
| C-Value | 207 | 144 | 226 | 166 | 175 | 151 | 212 | 147 | 245 | 231 |
| $R_t$-Value | 95.5 | 84.2 | 94.3 | 89.2 | 89.4 | 87.1 | 92.2 | 88.2 | 98.5 | 95.6 |
| Marshall Stability, lb | 2470 | 936 | 2604 | 1707 | 1750 | 1357 | 2423 | 1659 | 3349 | 2706 |
| Retained Marshall Stability, % | ---- | 37.9 | ---- | 65.6 | ---- | 77.5 | ---- | 68.5 | ---- | 80.8 |
| Water Content at Testing,% | 0.45 | 8.37 | 0.44 | 6.97 | 0.40 | 7.46 | 0.60 | 7.02 | 0.47 | 6.24 |
| Water Absorption, % | ---- | 8.05 | ---- | 6.48 | ---- | 6.92 | ---- | 6.33 | ---- | 5.53 |
| Dry Density, lb/ft$^3$ | 131.7 | 128.2 | 132.2 | 132.7 | 131.2 | 131.0 | 132.6 | 132.2 | 135.4 | 134.7 |
| VMA, % | 23.58 | 25.65 | 23.32 | 23.02 | 23.87 | 23.99 | 23.05 | 23.32 | 21.43 | 21.82 |
| Total Voids, % | 15.66 | 17.94 | 15.38 | 15.04 | 15.98 | 16.12 | 15.07 | 15.38 | 13.29 | 13.72 |
| Air Voids, % | 14.75 | 1.42 | 14.48 | 0.78 | 15.18 | 1.07 | 13.84 | 1.08 | 12.32 | 0.77 |

Curing Conditions: Cure -- One day in mold, extrusion, one day in oven at 100°F.
Water -- Identical cure as above followed by one-hour vacuum saturation, one-hour immersion.

the amount of aggregate particle crushing or degradation resulting from the compaction process. Table 14 and Figures 27 and 28 show the effects of compaction for four different emulsion-aggregate combinations and four levels of compactive effort.

It is obvious that the 40,000-lb static load of the AI method results in considerably more aggregate degradation than 75 blows of the Marshall hammer, and that the limestone aggregates degrade much more under laboratory compaction than do the gravel mixes. These results are indicative again of the need to substantially reduce the static load of the AI method in order to reduce aggregate degradation and to achieve densities comparable to those of the UI method specimens.

These results also indicate that the aggregate in laboratory-compacted specimens is degraded to a variable extent depending on binder content and aggregate type, and that this may represent an additional factor contributing to the inaccuracy of the design of emulsion mixes. Consequently, a limited study was conducted to investigate the effects of compaction as a function of binder content and aggregate type on aggregate degradation in Marshall specimens. The study involved the use of Maryland limestone combined with SS-1h emulsion. Sieve analyses were run prior to and after 50-blow compaction with the Marshall hammer. For comparison purposes, specimens were also compacted using natural Maryland gravel and sand (plus limestone filler) with SS-1h, the limestone with AC-20 (hot-mix), and the limestone and gravel/sand/limestone filler with no emulsion or asphalt cement.

The results are given in Table 15. Again, there was considerably more degradation with the limestone mixes than with the gravel mixes. When comparing 7.5 percent emulsion with 5.0 percent asphalt cement limestone specimens (approximately equal residual asphalt contents), there was considerably more degradation with the emulsion in spite of the higher fluids content. The use of 75 blows of the Marshall hammer for com-

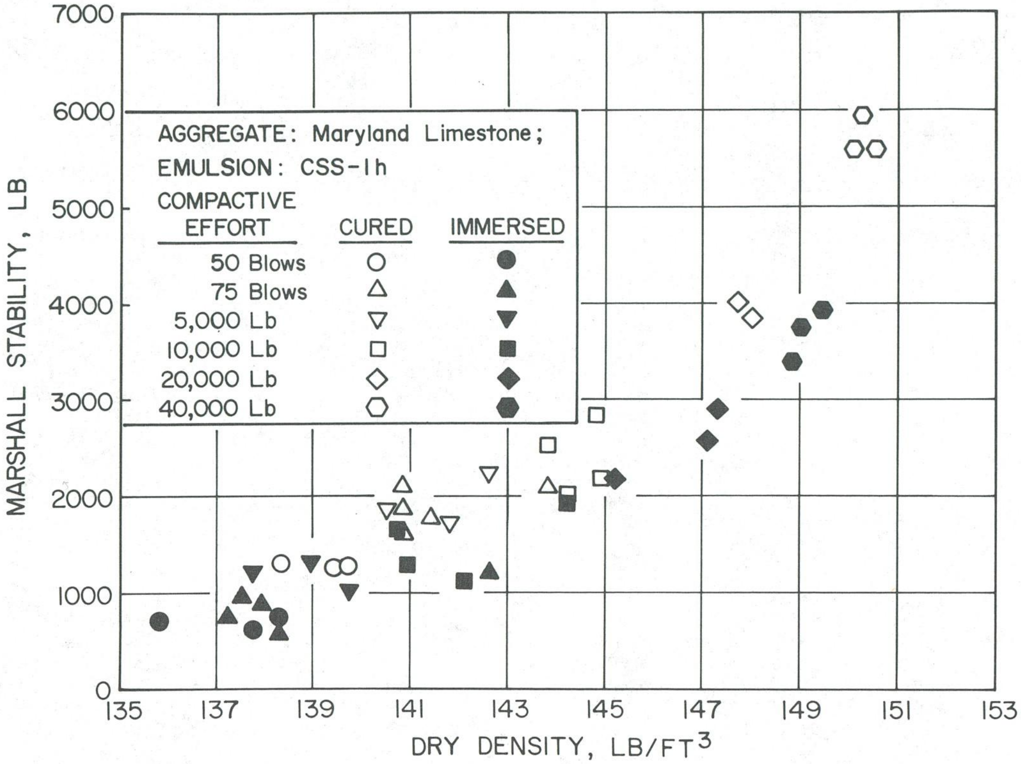

*Figure 19. Relationship between Marshall stability and dry density of limestone specimens as a function of compactive effort.*

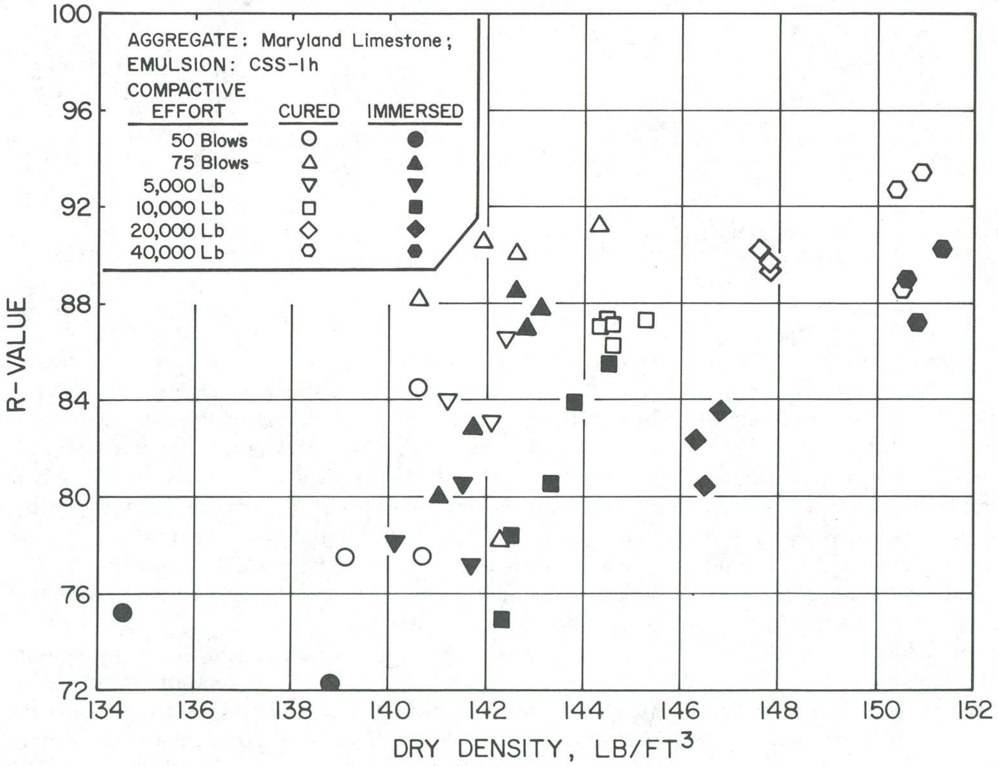

*Figure 20. Relationship between R-value and dry density of limestone specimens as a function of compactive effort.*

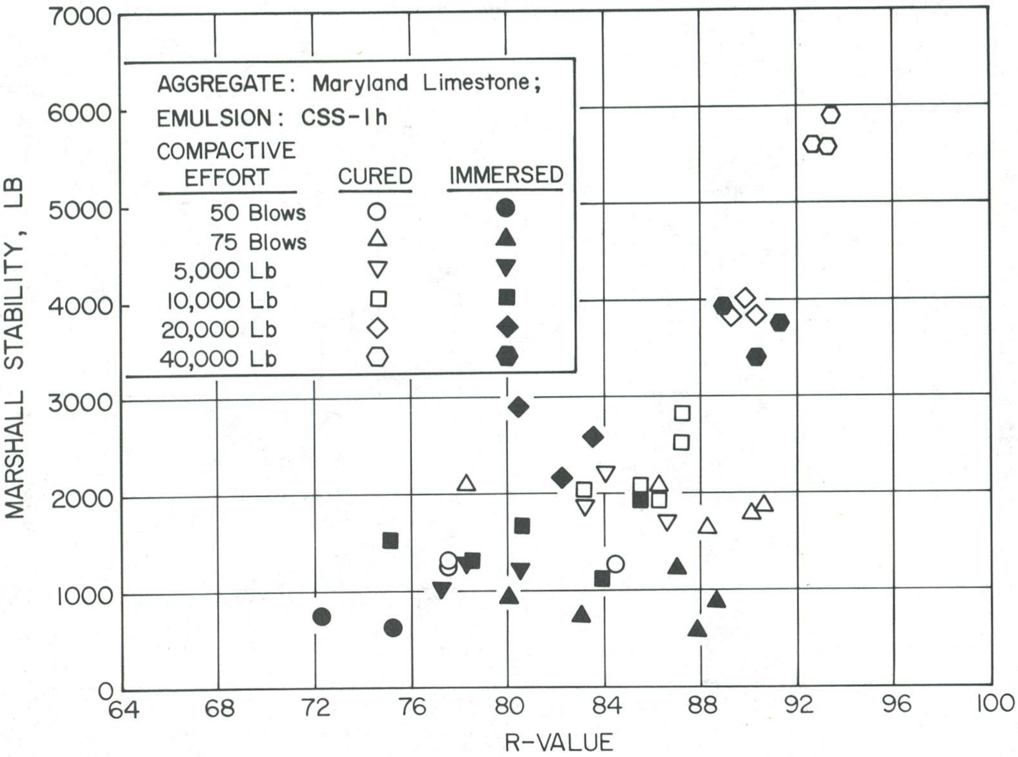

*Figure 21. Relationship between Marshall stability and R-value of limestone specimens as a function of compactive effort.*

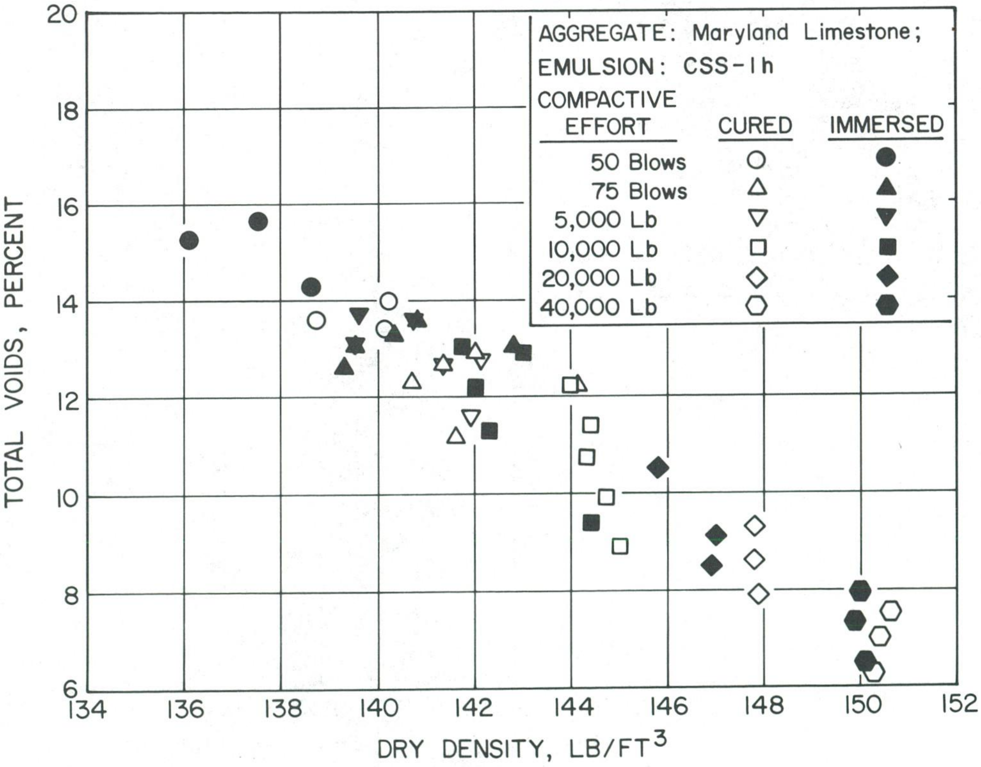

*Figure 22. Relationship between total voids and dry density of limestone specimens as a function of compactive effort.*

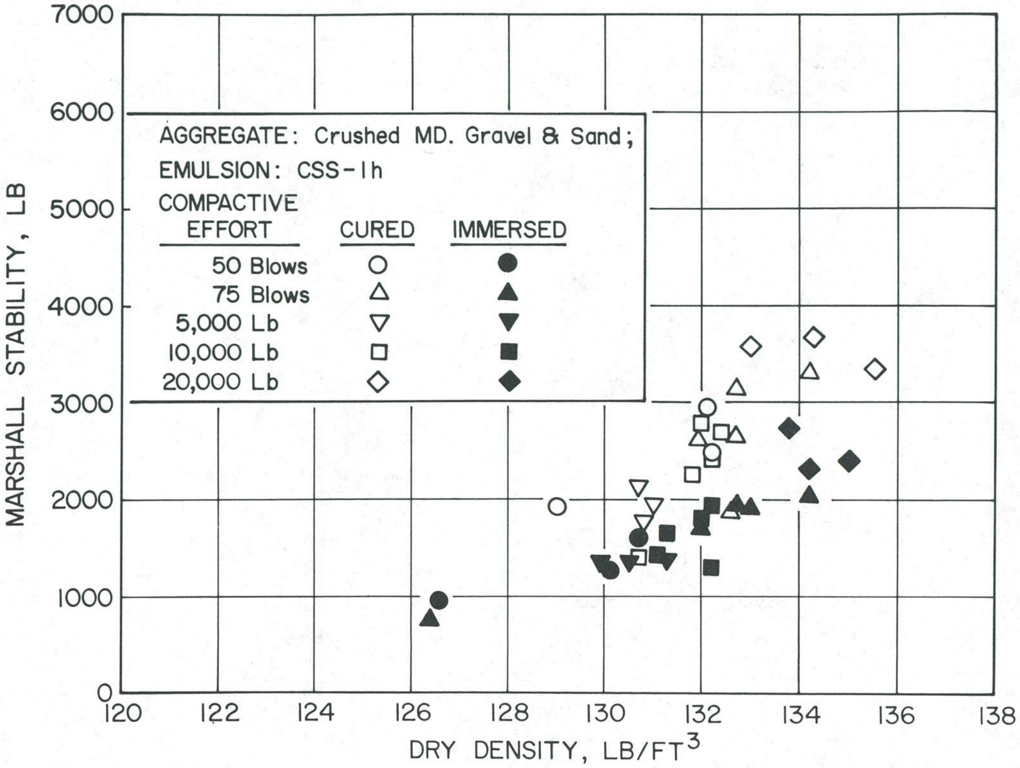

*Figure 23. Relationship between Marshall stability and dry density of gravel/sand specimens as a function of compactive effort.*

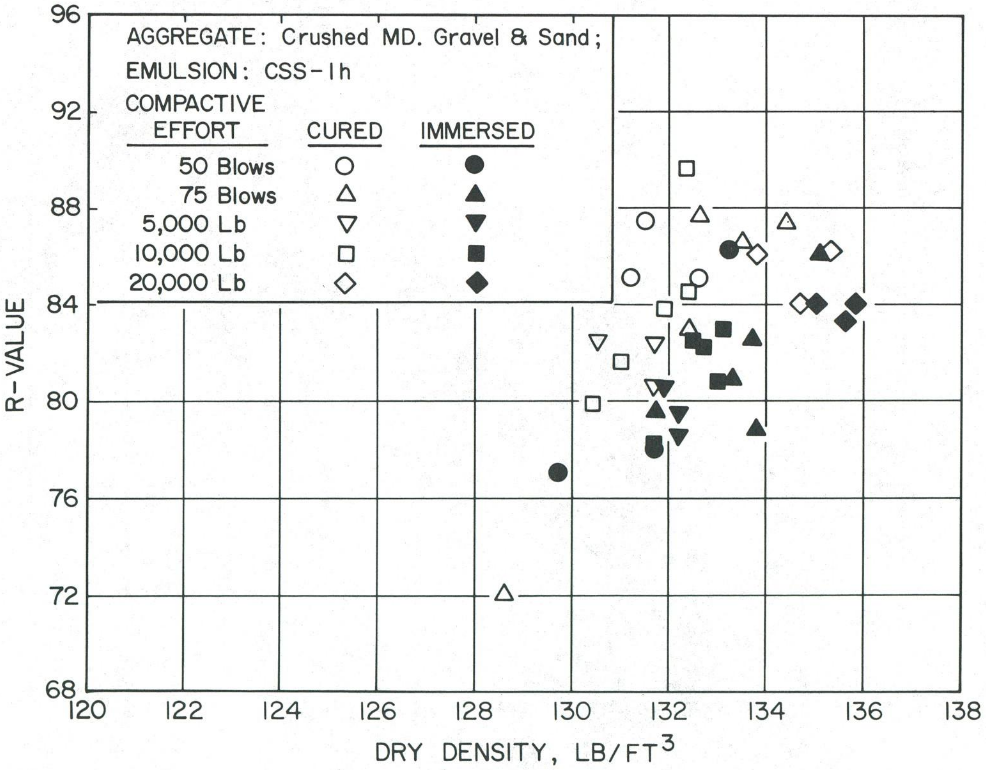

*Figure 24. Relationship between R-value and dry density of gravel/sand specimens as a function of compactive effort.*

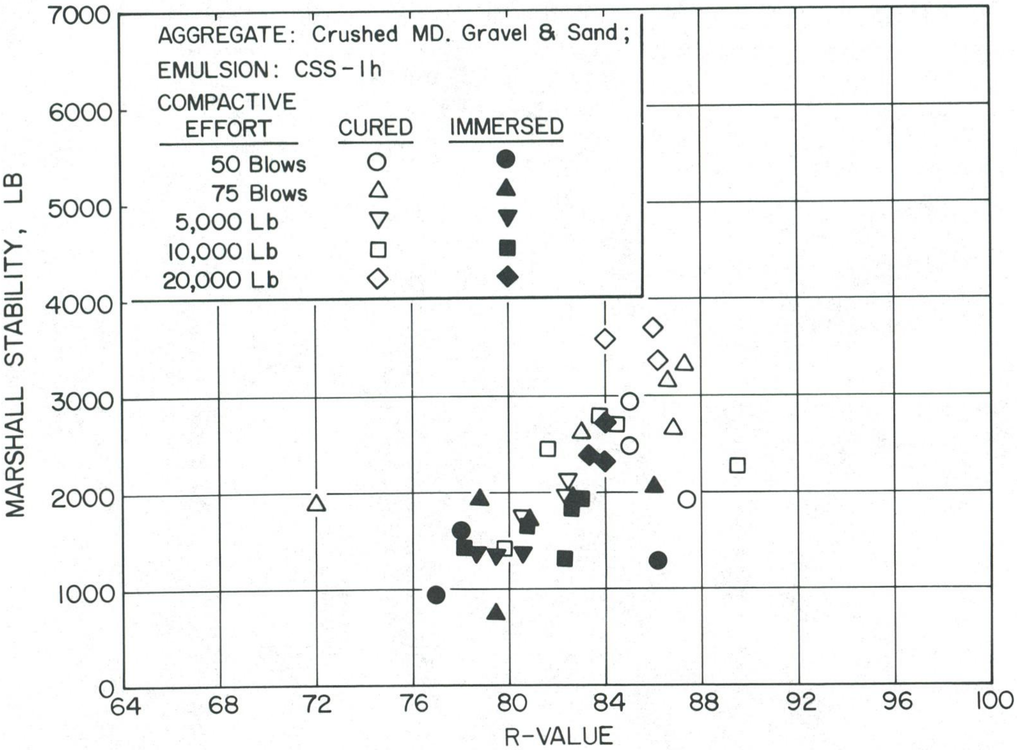

*Figure 25. Relationship between Marshall stability and R-value of gravel/sand specimens as a function of compactive effort.*

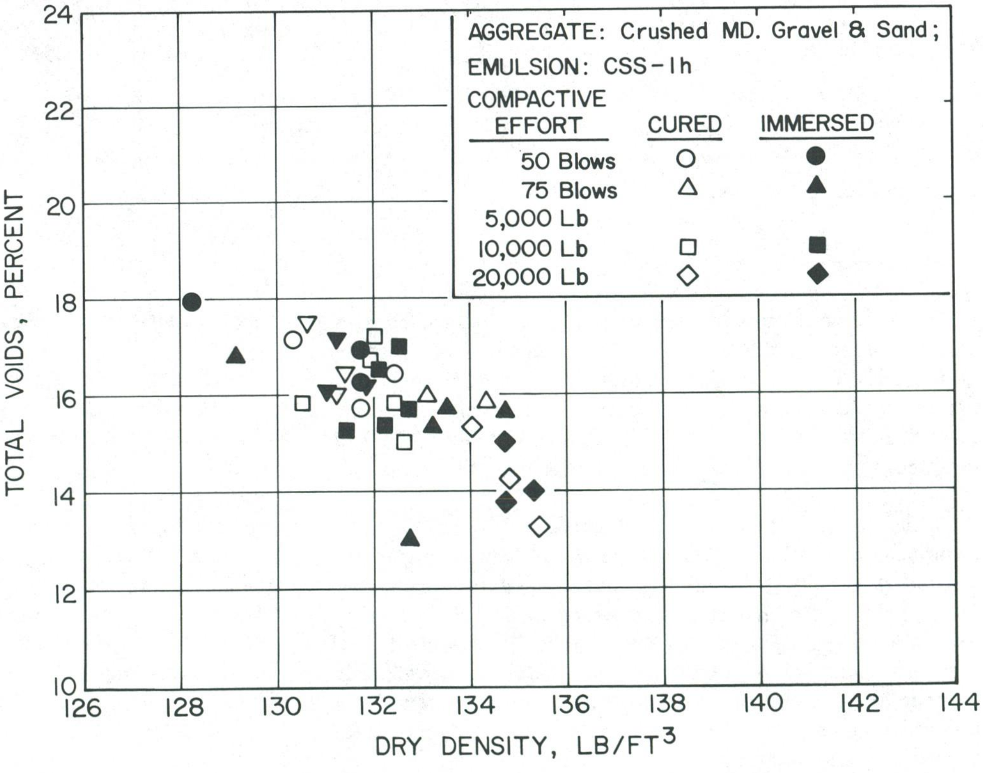

*Figure 26. Relationship between total voids and dry density of gravel/sand specimens as a function of compactive effort.*

**Table 14. Effect of compactive effort on degradation of mineral aggregates in emulsion paving mixtures.**

| AGGREGATE - EMULSION | SIEVE SIZE | ORIGINAL AGGREGATES | AFTER COMPACTION 40,000 lb Static Load | 75-Blows | 50-Blows | 35-Blows |
|---|---|---|---|---|---|---|
| | | PERCENT PASSING | | | | |
| VIRGINIA LIMESTONE | 3/4 in. | 92.1 | 95.9 | 94.4 | 93.2 | 92.0 |
| | 1/2 in. | 74.5 | 83.5 | 77.1 | 77.3 | 76.4 |
| (Coarse Gradation) | 3/8 in. | 60.2 | 73.6 | 64.7 | 63.2 | 62.0 |
| | No. 4 | 36.2 | 51.9 | 40.2 | 39.6 | 39.5 |
| EMULSION: CSS-1h | No. 8 | 24.3 | 35.1 | 27.1 | 26.2 | 26.0 |
| | No. 16 | 13.9 | 21.8 | 16.0 | 15.3 | 13.3 |
| (2.5 percent residual asphalt content) | No. 30 | 8.3 | 13.7 | 10.2 | 9.5 | 8.1 |
| | No. 50 | 5.1 | 8.6 | 6.7 | 6.2 | 5.6 |
| | No. 100 | 3.4 | 5.6 | 4.5 | 4.3 | 4.1 |
| | No. 200 | 2.3 | 3.5 | 3.3 | 2.8 | 3.0 |
| NATURAL MARYLAND GRAVEL, SAND AND LIMESTONE FILLER | 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | 1/2 in. | 94.3 | 94.5 | 94.8 | 93.1 | 95.3 |
| | 3/8 in. | 82.8 | 84.8 | 83.5 | 83.0 | 83.7 |
| | No. 4 | 53.7 | 57.9 | 54.2 | 54.3 | 54.3 |
| (Middle Gradation) | No. 8 | 39.8 | 44.4 | 41.7 | 41.0 | 40.4 |
| | No. 16 | 24.3 | 27.8 | 25.1 | 24.8 | 24.5 |
| EMULSION: CSS-1h | No. 30 | 17.1 | 19.5 | 18.1 | 18.0 | 17.3 |
| | No. 50 | 12.0 | 13.6 | 13.0 | 12.8 | 12.4 |
| (3.0 percent residual asphalt content) | No. 100 | 7.5 | 8.7 | 8.5 | 8.1 | 7.8 |
| | No. 200 | 5.1 | 6.0 | 6.2 | 5.9 | 5.4 |
| CRUSHED MARYLAND GRAVEL, SAND AND LIMESTONE FILLER | 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | 1/2 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | 3/8 in. | 95.0 | 95.2 | 94.9 | 94.8 | 95.3 |
| | No. 4 | 77.0 | 79.5 | 77.5 | 77.9 | 78.3 |
| (Fine Gradation) | No. 8 | 63.0 | 68.4 | 67.5 | 66.9 | 67.1 |
| | No. 16 | 50.0 | 53.1 | 51.5 | 51.4 | 51.5 |
| EMULSION: CSS-1h | No. 30 | 35.0 | 40.8 | 38.1 | 37.3 | 37.9 |
| | No. 50 | 23.4 | 27.2 | 25.5 | 24.6 | 26.0 |
| (3.0 percent residual asphalt content) | No. 100 | 13.1 | 15.8 | 14.4 | 13.8 | 14.7 |
| | No. 200 | 9.2 | 9.9 | 8.8 | 8.8 | 9.6 |
| MARYLAND LIMESTONE | 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | 1/2 in. | 84.9 | 91.4 | 87.3 | 88.6 | 86.1 |
| (Middle Gradation) | 3/8 in. | 70.1 | 81.2 | 73.9 | 75.0 | 73.9 |
| | No. 4 | 50.7 | 61.8 | 53.7 | 53.8 | 53.2 |
| EMULSION: AE-BM | No. 8 | 39.5 | 49.1 | 42.1 | 42.3 | 43.1 |
| | No. 16 | 27.2 | 35.6 | 30.2 | 31.4 | 31.3 |
| (3.5 percent residual asphalt content) | No. 30 | 19.0 | 26.9 | 22.5 | 24.2 | 24.0 |
| | No. 50 | 13.4 | 20.4 | 17.0 | 18.6 | 18.3 |
| | No. 100 | 9.3 | 15.1 | 12.7 | 13.9 | 13.6 |
| | No. 200 | 6.9 | 11.5 | 9.9 | 10.8 | 10.6 |

paction of hot-mix asphalt concrete specimens is associated with "heavy" design traffic loads (*23*). The data in Table 15 show that the use of 50 blows ("medium" traffic loads) results in greater degradation when using emulsion than when using asphalt cement. For these reasons, a reduction of from 75 to 50 blows for compacting EAMs with the Marshall hammer is recommended.

To determine if the amount of aggregate degradation varies significantly with the incremental increases in emulsion content associated with the strength test phase of a mix design, an additional series of limestone specimens was fabricated using emulsion contents that varied from 5.0 to 7.5 percent in 0.5 percent increments. As Table 16 shows, there was considerable degradation in all cases, but there was no definite trend with regard to emulsion content which indicates that the aggregate type is the primary factor.

The relationship of laboratory to field compaction is discussed in the field project evaluation section of this report.

### Design of Mixtures by Revised Design Methods

Based on the investigation of modifications to the reference design methods, numerous mix designs were run incorporating the recommended changes with regard to trial mixture composition, curing-water exposure procedures, and level of compactive effort. The results for the strength test phase of these mix designs, which included designs for three of the field verification projects, are shown in Tables 17 and 18 and in Figures 29 through 44. The curing procedure for all mixes was 1 day in the mold at room temperature plus 1 day out of the mold in an oven at 100°F. The water exposure procedure was the 2-hour vacuum-saturation procedure of the AI method. Compactive efforts were either 50 or 75 blows of the Marshall hammer or double-plunger static loads of 5,000 or 10,000 lb. Water contents at compaction were kept constant for all mixes except in the case where no mixing water was added, i.e., only emulsion was added to the aggregate. The initial trial emulsion contents for

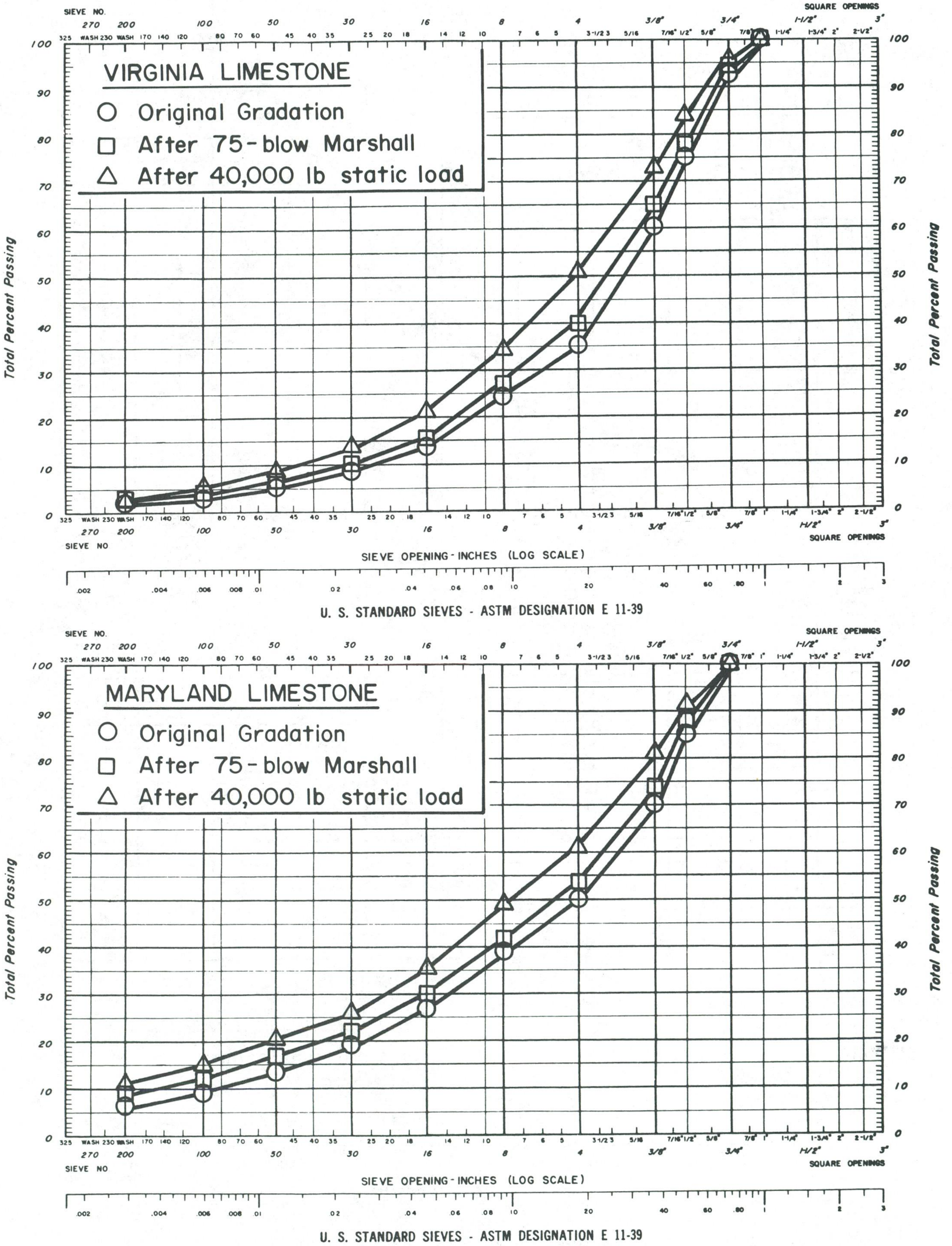

*Figure 27. Effect of compaction on degradation of aggregate in limestone mixtures.*

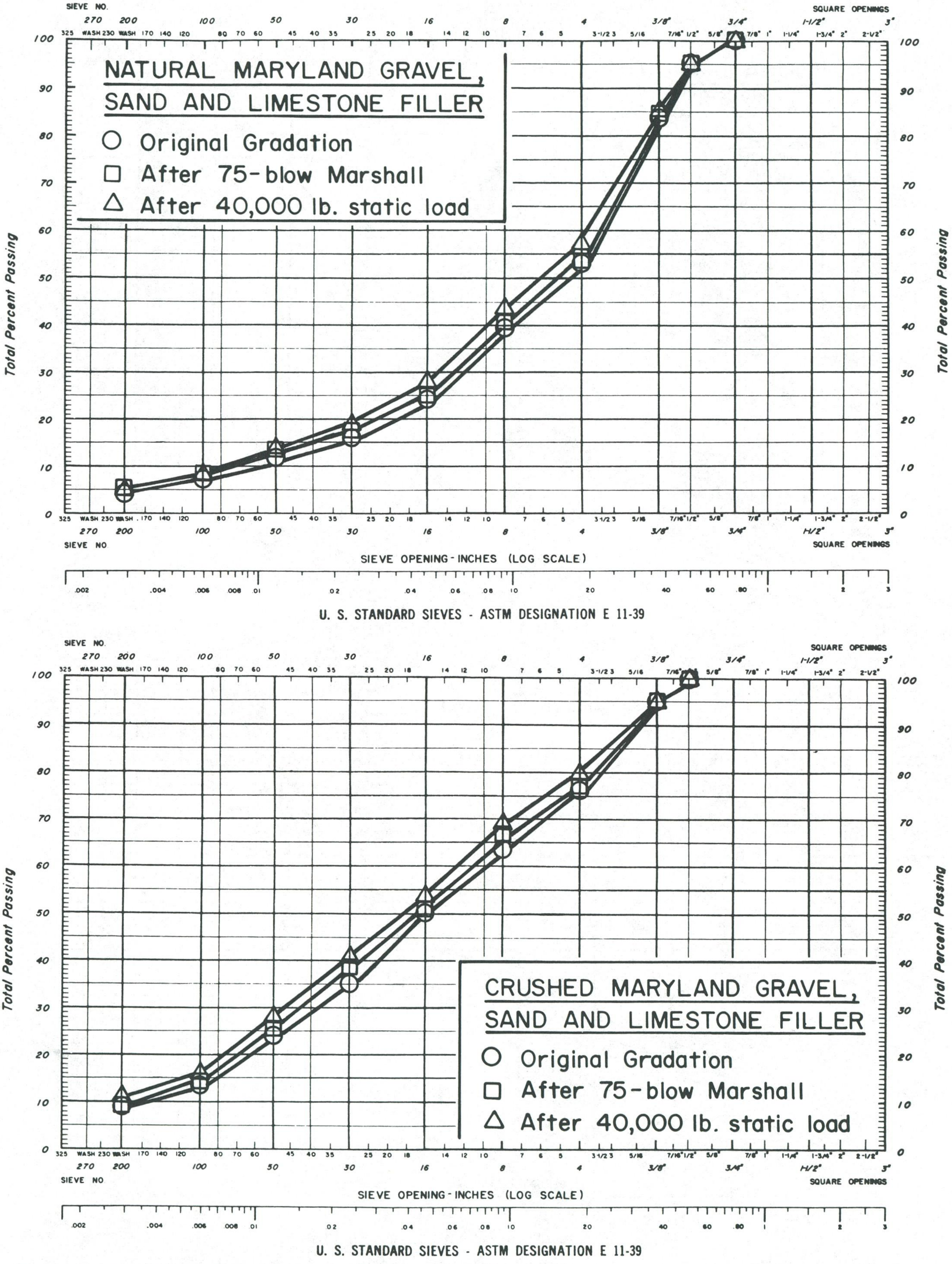

*Figure 28. Effect of compaction on degradation of aggregate in gravel mixtures.*

Table 15. Effect of binder content and aggregate type on aggregate fracture during Marshall compaction.

Compactive Effort: 50-Blow Marshall Hammer

| AGGREGATE | TYPE OF ASPHALT BINDER | BINDER CONTENT, Percent | AGGREGATE GRADATION-PERCENT PASSING | | |
|---|---|---|---|---|---|
| | | | SIEVE SIZE | BEFORE COMPACTION | AFTER COMPACTION |
| MARYLAND LIMESTONE | SS-1h | 0.0 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 85.8 | 90.3 |
| | | | 3/8 in. | 70.2 | 77.8 |
| | | | No. 4 | 50.5 | 57.4 |
| | | | No. 8 | 37.9 | 43.7 |
| | | 5.0 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 86.1 | 87.9 |
| | | | 3/8 in. | 70.4 | 74.4 |
| | | | No. 4 | 50.5 | 54.4 |
| | | | No. 8 | 38.4 | 42.0 |
| | | 7.5 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 85.2 | 88.4 |
| | | | 3/8 in. | 70.2 | 75.7 |
| | | | No. 4 | 50.5 | 54.4 |
| | | | No. 8 | 38.2 | 41.1 |
| | AC-20 | 5.0 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 85.2 | 88.3 |
| | | | 3/8 in. | 70.5 | 74.3 |
| | | | No. 4 | 51.1 | 53.3 |
| | | | No. 8 | 38.3 | 40.2 |
| NATURAL MARYLAND GRAVEL, SAND AND LIMESTONE FILLER | SS-1h | 0.0 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 96.1 | 96.5 |
| | | | 3/8 in. | 83.3 | 84.4 |
| | | | No. 4 | 53.6 | 55.5 |
| | | | No. 8 | 38.2 | 40.5 |
| | | 5.0 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 94.8 | 94.8 |
| | | | 3/8 in. | 83.0 | 83.4 |
| | | | No. 4 | 53.9 | 54.1 |
| | | | No. 8 | 38.4 | 38.6 |
| | | 7.5 | 3/4 in. | 100.0 | 100.0 |
| | | | 1/2 in. | 94.6 | 94.9 |
| | | | 3/8 in. | 83.7 | 83.9 |
| | | | No. 4 | 53.9 | 54.0 |
| | | | No. 8 | 38.4 | 38.5 |

Table 16. Effect of emulsion content on aggregate fracture of limestone specimens during Marshall compaction.

EMULSION: SS-1h AGGREGATE: Maryland limestone

COMPACTIVE EFFORT: 50-Blow Marshall Hammer

| SPECIMEN NUMBER: | 1 | 2 | 3 | 4 | 5 | 6 | AVERAGE OF FIVE UNCOMPACTED AGGREGATE SAMPLES |
|---|---|---|---|---|---|---|---|
| EMULSION CONTENT,% | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | |
| SIEVE SIZE | | | | | | | |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 88.9 | 88.1 | 90.5 | 90.1 | 88.1 | 89.8 | 85.4 |
| 3/8 in. | 75.6 | 76.5 | 75.9 | 77.0 | 75.3 | 76.3 | 70.3 |
| No. 4 | 57.3 | 58.6 | 56.9 | 56.0 | 54.2 | 56.2 | 50.7 |
| No. 8 | 43.3 | 41.2 | 41.2 | 41.3 | 39.4 | 41.6 | 38.1 |

Table 17. Design of emulsion paving mixtures by revised method using Marshall equipment.

| MINERAL AGGREGATE EMULSION COMPACTIVE EFFORT | MIXTURE COMPOSITION | | | | PROPERTIES OF CURED SPECIMENS | | | | | | PROPERTIES OF IMMERSED SPECIMENS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EMUL. CONT. % | RESID. ASPH. % | FLUID CONT. % | WATER CONT. % | DRY DENS. lb/ft³ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | MARSHALL STAB. lb | DRY DENS. lb/ft³ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | MARSHALL STAB. lb | RET. STAB. % | WATER ABSORP. % |
| MARYLAND LIMESTONE (MIDDLE GRADATION)<br>EMULSION: SS-1h<br>75 BLOWS | 3.5 | 2.2 | 7.2 | 5.0 | 144.8 | 17.1 | 12.2 | 11.8 | 0.2 | 5780 | 145.7 | 16.6 | 11.7 | 1.4 | 4.5 | 5095 | 88.1 | 4.5 |
| | 5.1 | 3.2 | 8.3 | 5.0 | 143.0 | 18.9 | 12.1 | 11.5 | 0.3 | 4808 | 144.5 | 18.0 | 11.1 | 0.9 | 4.5 | 3910 | 81.3 | 4.2 |
| | 6.7 | 4.2 | 9.3 | 5.0 | 143.8 | 19.2 | 10.3 | 9.4 | 0.4 | 3672 | 144.3 | 18.9 | 9.9 | 0.8 | 4.1 | 3108 | 84.6 | 3.7 |
| | 8.3 | 5.2 | 10.3 | 5.0 | 141.1 | 21.5 | 10.7 | 9.6 | 0.5 | 2434 | 142.3 | 20.8 | 10.0 | 0.8 | 4.3 | 2244 | 92.2 | 3.7 |
| | 9.9 | 6.2 | 11.3 | 5.0 | 139.6 | 23.1 | 10.5 | 8.7 | 0.8 | 1897 | 140.3 | 22.7 | 10.0 | 0.6 | 4.4 | 1452 | 76.5 | 3.7 |
| CRUSHED MD. GRAVEL, SAND AND LIMESTONE FILLER<br>EMULSION: SS-1h<br>75 BLOWS | 4.2 | 2.6 | 6.9 | 4.2 | 134.0 | 21.2 | 15.9 | 14.8 | 0.5 | 3579 | 135.0 | 20.6 | 15.3 | 1.3 | 6.7 | 1929 | 53.9 | 6.0 |
| | 5.8 | 3.6 | 7.9 | 4.2 | 133.2 | 22.4 | 15.2 | 13.7 | 0.7 | 2536 | 133.5 | 22.3 | 15.0 | 1.0 | 6.8 | 1312 | 51.7 | 6.0 |
| | 7.4 | 4.6 | 8.9 | 4.2 | 133.6 | 23.0 | 13.8 | 11.2 | 1.3 | 2035 | 132.5 | 23.6 | 14.5 | 0.5 | 6.9 | 899 | 44.2 | 5.6 |
| | 9.0 | 5.6 | 10.0 | 4.2 | 131.6 | 24.8 | 14.0 | 11.5 | 1.3 | 1468 | 131.5 | 24.9 | 14.0 | 0.8 | 6.6 | 686 | 46.7 | 5.4 |
| | 10.6 | 6.6 | 11.0 | 4.2 | 132.4 | 25.1 | 12.4 | 9.6 | 1.4 | 1209 | 128.0 | 27.5 | 15.2 | 0.6 | 7.6 | 380 | 31.4 | 6.0 |
| VA NO. 78 GRANITE (COARSE GRADATION)<br>EMULSION: CMS-2<br>50 BLOWS | 2.4 | 1.6 | 2.6 | 0.9 | 140.0 | 18.5 | 15.1 | 14.7 | 0.2 | 1023 | 137.6 | 19.9 | 16.5 | 2.7 | 6.3 | 1022 | 99.9 | 5.8 |
| | 4.0 | 2.6 | 4.1 | 1.3 | 139.2 | 19.7 | 14.2 | 13.7 | 0.2 | 1187 | 138.2 | 20.3 | 14.8 | 3.3 | 5.3 | 1243 | 104.7 | 4.9 |
| | 5.5 | 3.6 | 5.6 | 1.7 | 137.5 | 21.5 | 13.9 | 13.1 | 0.4 | 1170 | 136.1 | 23.1 | 13.6 | 3.4 | 4.9 | 1042 | 94.6 | 4.0 |
| | 7.0 | 4.6 | 7.2 | 2.2 | 136.5 | 22.8 | 13.3 | 11.7 | 0.8 | 1101 | 136.1 | 23.1 | 13.6 | 3.4 | 4.9 | 1042 | 94.6 | 4.0 |
| | 8.5 | 5.6 | 8.7 | 2.6 | 135.6 | 24.1 | 12.7 | 10.5 | 1.1 | 876 | 134.0 | 25.0 | 13.7 | 3.7 | 4.9 | 822 | 93.8 | 3.7 |
| VA NO. 8 GRANITE AND SAND (MIDDLE GRADATION)<br>EMULSION: CMS-2<br>50 BLOWS | 2.3 | 1.5 | 3.8 | 2.2 | 131.5 | 22.4 | 19.3 | 18.9 | 0.2 | 1328 | 134.5 | 20.6 | 17.5 | 1.2 | 7.7 | 1194 | 89.9 | 7.0 |
| | 3.8 | 2.5 | 4.9 | 2.2 | 132.6 | 22.5 | 17.4 | 17.0 | 0.2 | 1008 | 133.4 | 22.1 | 16.9 | 1.1 | 7.6 | 1099 | 109.0 | 7.2 |
| | 5.3 | 3.5 | 6.0 | 2.2 | 132.4 | 23.4 | 16.4 | 15.8 | 0.3 | 861 | 135.1 | 21.8 | 14.6 | 0.7 | 6.6 | 950 | 110.3 | 6.3 |
| | 6.9 | 4.5 | 7.1 | 2.2 | 131.2 | 24.7 | 15.8 | 13.9 | 0.9 | 680 | 132.8 | 23.9 | 14.9 | 2.0 | 6.3 | 787 | 115.7 | 5.5 |
| ARKANSAS GRAVEL AND SAND (MIDDLE GRADATION)<br>EMULSION: MS-2M<br>50 BLOWS | 3.7 | 2.5 | 5.5 | 2.9 | 134.0 | 20.9 | 15.8 | 15.4 | 0.2 | 2163 | 133.4 | 21.3 | 16.2 | 0.5 | 7.5 | 688 | 31.8 | 7.3 |
| | 5.2 | 3.5 | 6.5 | 2.9 | 136.7 | 20.1 | 12.9 | 12.2 | 0.3 | 2284 | 137.0 | 19.9 | 12.7 | 1.3 | 5.4 | 1038 | 45.4 | 4.9 |
| | 6.7 | 4.5 | 7.6 | 2.9 | 138.7 | 19.7 | 10.4 | 9.3 | 0.5 | 2365 | 138.2 | 20.0 | 10.7 | 1.2 | 4.5 | 880 | 37.2 | 3.9 |
| | 8.2 | 5.5 | 8.6 | 2.9 | 137.8 | 21.0 | 9.8 | 8.4 | 0.7 | 1587 | 134.7 | 22.8 | 11.8 | 1.0 | 5.3 | 525 | 33.1 | 4.6 |
| AR GRAVEL-SAND AND IND. FINES (MIDDLE GRADATION)<br>EMULSION: MS-2M<br>50 BLOWS | 3.7 | 2.5 | 8.2 | 5.6 | 132.2 | 23.5 | 18.5 | 16.9 | 0.8 | 2698 | 132.8 | 23.1 | 18.0 | 0.9 | 8.2 | 1083 | 40.1 | 7.4 |
| | 5.2 | 3.5 | 9.2 | 5.6 | 135.1 | 22.6 | 15.5 | 13.1 | 1.2 | 2606 | 131.1 | 24.9 | 17.9 | 0.6 | 8.5 | 615 | 23.6 | 7.2 |
| | 6.7 | 4.5 | 10.2 | 5.6 | 136.7 | 22.4 | 13.2 | 10.0 | 1.5 | 2383 | 134.7 | 23.6 | 14.5 | 0.4 | 6.8 | 955 | 40.1 | 5.2 |
| | 8.2 | 5.5 | 11.3 | 5.6 | 136.0 | 23.5 | 12.5 | 8.8 | 1.8 | 1937 | 134.3 | 24.4 | 13.5 | 0.2 | 6.5 | 679 | 35.0 | 4.6 |
| ARKANSAS GRAVEL AND SAND (MIDDLE GRADATION)<br>EMULSION: CSS-1<br>50 BLOWS | 4.0 | 2.5 | 5.9 | 3.4 | 132.2 | 22.0 | 17.0 | 16.8 | 0.1 | 1936 | 132.4 | 21.9 | 16.9 | 0.5 | 7.9 | 1685 | 87.0 | 7.4 |
| | 5.6 | 3.5 | 7.0 | 3.4 | 130.9 | 23.5 | 16.7 | 16.5 | 0.1 | 1455 | 130.8 | 23.6 | 16.7 | 0.7 | 7.9 | 1666 | 114.5 | 7.6 |
| | 7.2 | 4.5 | 8.0 | 3.4 | 130.5 | 24.4 | 15.7 | 15.5 | 0.1 | 1351 | 129.9 | 24.8 | 16.0 | 0.8 | 7.6 | 1406 | 104.1 | 7.5 |
| | 8.8 | 5.5 | 9.0 | 3.4 | 129.6 | 25.7 | 15.2 | 14.9 | 0.2 | 1172 | 130.2 | 25.3 | 14.7 | 0.8 | 7.0 | 1355 | 115.6 | 6.8 |
| AR GRAVEL-SAND AND IND. FINES (MIDDLE GRADATION)<br>EMULSION: CSS-1<br>50 BLOWS | 4.0 | 2.5 | 8.7 | 6.1 | 130.5 | 24.5 | 19.5 | 18.1 | 0.7 | 2514 | 131.1 | 24.1 | 19.1 | 1.0 | 8.8 | 2070 | 82.3 | 8.1 |
| | 5.6 | 3.5 | 9.7 | 6.1 | 129.4 | 25.8 | 19.0 | 17.3 | 0.8 | 2164 | 129.7 | 25.7 | 18.8 | 0.9 | 8.9 | 1986 | 91.8 | 8.1 |
| | 7.2 | 4.5 | 10.7 | 6.1 | 128.7 | 26.9 | 18.3 | 16.4 | 1.0 | 2186 | 129.5 | 26.5 | 17.8 | 1.0 | 8.5 | 2018 | 92.3 | 7.5 |
| | 8.8 | 5.5 | 11.8 | 6.1 | 127.7 | 28.2 | 17.8 | 15.6 | 1.1 | 1647 | 128.0 | 28.0 | 17.6 | 1.0 | 8.5 | 1720 | 104.4 | 7.3 |
| NEW YORK LIMESTONE (MIDDLE GRADATION)<br>EMULSION: HFMS-2Gh<br>50 BLOWS | 3.2 | 2.2 | 3.2 | 0.8 | 136.5 | 21.2 | 16.6 | 16.3 | 0.2 | 1689 | 138.0 | 20.3 | 15.6 | 2.4 | 6.1 | 1656 | 98.0 | 5.9 |
| | 4.7 | 3.2 | 4.7 | 1.1 | 137.9 | 21.1 | 14.4 | 13.4 | 0.5 | 1633 | 137.7 | 21.2 | 14.6 | 2.9 | 5.4 | 1527 | 93.5 | 4.9 |
| | 6.2 | 4.2 | 6.2 | 1.5 | 137.7 | 22.0 | 13.3 | 11.1 | 1.1 | 1135 | 136.5 | 22.7 | 14.1 | 3.6 | 5.0 | 1070 | 94.3 | 3.8 |
| | 7.6 | 5.2 | 7.6 | 1.8 | 138.7 | 22.2 | 11.5 | 8.0 | 1.7 | 1071 | 135.5 | 23.9 | 13.5 | 3.2 | 5.0 | 687 | 64.1 | 3.3 |
| NEW YORK GRAVEL/ LIMESTONE (MIDDLE GRADATION)<br>EMULSION: HFMS-2Gh<br>50 BLOWS | 4.4 | 3.0 | 4.4 | 1.1 | 127.8 | 26.6 | 23.1 | 22.5 | 0.3 | 1637 | 128.9 | 26.0 | 22.6 | 6.4 | 8.1 | 1702 | 104.0 | 7.8 |
| | 5.9 | 4.0 | 5.9 | 1.4 | 129.4 | 26.4 | 18.6 | 17.4 | 0.6 | 1652 | 127.9 | 27.3 | 19.6 | 5.3 | 7.3 | 1431 | 86.6 | 6.6 |
| | 7.3 | 5.0 | 7.3 | 1.8 | 129.8 | 26.9 | 17.2 | 15.0 | 1.1 | 1401 | 130.7 | 26.4 | 16.6 | 4.0 | 6.3 | 1424 | 101.6 | 5.4 |
| | 8.8 | 6.0 | 8.8 | 2.1 | 130.2 | 27.4 | 15.8 | 12.4 | 1.7 | 1122 | 127.9 | 28.6 | 17.3 | 3.3 | 7.2 | 914 | 81.5 | 5.6 |

**Table 18. Design of emulsion paving mixtures by revised method using Hveem equipment.**

| | MIXTURE COMPOSITION | | | | PROPERTIES OF EARLY CURE SPECIMENS | | | | | | | PROPERTIES OF VACUUM SATURATED SPECIMENS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AGGREGATE/EMULSION | EMUL. CONT. % | RESID. ASPH. % | FLUID CONT. % | WATER CONT. % | DRY B.S.G. lb/ft$^3$ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | $R_t$ VALUE | C VALUE | DRY B.S.G. lb/ft$^3$ | VMA % | TOTAL VOIDS % | AIR VOIDS % | WATER CONT. % | $R_t$ VALUE | C VALUE | WATER ABSORP. % |
| MARYLAND LIMESTONE | 3.5 | 2.2 | 7.2 | 5.0 | 145.5 | 16.7 | 11.9 | 9.2 | 1.2 | 102.5 | 281 | 147.1 | 15.7 | 10.8 | 1.3 | 4.1 | 109.7 | 367 | 3.9 |
| (MIDDLE GRADATION) | 5.1 | 3.2 | 8.3 | 5.0 | 144.4 | 17.2 | 10.2 | 7.4 | 1.2 | 98.5 | 255 | 147.4 | 16.4 | 9.3 | 0.9 | 3.7 | 101.9 | 238 | 3.4 |
| EMULSION: SS-1h | 6.7 | 4.2 | 9.3 | 5.0 | 146.3 | 17.8 | 8.7 | 5.3 | 1.5 | 93.0 | 182 | 147.8 | 17.0 | 7.7 | 0.4 | 3.2 | 101.2 | 274 | 2.8 |
| 10,000 lb Double- | 8.3 | 5.2 | 10.3 | 5.0 | 143.8 | 20.0 | 9.0 | 4.5 | 2.1 | 85.4 | 155 | 146.1 | 18.7 | 7.5 | 0.8 | 3.0 | 92.9 | 218 | 2.4 |
| Plunger Static Load | 9.9 | 6.2 | 11.3 | 5.0 | 142.1 | 21.7 | 8.8 | 3.4 | 2.5 | 79.7 | 130 | 144.4 | 20.4 | 7.4 | 0.9 | 3.0 | 83.9 | 163 | 2.1 |
| VA NO.8 GRANITE/SAND | 2.3 | 1.5 | 3.8 | 2.2 | 130.2 | 23.2 | 20.2 | 17.8 | 1.1 | 78.0 | 19 | 133.1 | 21.5 | 18.4 | 3.2 | 7.2 | --- | --- | 6.4 |
| (MIDDLE GRADATION) | 3.8 | 2.5 | 4.9 | 2.2 | 130.7 | 23.7 | 18.6 | 16.3 | 1.1 | 78.9 | 29 | 132.9 | 22.3 | 17.2 | 1.9 | 7.4 | 82.4 | 85 | 7.1 |
| EMULSION: CMS-2 | 5.3 | 3.5 | 6.0 | 2.2 | 132.5 | 23.3 | 16.2 | 13.3 | 1.4 | 82.4 | 48 | 135.8 | 21.5 | 14.2 | 2.1 | 5.7 | 84.4 | 92 | 5.3 |
| 5,000 lb Double- | 6.9 | 4.5 | 7.1 | 2.2 | 133.0 | 23.8 | 14.8 | 11.9 | 1.4 | 83.1 | 63 | 134.5 | 22.9 | 13.8 | 1.7 | 5.9 | 82.7 | 104 | 4.9 |
| Plunger Static Load | | | | | | | | | | | | | | | | | | | |
| ARKANSAS GRAVEL/SAND | 3.7 | 2.5 | 5.5 | 2.9 | --- | --- | --- | --- | --- | --- | --- | 129.3 | 23.7 | 18.8 | 3.4 | 7.6 | 76.4 | 27 | 6.0 |
| (MIDDLE GRADATION) | 5.2 | 3.5 | 6.5 | 2.9 | 135.3 | 20.9 | 13.8 | 10.0 | 1.8 | 83.2 | 51 | 136.1 | 20.5 | 13.3 | 0.7 | 6.0 | 83.6 | 54 | 4.9 |
| EMULSION: MS-2M | 6.7 | 4.5 | 7.6 | 2.9 | 136.9 | 20.8 | 11.6 | 7.7 | 1.9 | 85.6 | 107 | 135.0 | 21.9 | 12.8 | 1.0 | 5.8 | 82.7 | 36 | 5.1 |
| 5,000 lb Double- | 8.2 | 5.5 | 8.6 | 2.9 | 136.5 | 21.8 | 10.7 | 6.6 | 2.0 | 87.0 | 100 | 134.8 | 22.7 | 11.7 | 0.6 | 5.6 | 79.7 | 42 | 4.9 |
| Plunger Static Load | | | | | | | | | | | | | | | | | | | |
| ARKANSAS GRAVEL/SAND | 4.0 | 2.5 | 5.9 | 3.4 | 130.6 | 22.9 | 17.9 | 14.1 | 1.8 | 80.5 | 48 | 131.5 | 22.4 | 17.4 | 0.6 | 7.7 | 87.4 | 113 | 7.7 |
| (MIDDLE GRADATION) | 5.6 | 3.5 | 7.0 | 3.4 | 131.5 | 23.1 | 16.2 | 13.4 | 1.4 | 82.5 | 61 | 132.5 | 22.6 | 15.6 | 0.5 | 7.1 | 90.1 | 152 | 7.1 |
| EMULSION: CSS-1 | 7.2 | 4.5 | 8.0 | 3.4 | 132.4 | 23.4 | 14.5 | 11.5 | 1.5 | 82.2 | 67 | 132.2 | 23.5 | 14.6 | 0.5 | 7.0 | 89.5 | 159 | 6.7 |
| 5,000 lb Double | 8.8 | 5.5 | 9.0 | 3.4 | 133.2 | 23.6 | 12.8 | 9.9 | 1.4 | 84.0 | 93 | 133.9 | 23.2 | 12.3 | 0.3 | 5.9 | 88.3 | 137 | 5.5 |
| Plunger Static Load | | | | | | | | | | | | | | | | | | | |
| NEW YORK LIMESTONE | 3.2 | 2.2 | 3.2 | 0.8 | 139.2 | 19.6 | 14.9 | 13.5 | 0.7 | 91.4 | 131 | 137.8 | 20.4 | 15.8 | 2.0 | 6.4 | 94.0 | 162 | 6.1 |
| (MIDDLE GRADATION) | 4.7 | 3.2 | 4.7 | 1.1 | 140.2 | 19.8 | 13.0 | 10.7 | 1.1 | 91.5 | 111 | 139.5 | 20.2 | 13.5 | 2.3 | 5.1 | 91.9 | 125 | 4.5 |
| EMULSION: HFMS-2Gh | 6.2 | 4.2 | 6.2 | 1.5 | 139.8 | 20.8 | 12.0 | 9.0 | 1.4 | 90.5 | 100 | 138.1 | 21.8 | 13.1 | 3.0 | 4.7 | 90.5 | 141 | 3.8 |
| 10,000 lb Double- | 7.6 | 5.2 | 7.6 | 1.8 | 141.0 | 20.9 | 10.0 | 5.5 | 2.1 | 91.8 | 109 | 136.7 | 23.3 | 12.7 | 2.6 | 4.9 | 88.8 | 141 | 3.4 |
| Plunger Static Load | | | | | | | | | | | | | | | | | | | |
| NEW YORK GRAVEL/ | 4.4 | 3.0 | 4.4 | 1.1 | 132.0 | 24.2 | 18.2 | 16.1 | 1.0 | 89.2 | 112 | 132.3 | 24.0 | 18.0 | 2.9 | 7.3 | 93.3 | 197 | 7.0 |
| LIMESTONE | 5.9 | 4.0 | 5.9 | 1.4 | 133.0 | 24.4 | 16.4 | 13.5 | 1.4 | 89.4 | 127 | 130.4 | 25.8 | 18.0 | 3.8 | 7.0 | 92.2 | 180 | 6.5 |
| (MIDDLE GRADATION) | 7.3 | 5.0 | 7.3 | 1.8 | 132.2 | 25.5 | 15.7 | 12.0 | 1.8 | 87.2 | 96 | 133.0 | 25.1 | 15.2 | 3.7 | 5.7 | 89.3 | 182 | 4.5 |
| EMULSION: HGMS-2Gh | 8.8 | 6.0 | 8.8 | 2.1 | 134.6 | 24.9 | 13.0 | 8.2 | 2.3 | 88.0 | 117 | 132.4 | 26.2 | 14.4 | 2.5 | 5.9 | 85.6 | 137 | 4.2 |
| 10,000 lb Double- | | | | | | | | | | | | | | | | | | | |
| Plunger Static Load | | | | | | | | | | | | | | | | | | | |

the coating and compaction tests were derived using the CKE oil ratio method and, in most instances, four residual asphalt contents (in increments of 1 percent) were investigated in the strength test phase.

As the data in Table 17 (Marshall equipment) indicate, there are few peaks in Marshall stability for immersed specimens. Instead, there is usually a decrease in stability with increasing residual asphalt content for both cured and immersed specimens. However, in certain instances there are peaks with regard to percent retained stability which may be a better indicator of water susceptibility than the stability itself. There is no particular pattern for dry densities—some decreasing with increases in residual asphalt content, some steadily increasing, and others showing peaks. The percentage of total voids varies over a large range of values depending on aggregate type, which makes its inclusion in the design criteria rather questionable.

With respect to the Hveem specimens of Table 18, the three limestone mixes show decreases in $R_t$-value (which includes the effect of C-value) with increases in residual asphalt content for vacuum saturated specimens, which possibly indicates the degrading effects of compaction on limestone aggregates. On the other hand, peaks in dry densities were obtained for these mixes. The gravel and granite mixes show peaks for both $R_t$-value and dry density of vacuum saturated specimens, but in many instances the peak in strength value does not correspond with the peak value for dry density. Also, it is difficult to relate "early cure" specimen properties to those of vacuum saturated specimens because the emulsion content resulting in "optimum" properties is often different for both. Of course, as has been noted before, emphasis needs to be placed on the properties of the vacuum saturated specimens because of the importance of water susceptibility for emulsion mixes.

In comparing Tables 17 and 18, it is apparent that dry densities are generally comparable between 50-blow and 5,000-lb static load specimens. However, the 5,000-lb load was not capable of adequately compacting certain specimens at lower emulsion contents and, therefore, it is again recommended that a 10,000-lb double-plunger static load be used when running mix designs with Hveem equipment.

To summarize, the test data in these two tables indicate that, for most emulsion-aggregate combinations, it is not possible to base the selection of the "optimum" specimen content on just one property such as peak immersed stability. Instead, the selection has to be based on the best combination of properties such as stability, dry density, and percent retained stability, with emphasis on the properties of specimens exposed to water.

## FIELD VERIFICATION OF THE MIX DESIGN FOR DENSE-GRADED MIXES

### Literature Review

Prior to the evaluation of actual field construction projects utilizing emulsified asphalt paving mixtures, the pertinent information in the trade literature was reviewed. This review indicated that many types of conventional paving equipment can be used to produce cold-mixed, cold-laid pavement using emulsified asphalts. It is apparent that stationary or portable central plants are preferred for mixing and that both pugmill and drum mixers have been used (*3*). Equipment for in-place mixing has ranged from motor-grader blades to modern, fully automated paving machines (*24*). Paving or mixture laydown may be accomplished by blade or paver.

Mix control during field operations can be simple or more elaborate. Single or multiple aggregate stockpiles can be used and aggregate-feed techniques can vary from a simple gated hopper above a moving belt to a sophisticated multiple-bin cold feed system.

Two important considerations are mixing time and water content control. Mixing time can be varied or it can be adjusted by changing the location of the emulsion spray bar in the pugmill or by installing a "dam" at the pugmill discharge (*24*). If added mixing water is required, the plant will need either water storage facility or an external water supply. The water content of the aggregate stockpile is also important because although most emulsions are mixed with moist or wet aggregates, some are compatible only with surface-dried aggregate (*3*).

Plant-prepared emulsion mixes can be transported to the job-site in a manner similar to that of hot mixes, although transportation timing is less critical. Also, depending on the composition of the mix, sometimes it may be possible to stockpile it for several days prior to transporting it to the job site (*14*).

There are also environmental or climatic factors to consider when using emulsions. Successful mixing and laydown can generally take place anytime the air temperature is above 40°F. However, to avoid saturation and to control early curing of the mix, construction should not occur during periods of rain or dense fog (*24*). Also, traffic should be kept off the pavement for a reasonable length of time to allow for adequate initial curing.

With regard to compaction, there is no preferable or set combination of equipment and rolling patterns to be used. Initial, intermediate, and finish rolling can involve the use of light vibratory or conventional steel-wheel rollers and pneumatic-tired rollers (*3*).

The timing for compaction depends on the nature of the mix. If water for compaction is less than that for mixing, aeration may be needed prior to initial rolling. Several recommendations for the time of initial compaction have been proposed: (1) at time of emulsion breaking; (2) when optimum fluids or water content is achieved; and (3) when the mix appears stable under the roller (*3*). Compaction timing will also depend on the thickness of the lift due to differences in curing between the upper and lower portions of the layer. It is suggested that 2-in. compacted lifts can be used, but success has been achieved with layers up to 6 in. in compacted thickness.

Generally, the details of construction practices and their control are not as critical with emulsion mixes as with hot-prepared paving mixes. Follow-up corrective steps such as reaerating a wet pavement with a motor grader or recompacting a low density area may be undertaken at a later date after initial compaction. Thus, the actual end product can be achieved after a considerable length of time following initial laydown (*14*). This points out the flexibility and practicality of dense-graded emulsified asphalt paving mixtures.

### Planning, Design, and Analysis of Field Projects

Four field projects, located in various parts of the country, were studied as a part of this research program. These projects were located in Harrisonburg, Virginia; Saline County, Arkansas; Chesapeake, Virginia; and Schuyler County, New York.

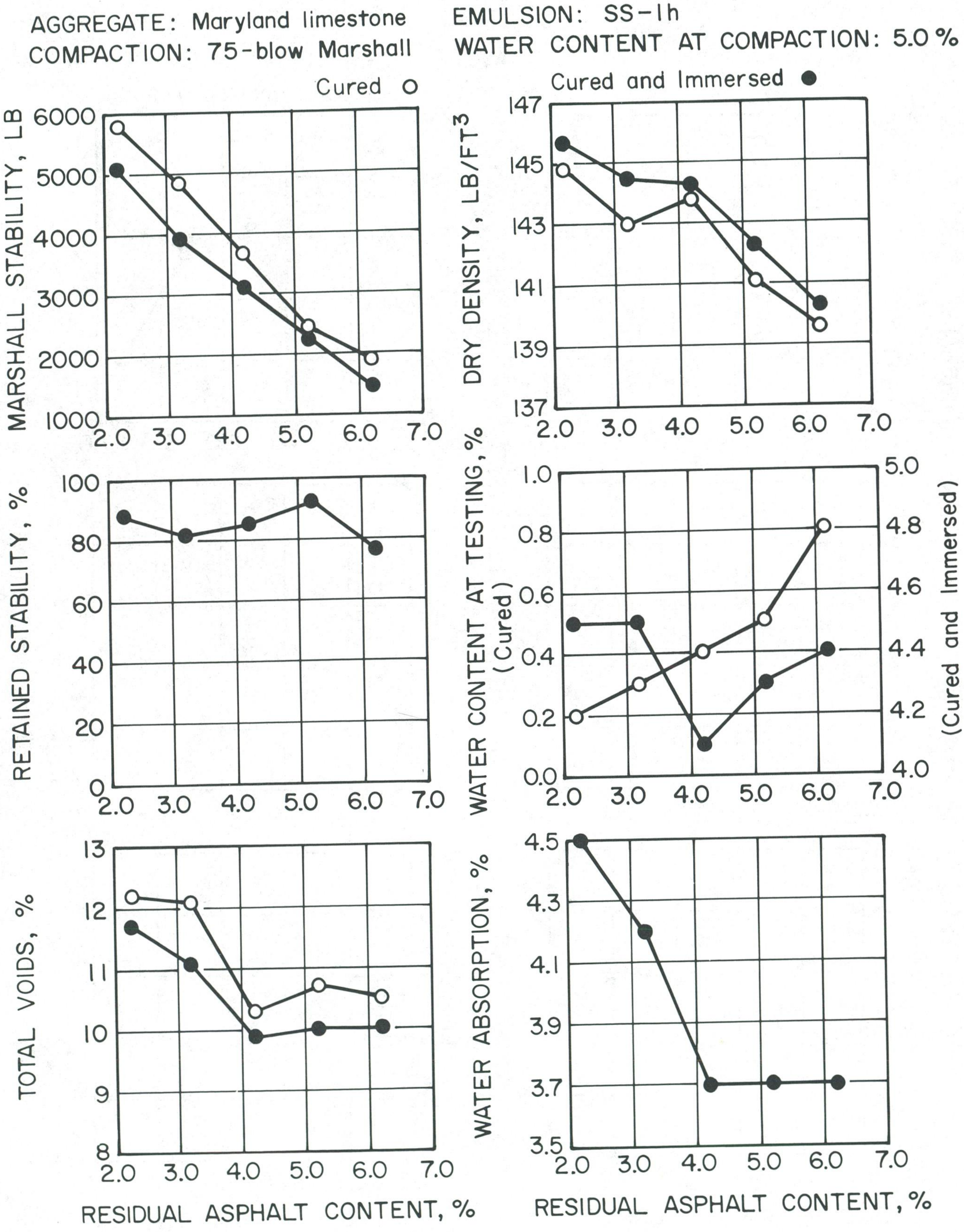

*Figure 29. Design of emulsion paving mixtures by revised method using Marshall equipment.*

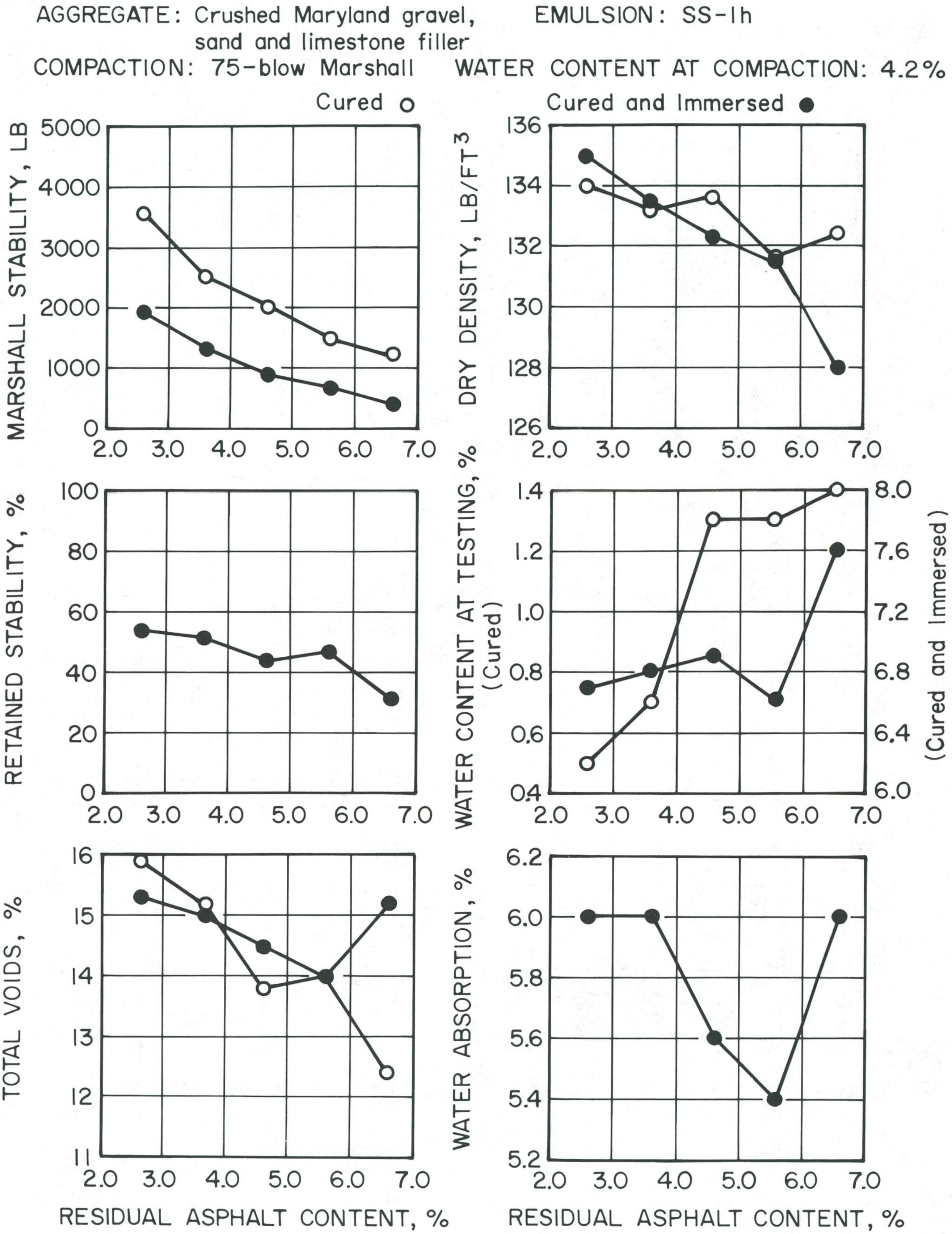

*Figure 30. Design of emulsion paving mixtures by revised method using Marshall equipment.*

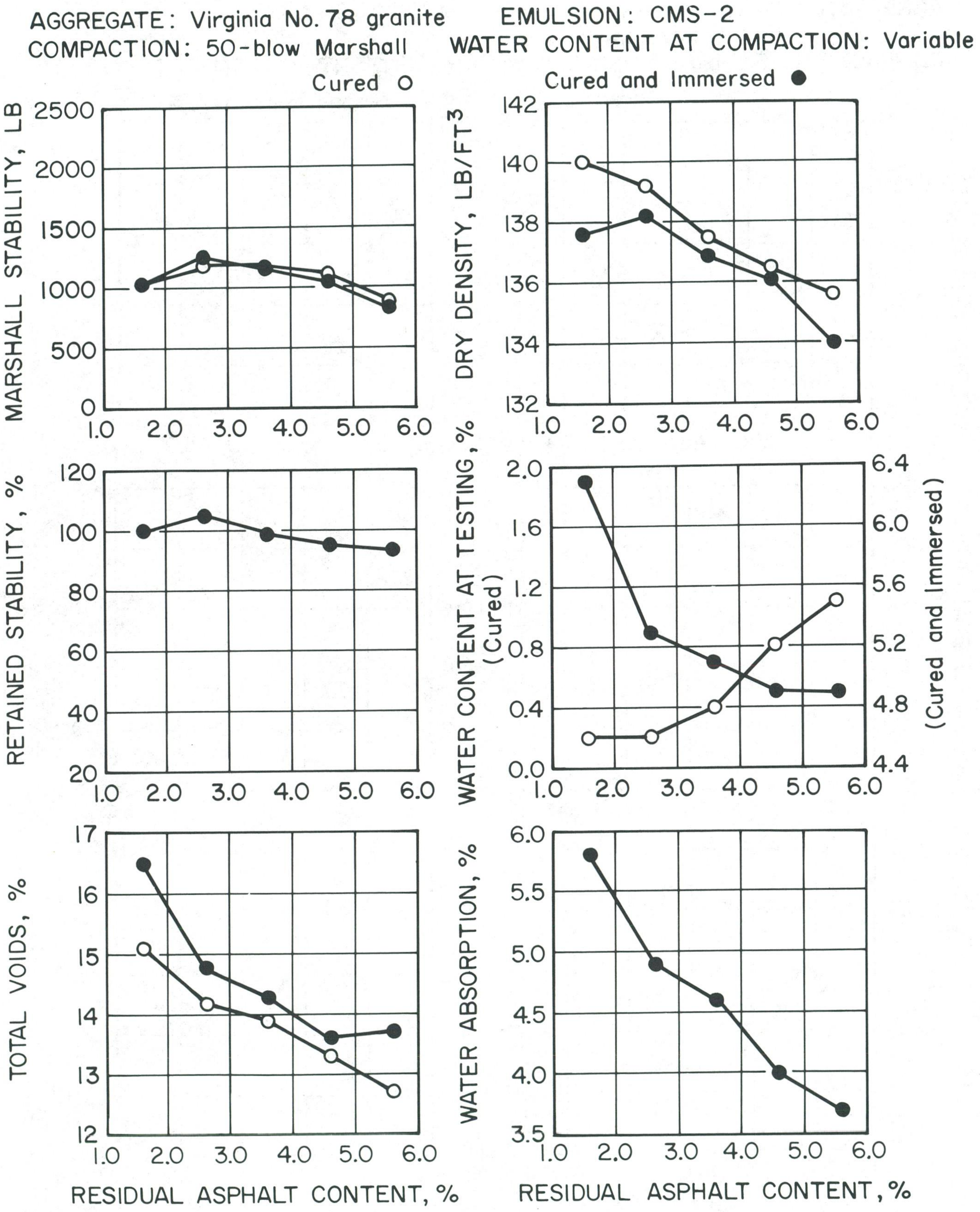

*Figure 31. Design of emulsion paving mixtures by revised method using Marshall equipment.*

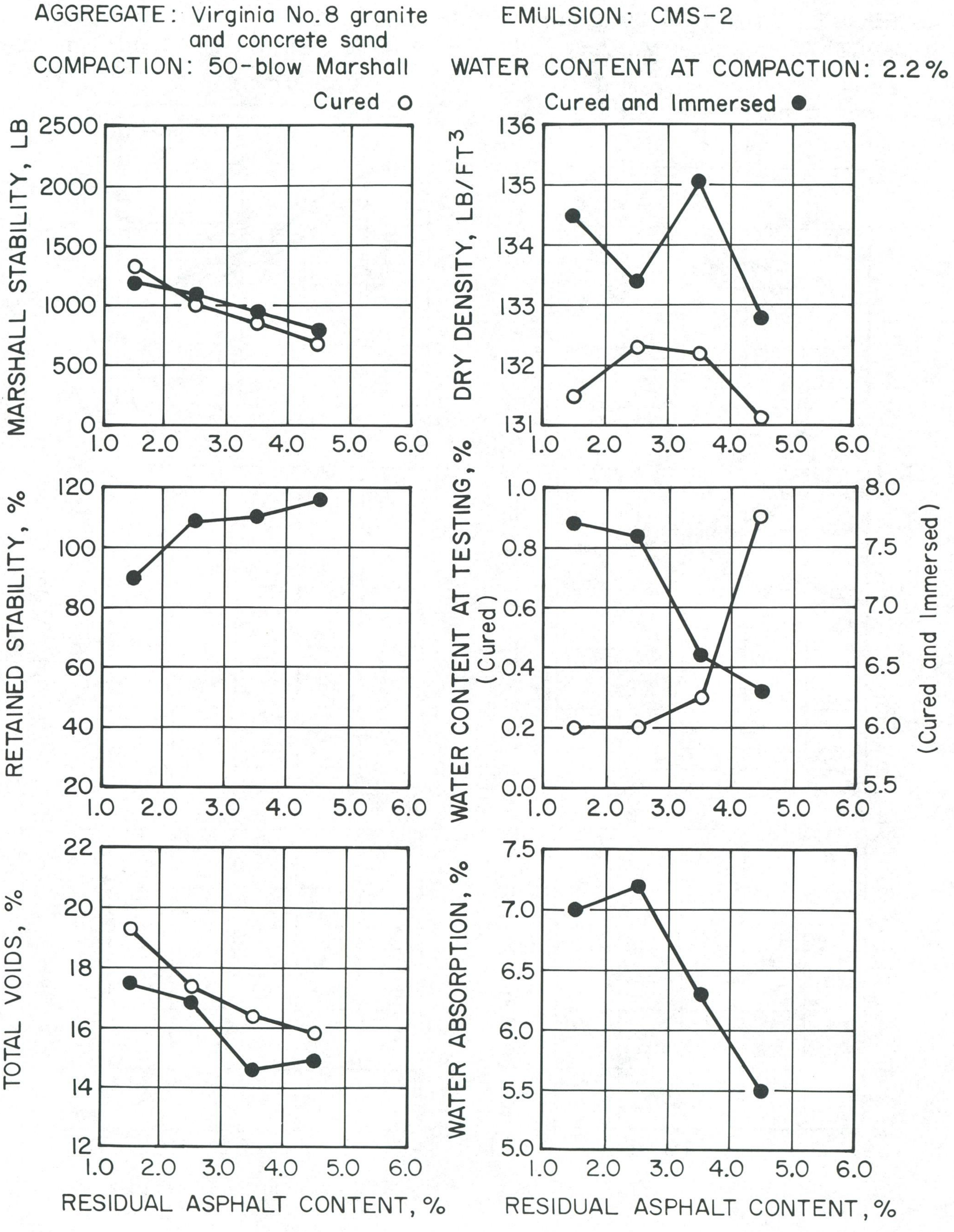

*Figure 32. Design of emulsion paving mixtures by revised method using Marshall equipment.*

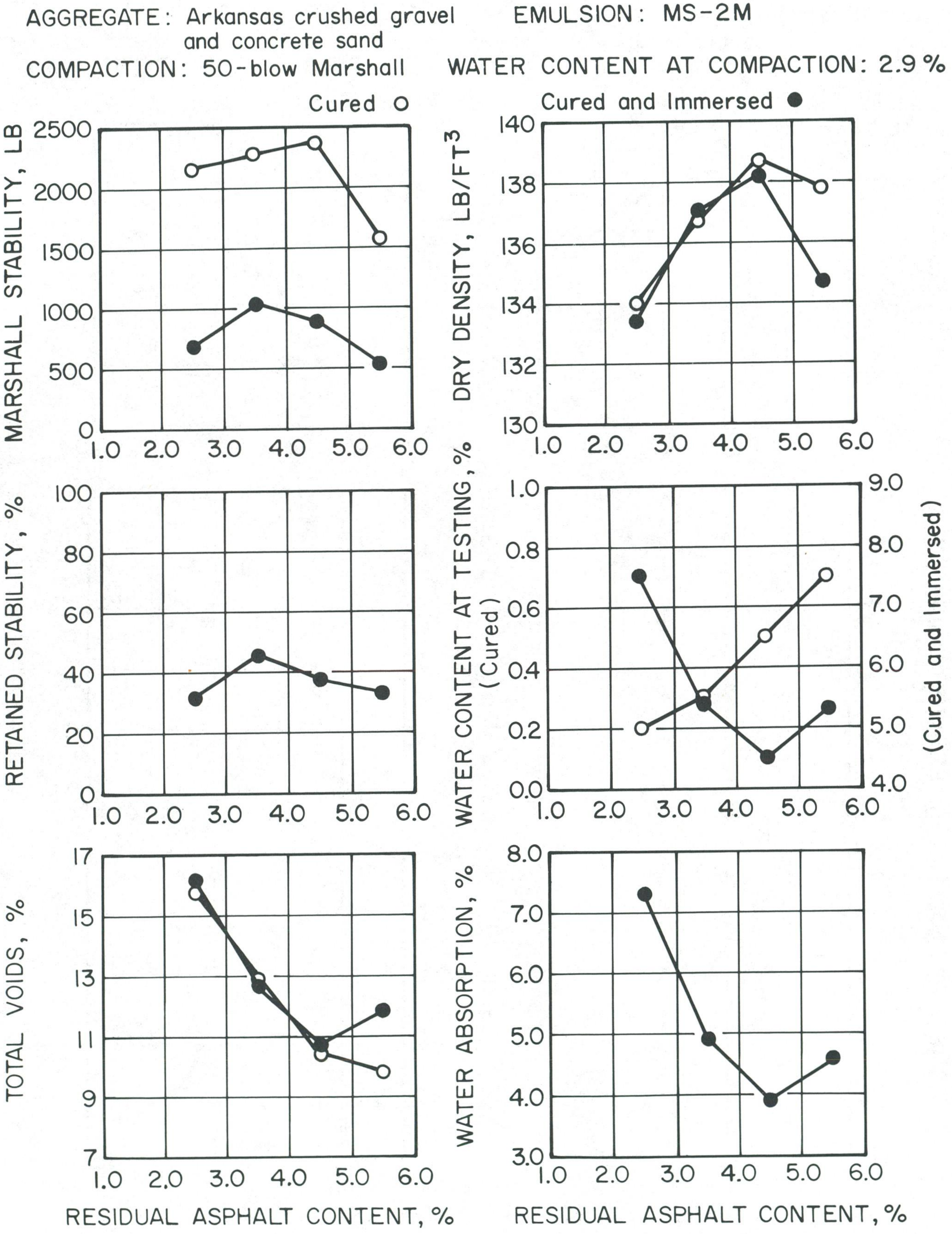

*Figure 33. Design of emulsion paving mixtures by revised method using Marshall equipment.*

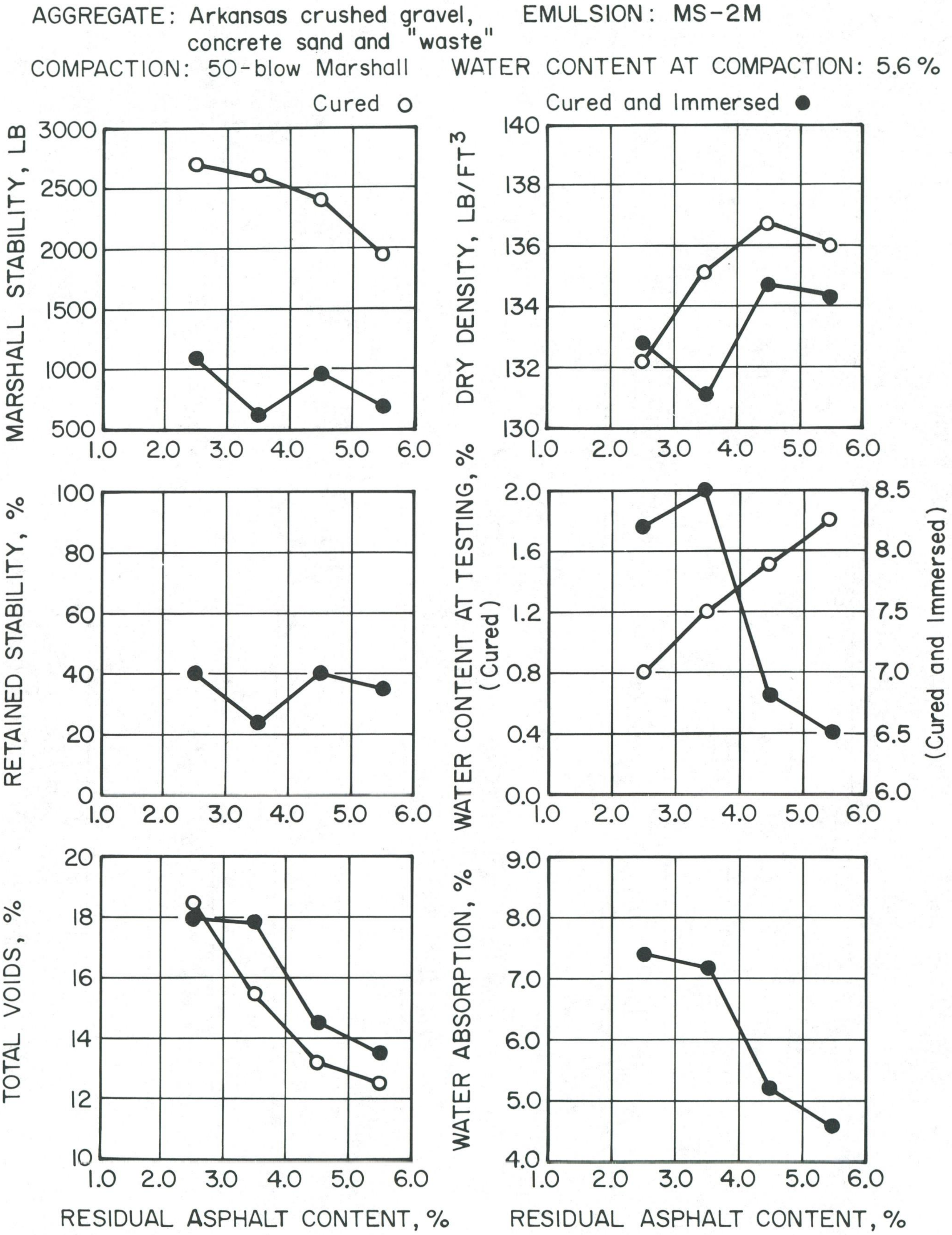

*Figure 34. Design of emulsion paving mixtures by revised method using Marshall equipment.*

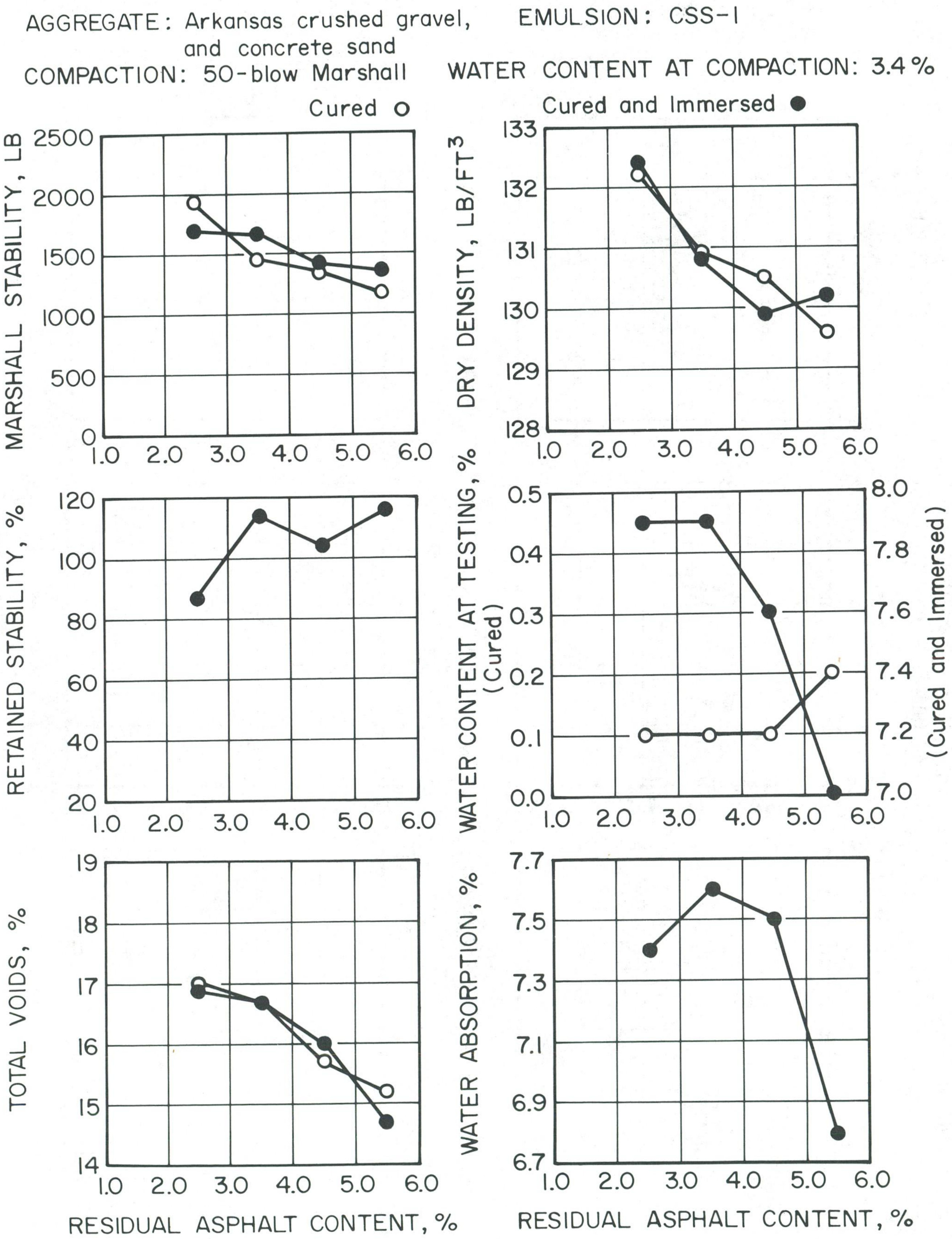

*Figure 35. Design of emulsion paving mixtures by revised method using Marshall equipment.*

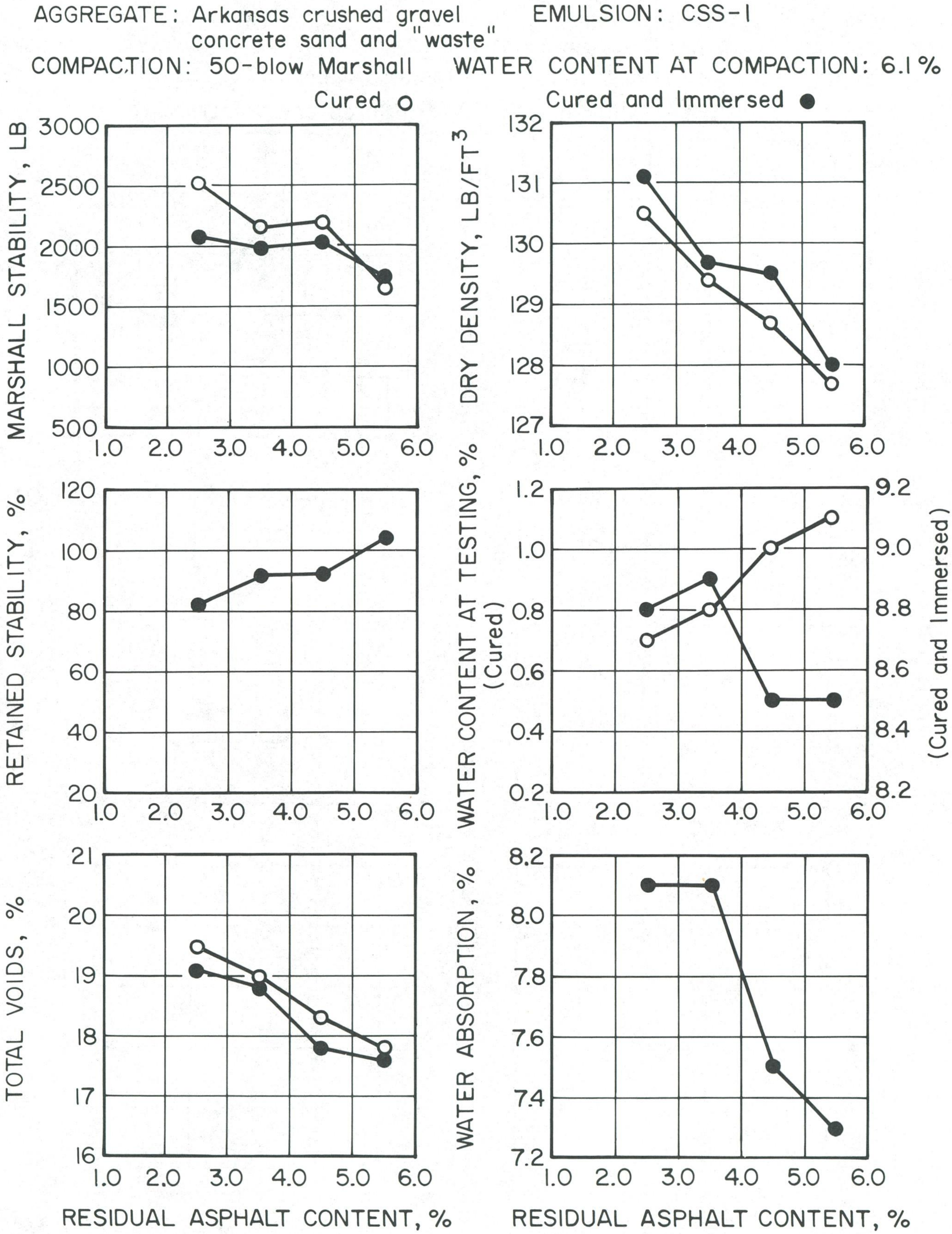

*Figure 36. Design of emulsion paving mixtures by revised method using Marshall equipment.*

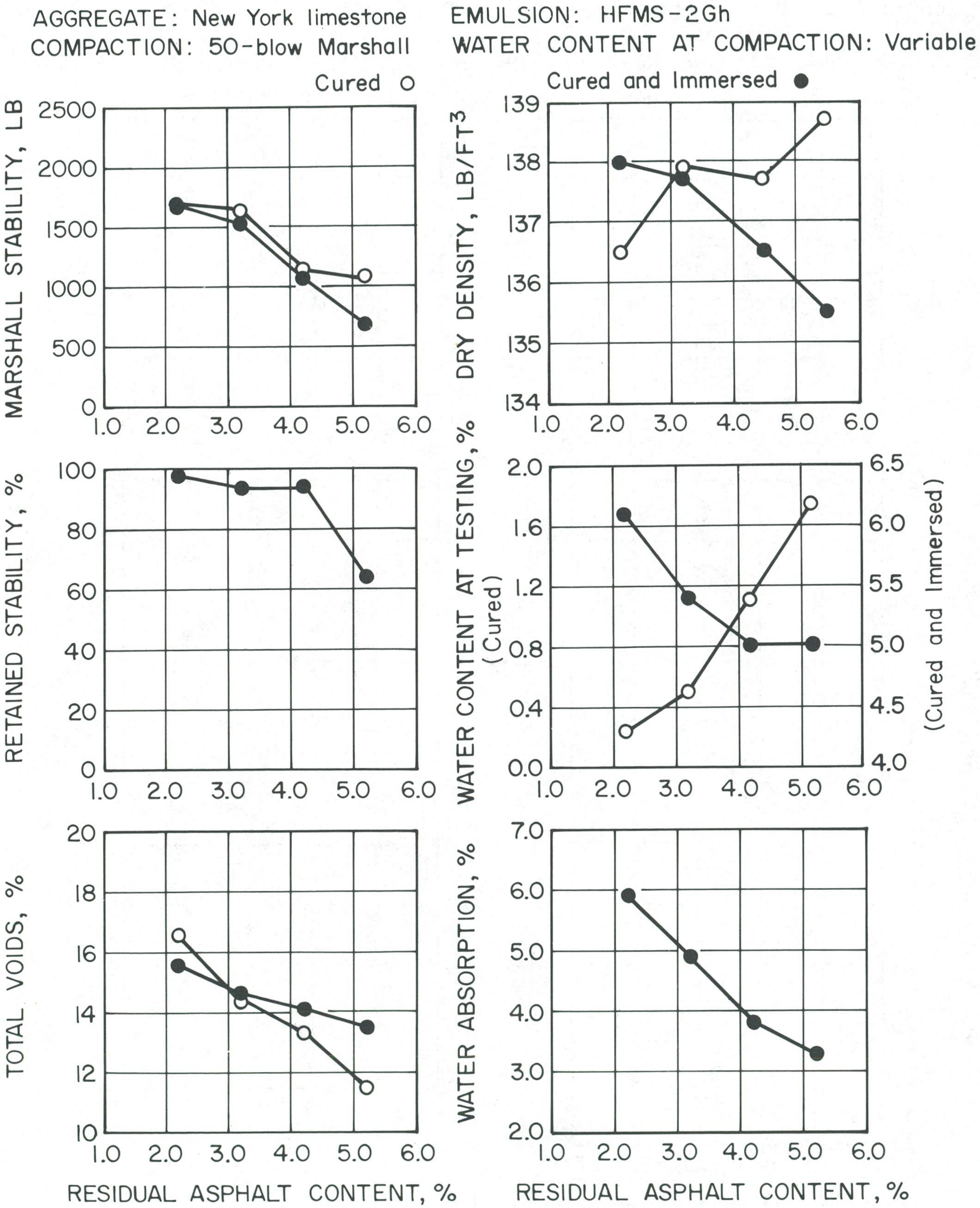

*Figure 37. Design of emulsion paving mixtures by revised method using Marshall equipment.*

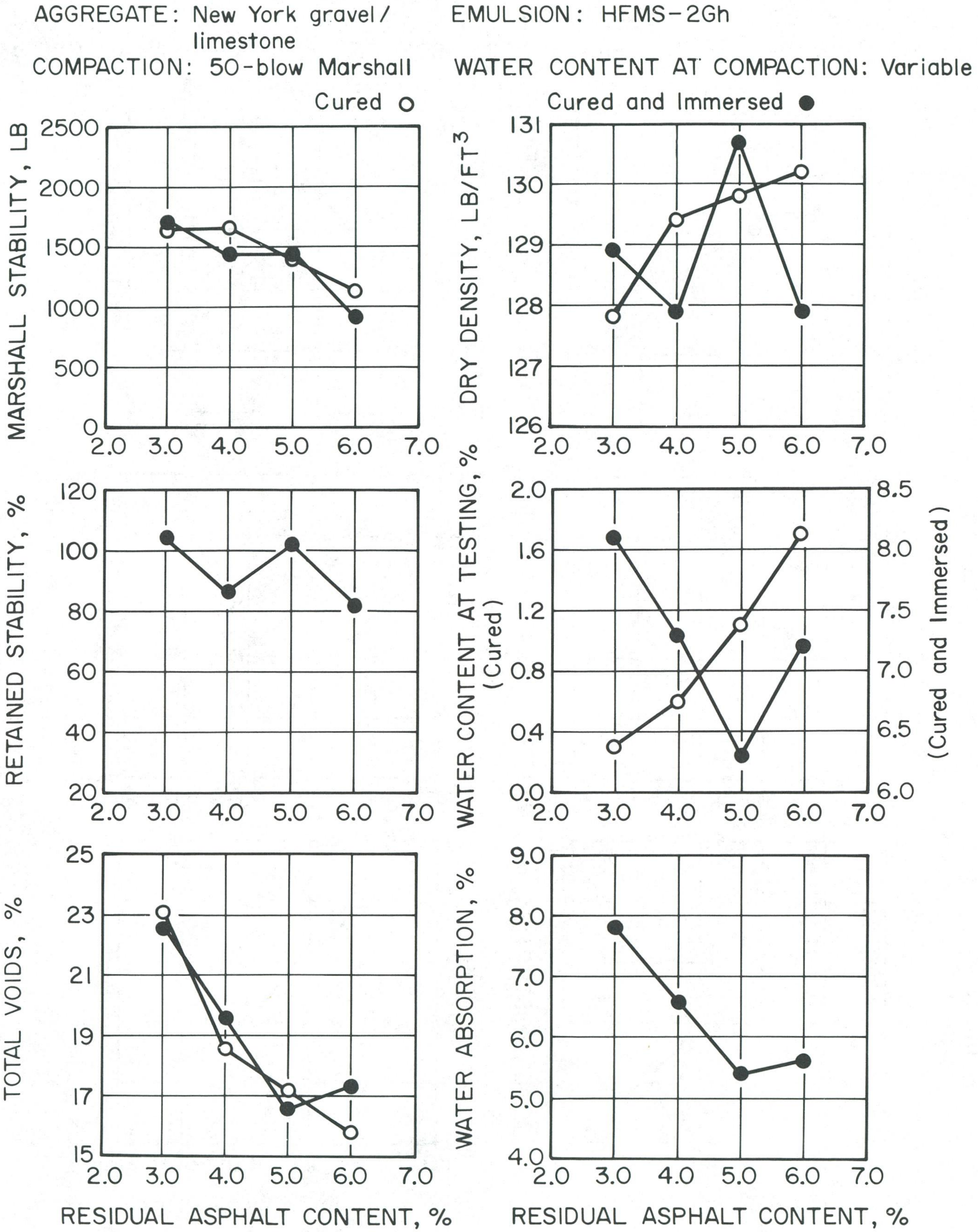

*Figure 38. Design of emulsion paving mixtures by revised method using Marshall equipment.*

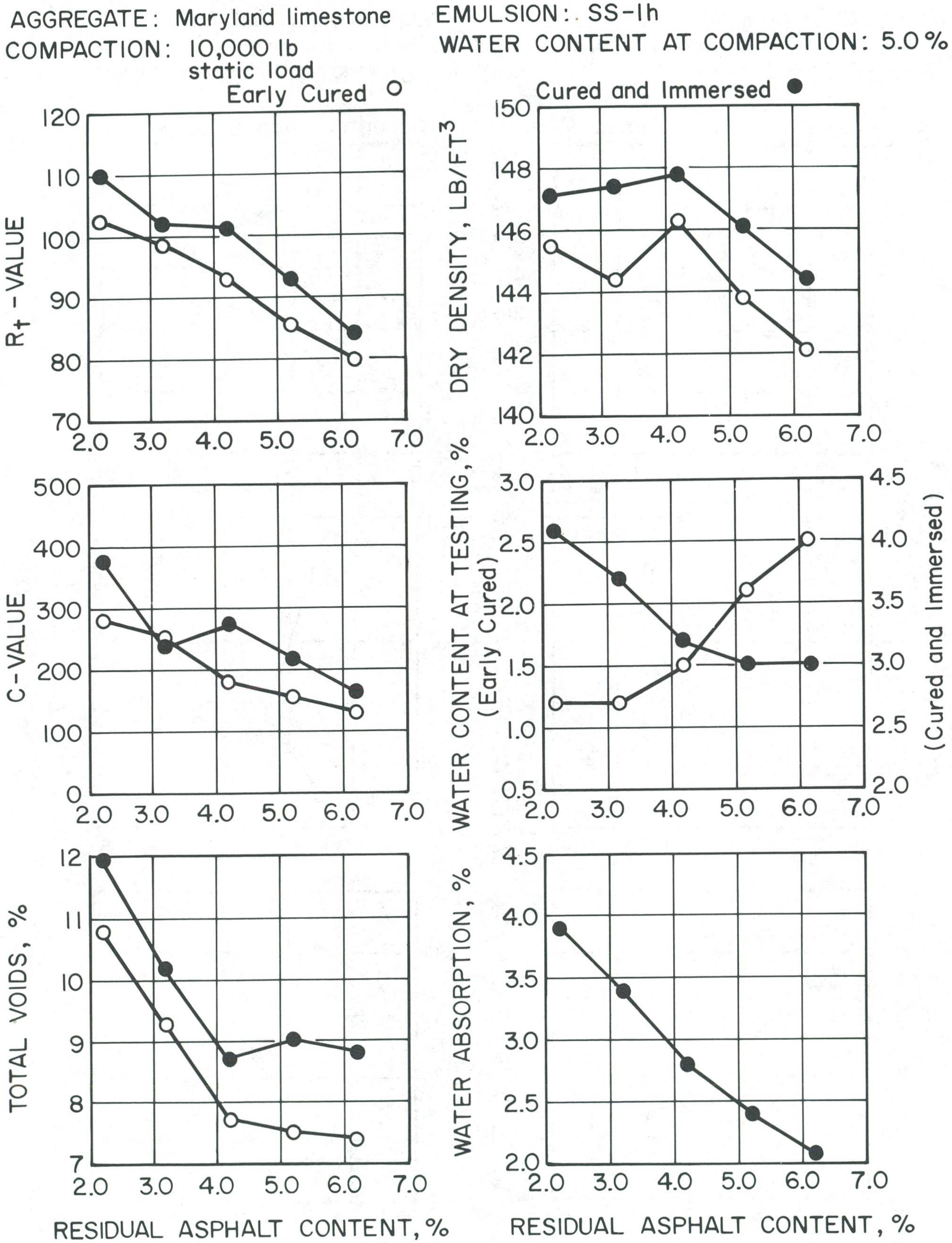

*Figure 39. Design of emulsion paving mixtures by revised method using Hveem equipment.*

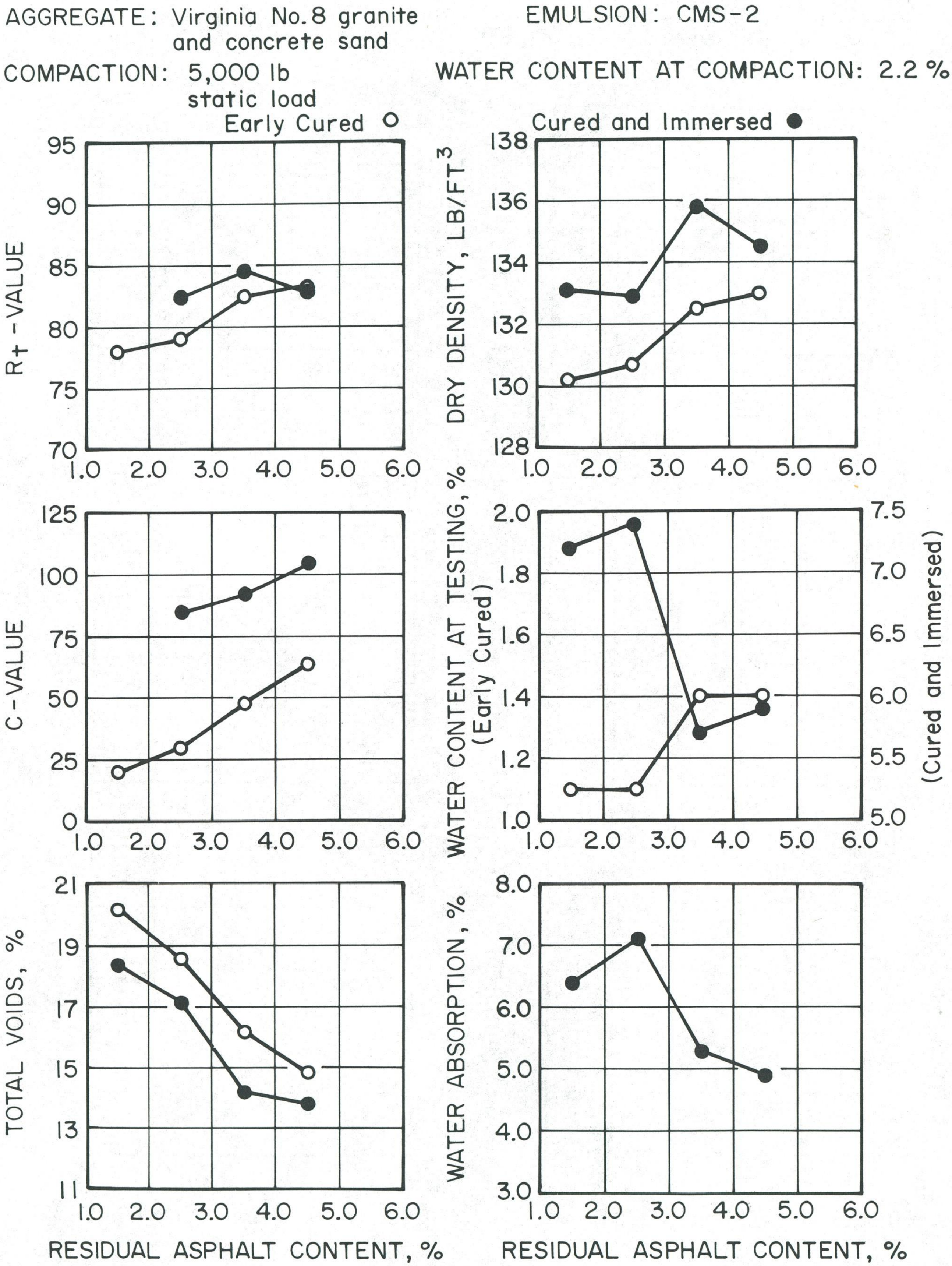

*Figure 40. Design of emulsion paving mixtures by revised method using Hveem equipment.*

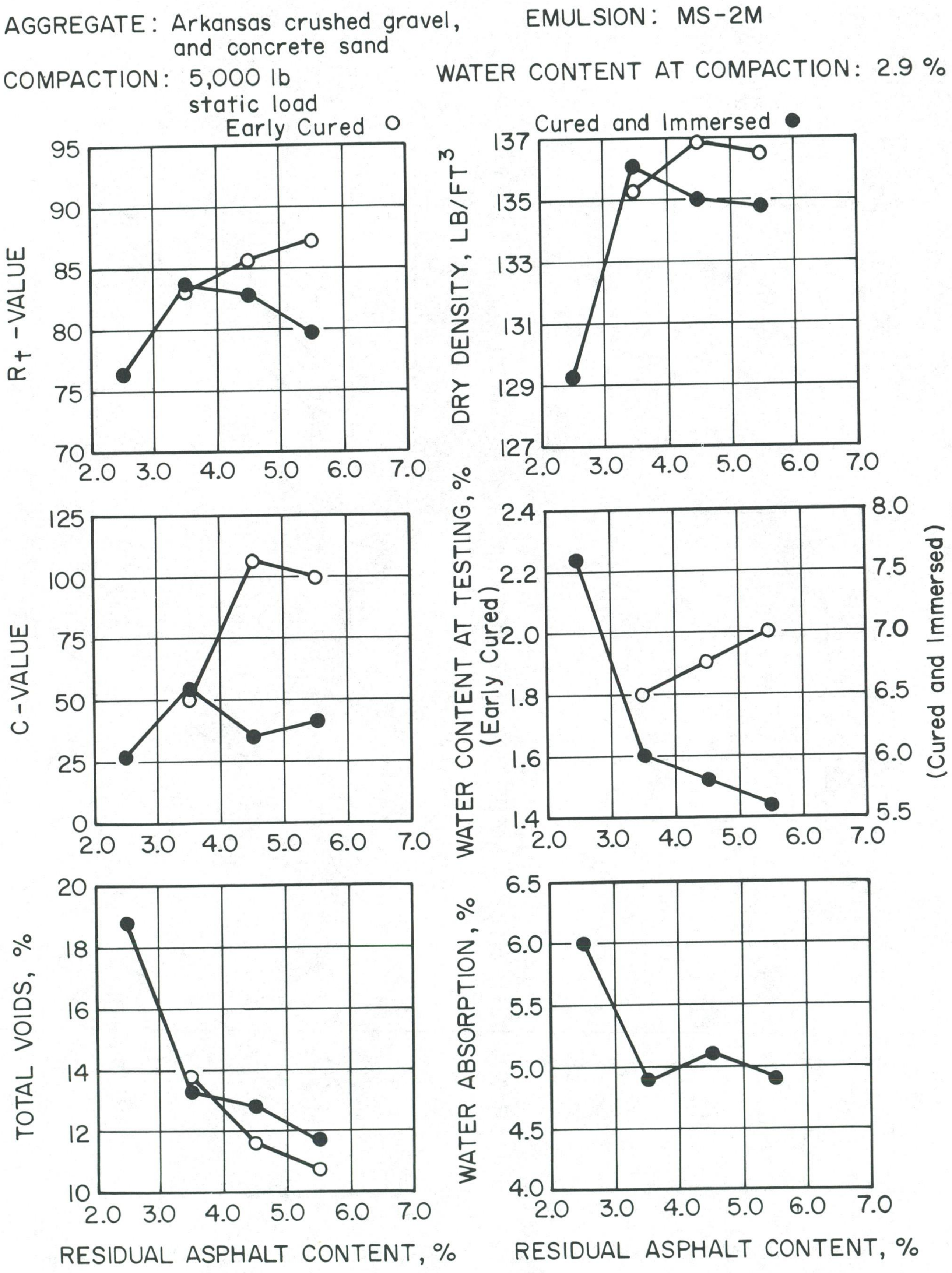

*Figure 41. Design of emulsion paving mixtures by revised method using Hveem equipment.*

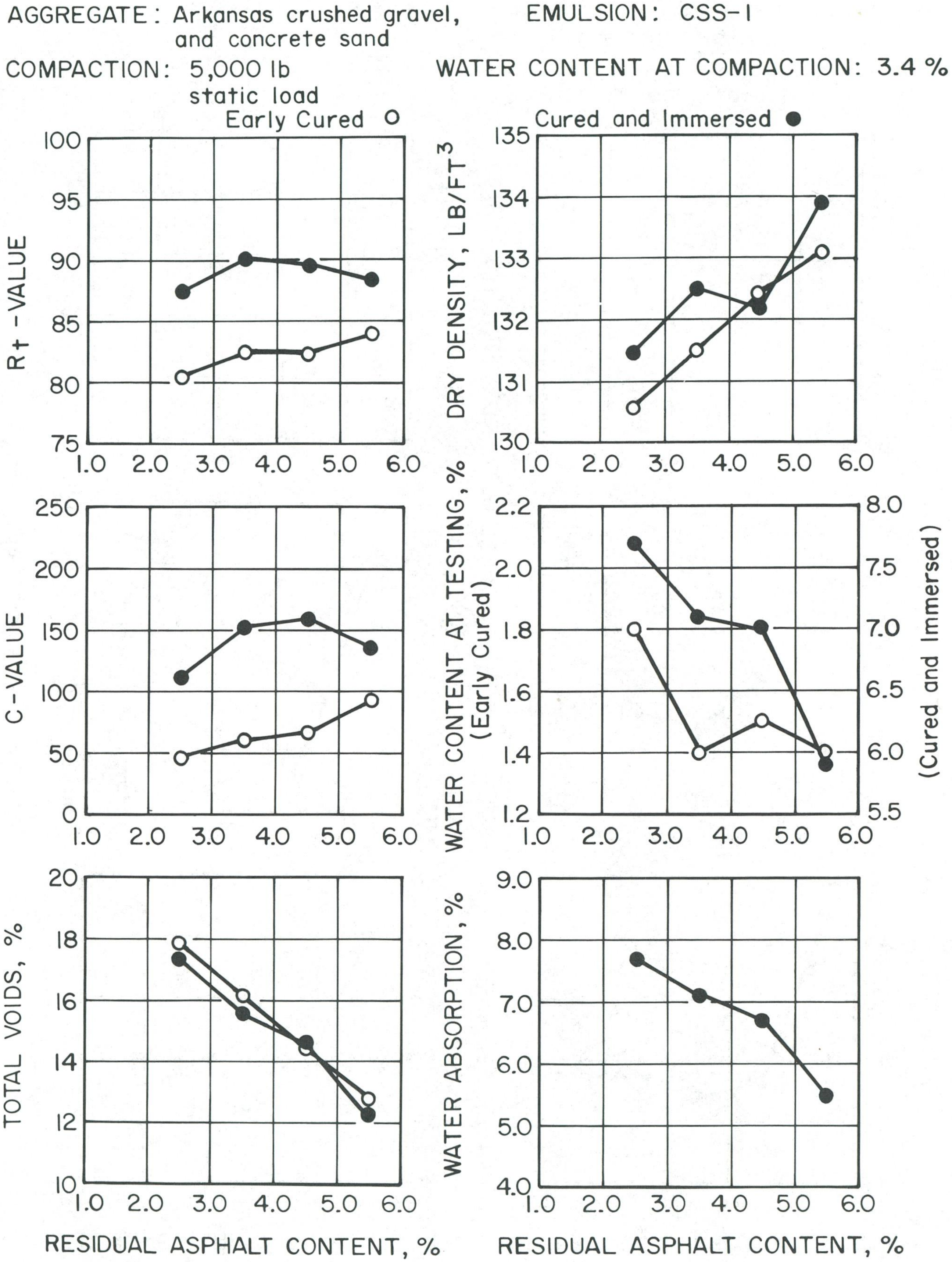

*Figure 42. Design of emulsion paving mixtures by revised method using Hveem equipment.*

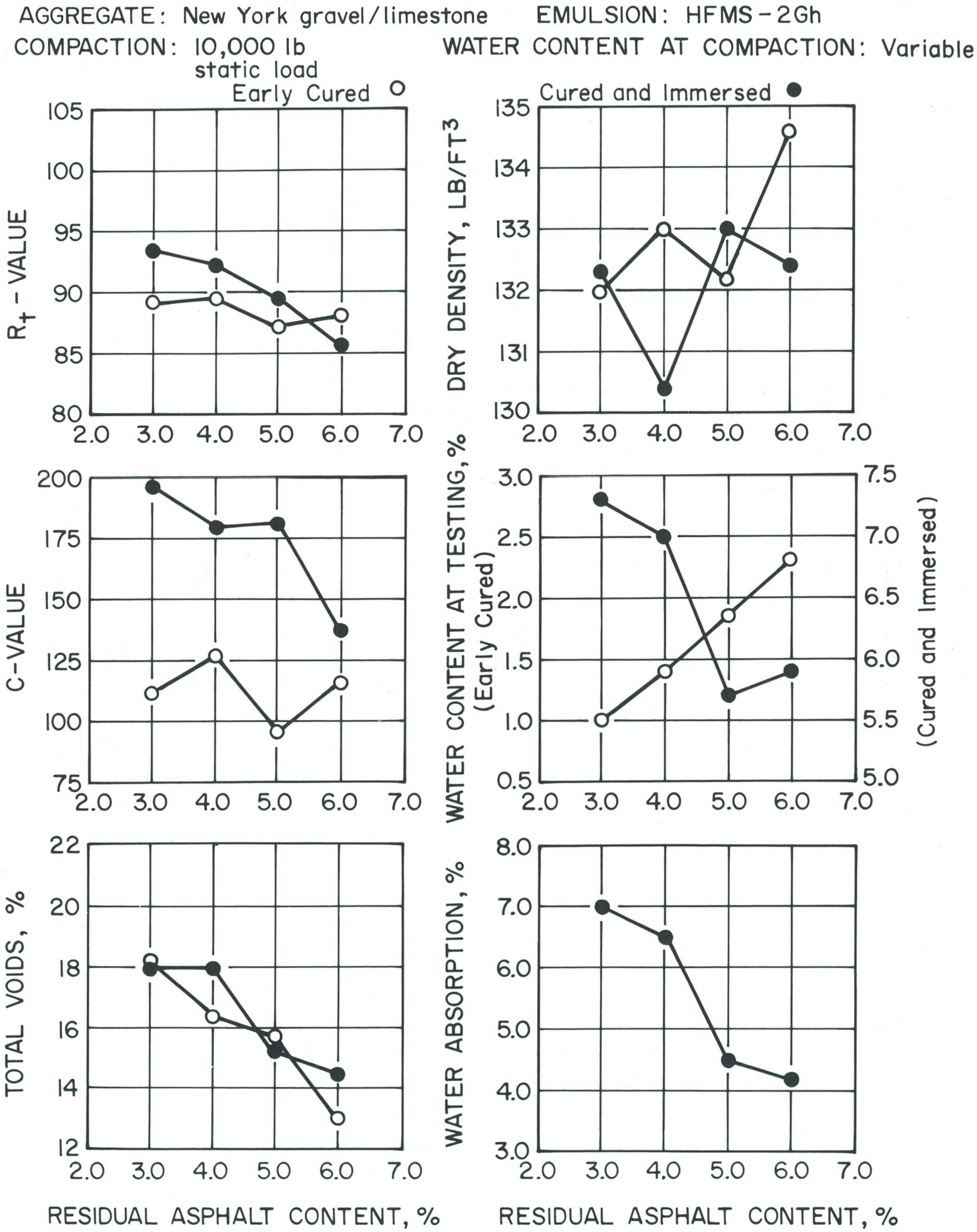

*Figure 43. Design of emulsion paving mixtures by revised method using Hveem equipment.*

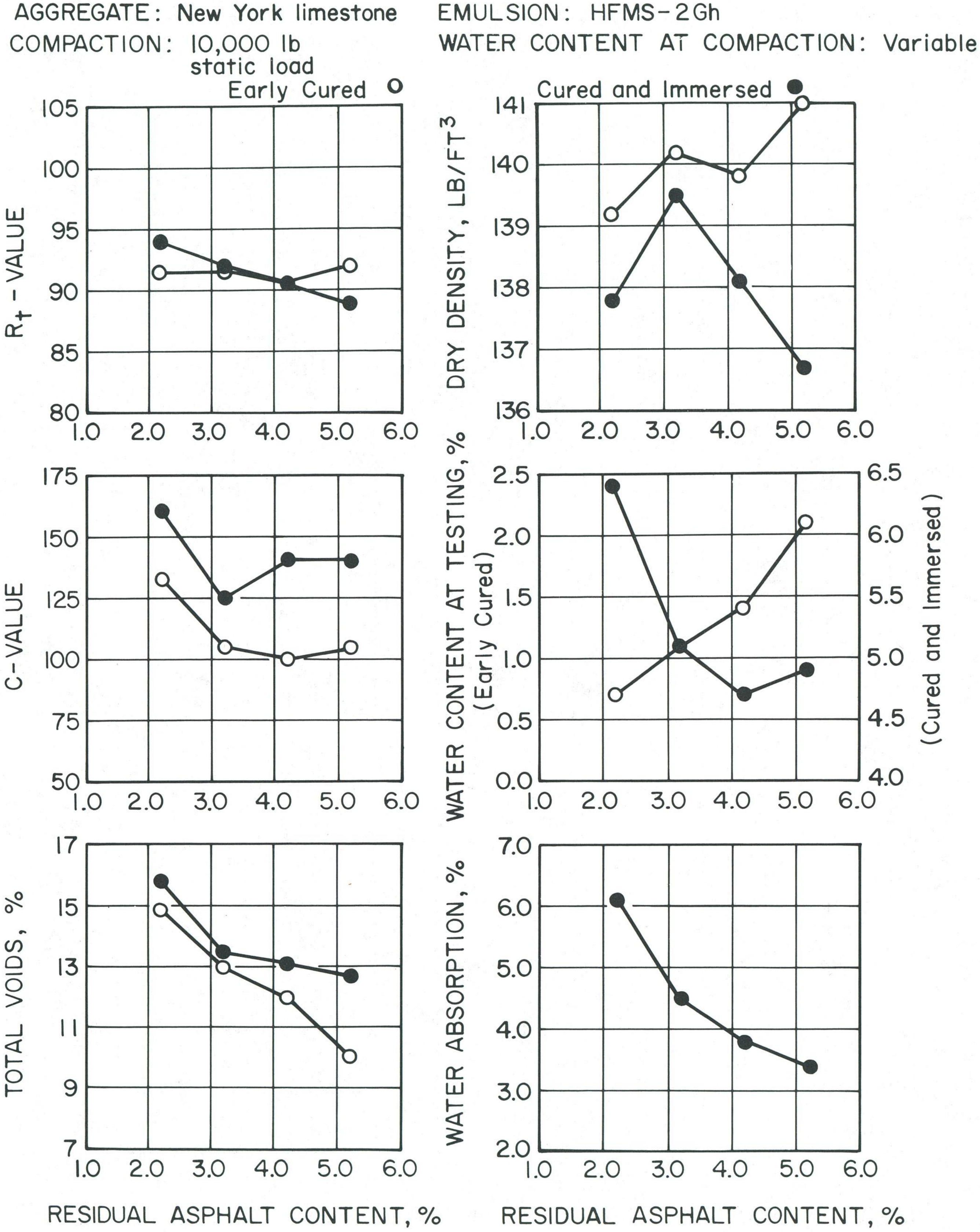

*Figure 44. Design of emulsion paving mixtures by revised method using Hveem equipment.*

These projects involved a variety of construction materials, construction techniques, and climatic conditions. Table 19 provides general information on all four field projects. Tables 20 and 21 provide information on the properties of mineral aggregate and emulsions used in these projects. Figures 45 through 48 show mineral aggregate gradations for each field project. In all cases, sufficient samples of materials were obtained prior to construction and mix designs were run using these job-site materials. When possible, job-mix formulas were established and recommended prior to construction. Sampling of materials and mixes took place before and during construction, and, where possible, after the pavement was exposed to traffic and environmental effects. The following sections describe and discuss the specifics of each project.

### *Harrisonburg, Virginia, Field Project*

*Details of Construction.* This 3-mile long project on a 20-ft wide 2-lane county road (Route 765) was located near Harrisonburg, Virginia. Half of the project was constructed in the fall of 1979 and the remainder was scheduled for completion in the summer of 1980. The second half of the project was selected for study as part of this research. Original plans had called for an 8-in. thick emulsion treated base, laid in two 4-in. lifts over a clay subgrade, to be topped by a standard emulsion seal coat. It should be noted that by the spring of 1980, the section laid the previous fall was showing considerable signs of deterioration. This section had been laid under wet weather conditions and was rolled within 1 hour after laydown, which apparently inhibited curing of the relatively thick lifts. The mineral aggregate for the study project was crusher-run limestone that qualified as dense-graded but was lacking in fines. Table 20 summarizes all pertinent properties of the aggregate. The emulsified asphalt for the project was CSS-1h (containing antistrip agent) which is used throughout Virginia for slurry seal applications. Properties of the emulsion are given in Table 21. On the basis of laboratory work using the Marshall equipment (UI method curing-water exposure procedures), an emulsion content of 5.7 percent, or a residual asphalt content of 3.8 percent, and an added mixing water content of approximately 2.5 percent (total water content of 4.4 percent) were recommended. Using a modified compactive effort of 50 blows of the Marshall hammer, this mix resulted in the highest percent retained stability after capillary soaking (91.4 percent retained with a soaked Marshall stability of 2,405 lb) and the lowest percent of water absorption (1.6 percent). (This mix design was not included in the reference method evaluation section because of the modification to compactive effort.) Results when using 75 blows are given in Table 3.

The Virginia Department of Highways and Transportation, whose personnel performed the work, concurred with this recommendation, but decided to aim for 4.0 to 4.2 percent residual asphalt content to avoid "lean" mixes as a result of nonuniformity in mixing. The aggregate stockpile was sprinkled for 3 days prior to initial construction which resulted in a stockpile moisture content of approximately 2 percent on the first day of mixing. The construction of the remaining 1½ miles of the project began on the morning of June 25, 1980.

A portable continuous pugmill mixer called a "Porta-Pugg" was erected at the limestone quarry located next to the road being paved. The aggregate from a single stockpile was fed into the Porta-Pugg's mixing chamber by a conveyor belt, mixed with the emulsion for about 7 sec and then deposited into waiting dump trucks. Initially, no additional water was added because it was thought that the water content of the stockpile was adequate for mixing. The mix appeared "soupy," though the aggregate appeared to be 100 percent coated. These initial mixes were deposited directly on apron areas at the intersection of two county roads (Routes 753 and 765) and then spread with a motor grader. After initial curing of a few hours, it became evident that most of the larger aggregate particles had little or no coating, possibly because of inadequate mixing. Unfortunately, the mixing time could not be adjusted with the Porta-Pugg employed for this job. It was decided to add a small amount

**Table 19. Summary of information on four field projects.**

| LOCATION | EMULSION AGGREGATE | PAVEMENT TYPE | MIXING | AGGREGATE FEED | PAVING | COMPACTION |
|---|---|---|---|---|---|---|
| Harrisonburg, VA RT-765 | CSS-1h/ limestone | base 8 inches | portable pugmill (continuous) | single stockpile | Jersey spreader | three-wheel steel roller |
| Saline Co., AR County Roads | MS-2M<br>CSS-1/<br>gravel-sand<br>gravel-sand-"waste" | overlay 3 inches | drum-mixer | three-bin cold feed | "Trac Paver" | steel wheel tandem roller<br>pneumatic-tired roller |
| Chesapeake, VA | CMS-2/ granite sand | overlay 1 1/2 inches | Midland paver | from single stockpile | Midland Paver | steel-wheel tandem roller |
| Schuyler Co., NY RT-79 | HFMS-2Gh/ limestone<br>gravel-limestone | binder course 1 1/2 inches<br>surface course 1.0 inch | portable pugmill (continuous) | four-bin cold feed | pneumatic-tired paver | steel-wheel tandem roller |

**Table 20. Properties of mineral aggregate used for field projects.**

| PROJECT LOCATION | HARRISONBURG, VA. | SALINE COUNTY, ARKANSAS | | CHESAPEAKE, VA. | SCHUYLER COUNTY, NEW YORK | |
|---|---|---|---|---|---|---|
| MINERAL AGGREGATE | LIMESTONE | CRUSHED GRAVEL CONCRETE SAND REYNOLDS "WASTE"[a] | CRUSHED GRAVEL/ CONCRETE SAND | NO. 8 GRANITE/ CONCRETE SAND | GRAVEL/LIMESTONE (SURFACE COURSE) | LIMESTONE (BINDER COURSE) |
| GRADATION OF AGGREGATE[c] | COARSE | MIDDLE | MIDDLE | MIDDLE | MIDDLE | MIDDLE |
| U.S. STANDARD SIEVE | | | PERCENT PASSING | | | |
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 92.1 | 99.8 | 100.0 | 100.0 | 100.0 | 92.8 |
| 1/2 in. | 74.5 | 94.4 | 94.5 | 99.1 | 100.0 | 79.0 |
| 3/8 in. | 60.2 | 78.4 | 75.5 | 89.1 | 100.0 | 66.2 |
| No. 4 | 36.2 | 56.8 | 50.7 | 54.4 | 78.7 | 50.6 |
| No. 8 | 24.3 | 45.5 | 38.1 | 41.7 | 46.1 | 37.9 |
| No. 16 | 13.9 | 37.2 | 29.5 | 32.2 | 17.3 | 16.9 |
| No. 30 | 8.3 | 29.9 | 23.3 | 19.9 | 8.6 | 9.2 |
| No. 50 | 5.1 | 21.7 | 15.8 | 9.2 | 5.5 | 5.8 |
| No. 100 | 3.4 | 10.4 | 6.4 | 3.8 | 3.8 | 4.0 |
| No. 200 | 2.3 | 4.9 | 2.4 | 2.1 | 3.1 | 2.9 |
| SPECIFIC GRAVITY | | | | | | |
| Bulk | 2.686 | 2.605 | 2.585 | 2.612 | 2.604 | 2.627 |
| Bulk (SSD) | 2.704 | 2.640 | 2.604 | 2.636 | 2.643 | 2.658 |
| Apparent | 2.736 | 2.701 | 2.649 | 2.676 | 2.709 | 2.714 |
| WATER ABSORPTION, % | 0.68 | 1.35 | 0.92 | 0.92 | 1.48 | 1.24 |
| UNIT WEIGHT, lb/cu ft | 129.6 | 118.6 | 120.8 | 117.5 | 99.7 | 102.7 |
| SAND EQUIVALENT | 67 | 70 | 77 | 93 | 95 | 93 |
| LOS ANGELES ABRASION, % | 18.9 | 36.0 | 36.0 | 26.8 | 28.7 | 28.8 |
| SOLUBILITY IN HCL, % | | | | | | |
| Passing No. 4 Sieve | 89.8 | 64.1[b] | 1.0 | 1.4 | 72.8 | 79.1 |
| Retained on No. 4 Sieve | 91.1 | 63.8[b] | 0.5 | 1.7 | 65.2 | 72.8 |
| CENTRIFUGE KEROSENE EQUIVALENT | | | | | | |
| CKE, % | 3.1 | 5.1 | 2.7 | 2.1 | 2.3 | 3.0 |
| Surface Capacity, % | 2.5 | 2.9 | 2.9 | 2.5 | 3.1 | 2.8 |
| Oil Ratio, % | 3.0 | 5.4 | 4.5 | 3.4 | 4.6 | 3.8 |

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[a] Reynolds "waste", an aluminum ore residue.

[b] Tests on Reynolds "waste" only.

[c] Coarse and Middle gradations describe relative fineness of aggregate.

**Table 21. Properties of asphalt emulsions used for field projects.**

| | EMULSIFIED ASPHALT | | | | |
|---|---|---|---|---|---|
| | CSS-1h | MS-2M | CSS-1 | CMS-2 | HFMS-2Gh |
| | LOCATION | | | | |
| | Harrisonburg, | Saline County | | Chesapeake, | Schuyler Co., |
| TESTS ON EMULSIONS | | | | | |
| Viscosity, Saybolt Furol at 77°F (25°C), sec | 30.7 | 80.4 | 20.2 | ---- | 2879.6 |
| Viscosity, Saybolt Furol at 122°F (50°C), sec | ---- | ---- | ---- | 20.2 | ---- |
| Settlement, 5-day, % | 2.79 | ---- | ---- | ---- | ---- |
| Storage Stability Test, 24 hours, % | ---- | 0.4 | 0.6 | 0.3 | 0.8 |
| Cement Mixing Test, % | 0.2 | ---- | 0.0 | ---- | ---- |
| Particle Charge Test | positive | ---- | positive | positive | ---- |
| Sieve Test, % | 0.03 | 0.02 | 0.01 | 0.03 | 0.04 |
| Distillation: | | | | | |
| Residue, % | 66.8 | 66.9 | 62.2 | 65.6 | 68.1 |
| Oil Distillate, % | 0.5 | 2.3 | 1.5 | 5.7 | 8.2 |
| Water, % | 32.7 | 30.8 | 36.3 | 28.7 | 23.7 |
| TESTS ON RESIDUE | | | | | |
| Penetration, 77°F (25°C), 100g, 5 sec | 91 | 122 | 96 | 155 | 69 |
| Ductility, 77°F (25°C), 5cm/min, cm | 150+ | 150+ | 150+ | 95.8 | 96.8 |
| Specific Gravity | 1.025 | 1.028 | 1.028 | 1.015 | 1.023 |
| Viscosity, 140°F (60°C), poises | 1692 | 1016 | 1915 | 751 | 3139 |
| Viscosity, 275°F (135°C), cSt | 374 | 414 | 409 | 253 | 3257 |
| Ash Content, % | 0.33 | 0.13 | 0.14 | 0.16 | 0.40 |
| Float Test, 140°F (60°C), sec | ---- | ---- | ---- | ---- | 1200+ |

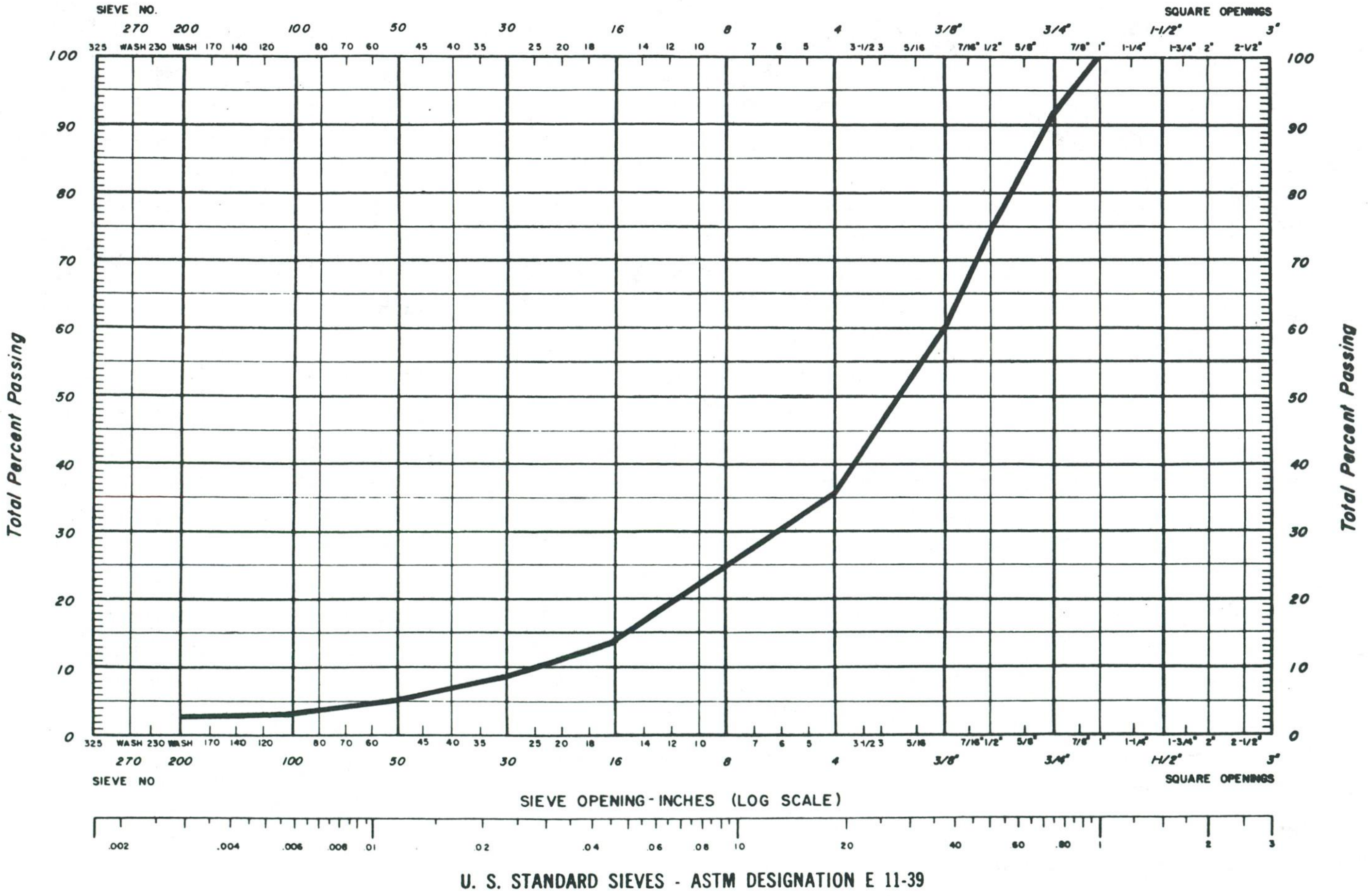

*Figure 45. Gradation of limestone used for Harrisonburg, Virginia, project.*

of water directly to the mixing chamber of the Porta-Pugg in order to achieve better aggregate coating. Extraction tests run on a number of batches indicated a 3.2 to 3.7 percent range for the residual asphalt contents.

In the afternoon, paving began on a steep section of Route 765. The mix was dumped from trucks into a Jersey spreader and laid approximately 6½ in. thick directly on the clay subgrade (4 in. after compaction). Because of low residual asphalt contents measured in the morning mixes, the emulsion content was increased in order to come closer to the 4 percent target value. There was a noticeable difference in the mixture when the emulsion from the second tanker was used. This difference might have been due to the quality of the emulsion, the difference in temperature of the emulsion in each of the two tankers or irregularities in the feed from the tanker to the mixing chamber. To avoid sealing the surface, it was decided not to roll the lift until it had completely "cured out," even if it meant waiting for 24 hours.

Inspection on the following day (June 26), revealed that the mixture still had not "cured out." A grader was used to break up and then blade the mix from one side of the road to the other to aid the aeration. Based on previous experience with the curing process, it was decided to permit normal traffic to compact the pavement over the next few days and then roll it sometime the following week. Also, a decision was made to switch from 4-in. to 2-in. lifts in order to speed up the curing process.

After 4 days, on June 30, a 3-wheel steel roller was used for final compaction of the initial 4-in. lift. It had little effect because most of the compaction had resulted from normal traffic.

Also on that day, construction was begun on a 2-in. lift (3-in. prior to compaction) at a site near the quarry. The mixture was deposited on a 2-in. dense-graded aggregate layer which had previously been laid and rolled on the subgrade in order to improve drainage. Construction of this lift was continued on July 7, 8, and 9. By this time, residual asphalt contents were around 5 percent. Also, the later sections contained aggregate to which more fine material had been added. It rained on July 8, and inspection the following day revealed that the emulsion had not broken beneath the surface and that the layers were saturated with water; tests revealed a water content of approximately 4 percent. On July 9, a second 2-in. thick layer was placed on top of the first 4-in. lift placed on June 25 and 26. This lift was compacted with the roller only 2 hours after laydown.

On July 31, further construction was scheduled. At that time, rolling took place within an hour or two after laydown and water contents of the mixture at time of compaction were considerably less than before. The results, though better than what was achieved the previous fall, were still not very satisfactory and, in fact, the sections with more fines had turned out worse than those sections with the coarse gradation.

The unsatisfactory performance of CSS-1h emulsion with this mix, coupled with an inordinately long construction time, forced

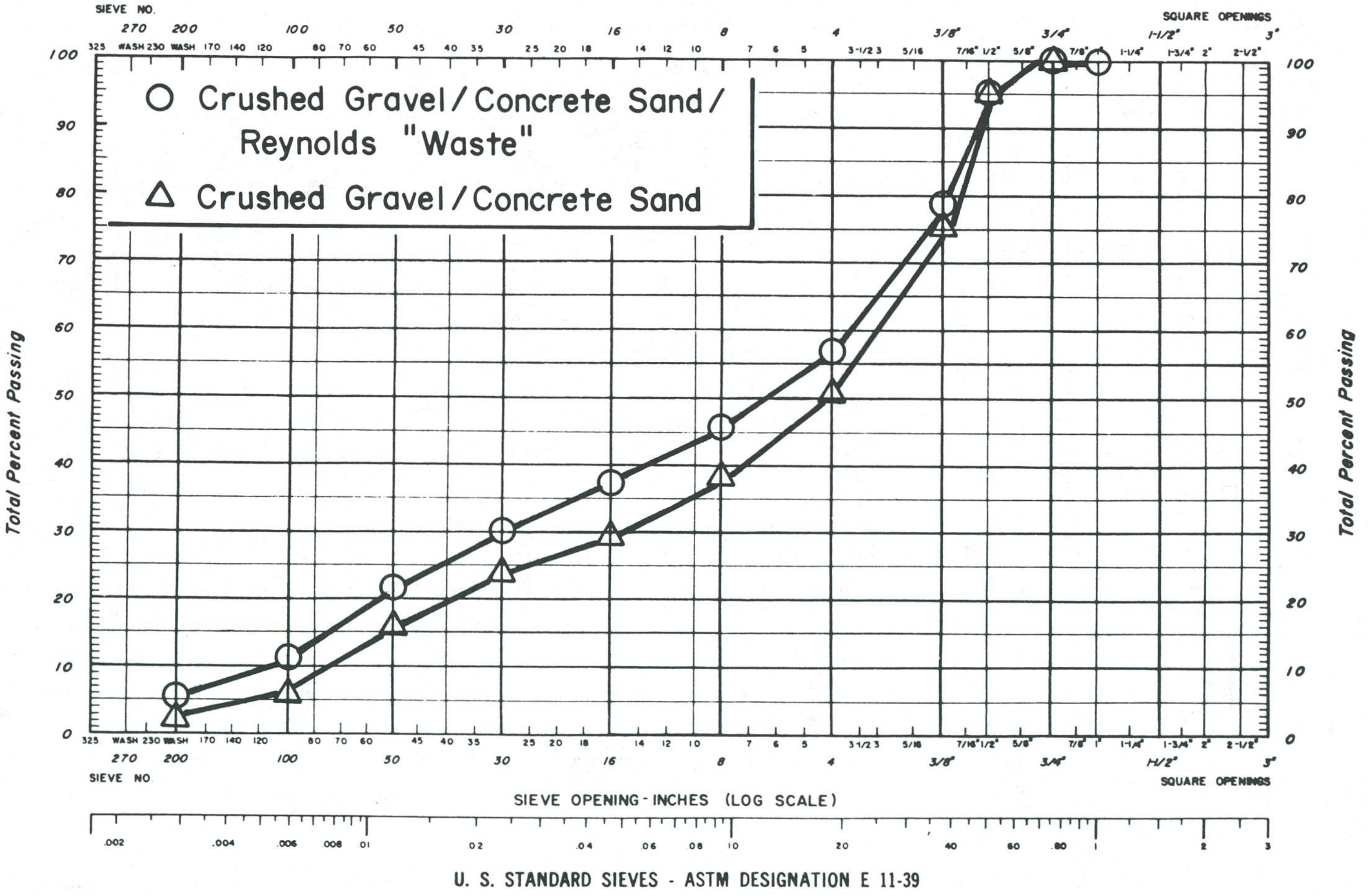

*Figure 46. Gradation of aggregates used for Saline County, Arkansas, project.*

the Virginia DHT to switch to a standard hot-mix overlay for finishing the job. Problems observed during construction included lack of control in the mixing process, lack of uniformity in the mixture, inadequate coating of larger aggregate particles, "soupy" mixes resulting from too much water or emulsion in an attempt to achieve 100 percent coating, "balling up" of asphalt and fines, and the inability of the pavement to "cure out" uniformly because of its thickness and the sealing effect of traffic which was not blocked off during construction. Also, it was evident that the mixing time was too short, resulting in poor coating of larger aggregate particles. The timing of compaction with the 3-wheel steel roller was also erratic, which resulted in premature sealing of the pavement surface and prevented adequate drying and curing of lower layer depths.

*Tests on Field Samples.* Tests were made at the Harrisonburg, Virginia, construction site on three separate occasions in June and July, 1980. Water contents of both the stockpile and mixes were determined at various stages of construction and at various times of the day. Additional aggregate and mix samples were sealed in plastic bags for later analysis in the laboratory. The data from these tests are summarized in Table 22.

Water contents of the aggregate from the stockpile were 0.9 percent or less, while those of the mix samples taken from the trucks receiving the mix from the Porta-Pugg ranged from 2.1 to 3.2 percent. Water that was fed directly to the mixing chamber added only about 0.3 percent moisture. Thus, most of the water in the mix was incorporated with the emulsion. However, as the water content range indicates, it was difficult to regulate either the flow of the emulsion or of the water into the mixing chamber.

Water contents of samples taken from the road ranged from as low as 1.5 percent (5 hours after laydown) to as high as 4.0 percent (after a rainstorm). A sample from the first 4-in. lift, approximately 18 hours after laydown, still had a water content of 2.2 percent. This inadequate curing prompted a switch to 2-in. lifts for the remainder of the project.

Dry densities, determined in-place by the sand-cone method, ranged from approximately 126 $lb/ft^3$ after several hours of compaction by local traffic (including heavily loaded trucks), to approximately 145 $lb/ft^3$ after three passes of a 3-wheel steel roller within several hours after laydown.

Extraction tests were made on nine samples of mixture taken either from trucks prior to laydown or from several road locations immediately after laydown. These tests indicate that residual asphalt contents ranged from as low as 2.4 percent to as high as 4.5 percent. The test data that are summarized in Table 22 show a wide range in mix properties indicating the unsuccessful attempts to vary the mix components in order to achieve a satisfactory mixture and pavement.

*Comments on Performance.* In summary, the difficulties en-

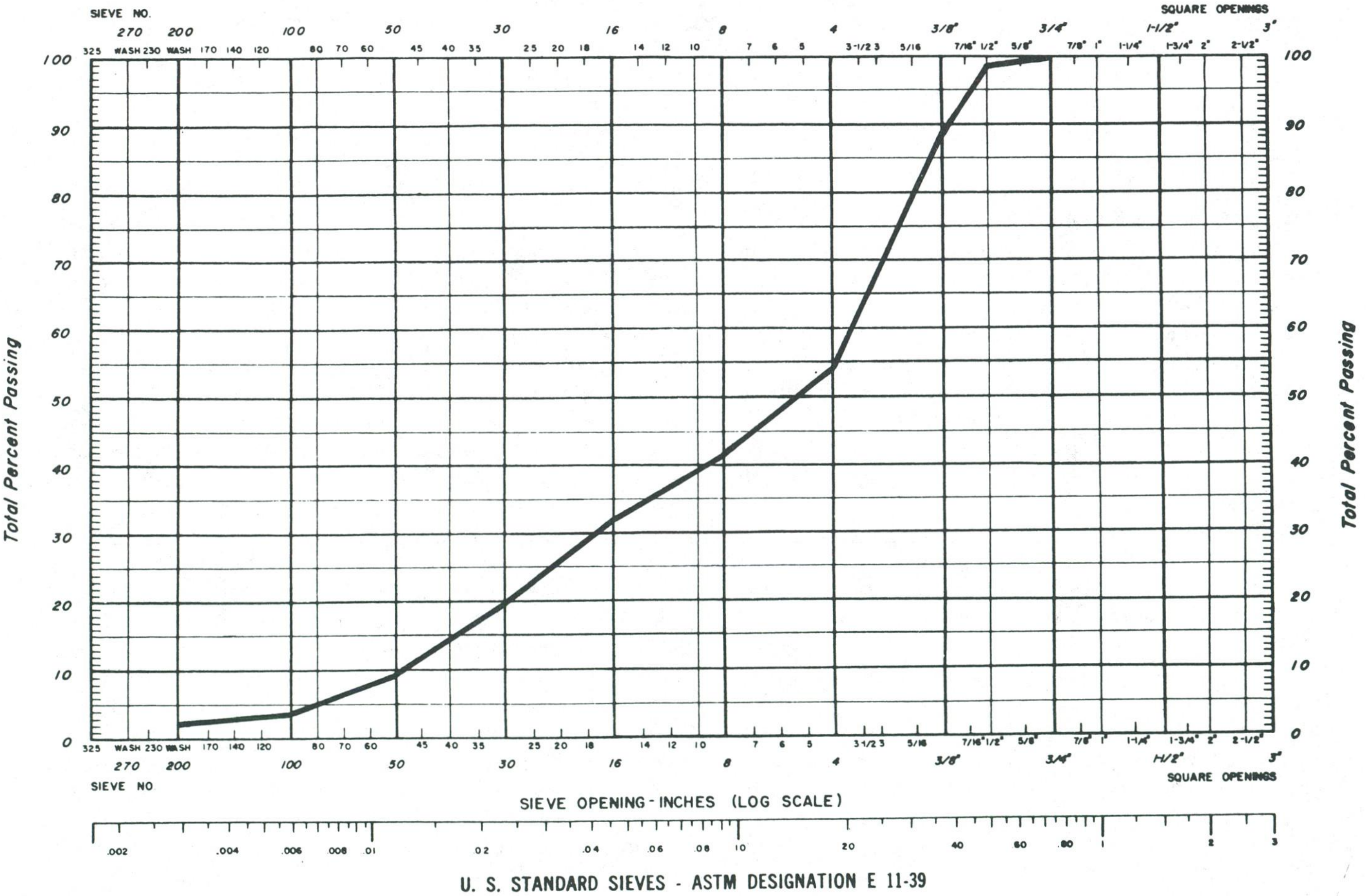

*Figure 47. Gradation of No. 8 granite/concrete sand used for Chesapeake, Virginia, project.*

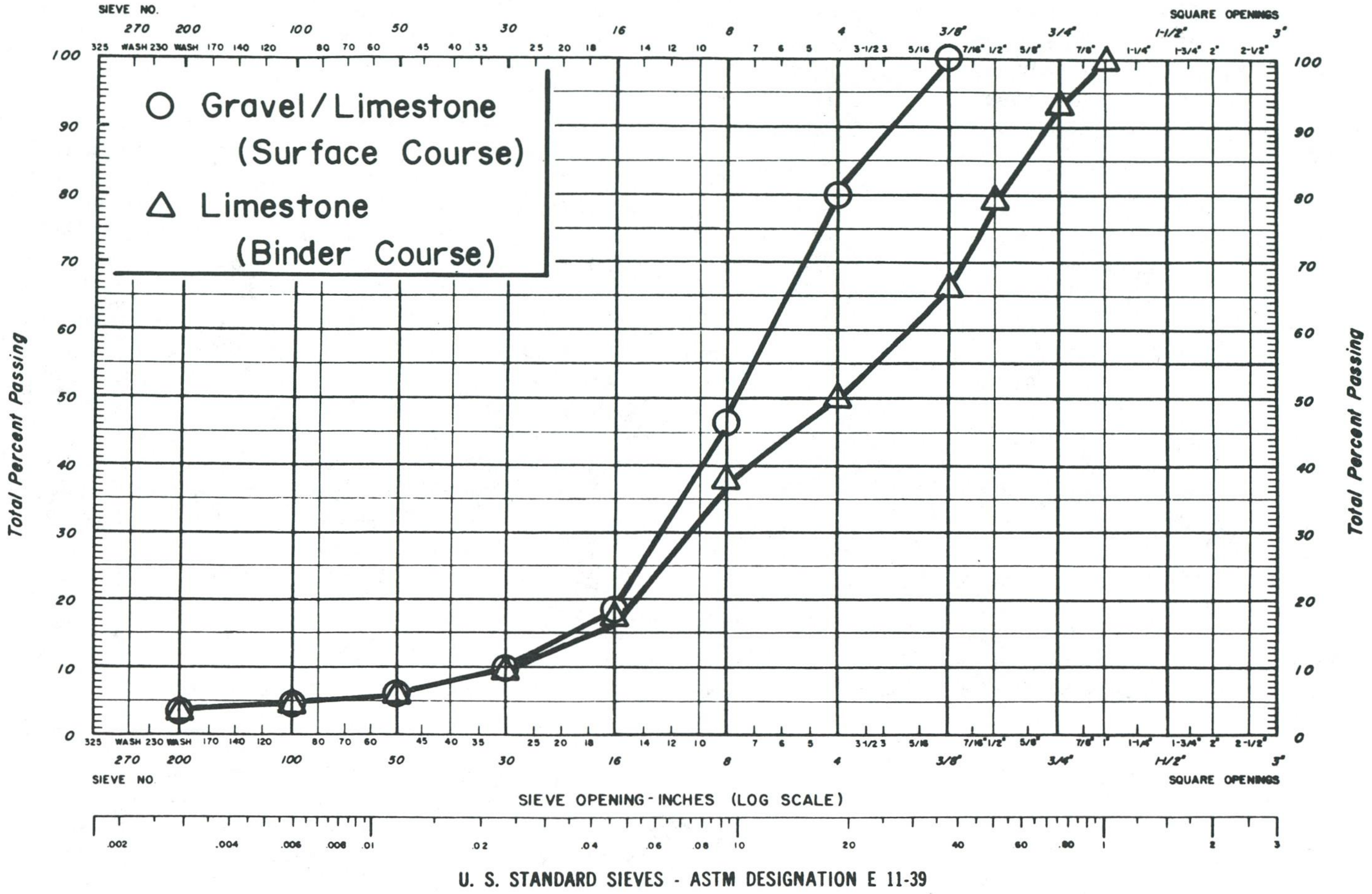

*Figure 48. Gradation of aggregates used for Schuyler County, New York, project.*

countered with this project were due more to inadequate construction techniques and poor control of different construction phases than to inherent problems with the construction materials or with the emulsion mix itself.

The mix designs made in the laboratory did not indicate any problems that could be expected in the field application. Thus, this first field project demonstrated the overwhelming importance of good construction techniques and practices when placing cold emulsion mix and the difficulty of interpreting and applying a small-scale laboratory mix design to actual field conditions.

Experience with the Harrisonburg, Virginia, project led to a belief that emulsions other than CSS-1h, such as solvent-containing medium-setting anionics, would perform better. However, such emulsions were not readily available in Virginia.

### *Saline County, Arkansas, Field Project*

*Details of Construction.* This project involved approximately 3-in. thick lifts over two separate half-mile sections of 2-lane secondary county roads. One section was a surface layer placed on a gravel road treated with 0.3 gal/sq yd penetrating prime. The other was an overlay of an existing asphalt pavement. Four emulsion-aggregate combinations were used. Both MS-2M (containing a relatively large amount of low-volatility solvent) and CSS-1 were combined with a 75-25 blend of crushed gravel and concrete sand, and with a 65-25-10 blend of crushed gravel, concrete sand, and industrial waste material composed primarily of calcareous fines. (See Tables 20 and 21 for properties of aggregates and emulsions.)

Modified UI and AI method mix designs were run on all four combinations, and test data are given in Tables 17 and 18 and in Figures 33 through 36, 41, and 42. Because of the absorptivity of the calcareous fines, much more water was required for the 65-25-10 mixes than for the 75-25 mixes in order to achieve adequate coating and densification. Generally, mixes with CSS-1 required more total water, exhibited less uniform coating, but were considerably less susceptible to water than those with MS-2M. When compacted with 50 blows of the Marshall hammer, mixes with MS-2M had considerably higher dry densities than those of mixes with CSS-1. Also, dry densities of MS-2M mixes tended to increase with increasing residual asphalt or emulsion content, while those of CSS-1 mixes generally decreased with increasing residual asphalt content. In spite of higher dry densities and better coating, mixes with MS-2M were much more water susceptible as shown by substantial decreases in Marshall stability after vacuum saturation. It should be noted that the addition of the calcareous fines resulted in substantial increases in optimum water content for compaction—from 2.9 to 5.6 percent with MS-2M and from 3.4 to 6.1 percent with CSS-1.

Based on the optimum combination of stabilities and dry densities, 4.5 percent residual asphalt content was selected as the target value for the field for mixes with MS-2M emulsion. The results when using CSS-1 were not as conclusive, but an acceptable target value was judged to lie between 3.5 and 4.5 percent.

Saline County used a drum mixer with three cold-feed bins for blending the aggregate and mixing it with the emulsion. The plant was calibrated prior to actual mixing for an output range from 50 to 70 tons per hour. The mix traveled approximately 12 ft in the mixing chamber before being discharged into a 20-ton surge silo. Emulsion-aggregate mixing time, estimated at 30 to 35 sec, could be adjusted by changing the length of the pipe carrying the emulsion into the mixing chamber. A hole was drilled into the chamber to allow the connecting of a water-feed line for added mixing water if needed. The mix was laid using a self-propelled paver called a "Trac Paver."

Monitoring of construction took place during early July 1981, when one 9-ft wide lane approximately a half-mile in length, was laid using MS-2M and the 75-25 aggregate blend. The drum mixing plant was initially calibrated to operate at 60 tons of mix per hour with 16 gal per min of emulsion, which translates into a 7 percent emulsion content (4.7 percent residual asphalt content) based on aggregate weight. Recent rains had left the aggregate stockpiles with water contents in the 5 to 7 percent range at the beginning of construction, giving total water contents in the 7 to 9 percent range which was considerably higher than the 2.9 percent established as optimum in the laboratory. Because of this excess moisture, a decision was made to turn on the drum burner. This had little noticeable effect on the mix temperature (approximately 90°F with or without heat) but did help to remove the excess water. After the stockpiles had a chance to dry out, only the blower was left running.

Approximately 30 min after laydown, just as the emulsion started to break, the mix was given one pass of a 10-ton steel-wheel tandem roller. The intent was to push out excess water without sealing in the remaining water. One hour after laydown, it was given another pass of the roller. Two passes of a 10 to 12-ton pneumatic-tired roller 24-hours after laydown completed the rolling operation.

During the second day of construction, samples of both the aggregate and the mix were obtained and analyzed by the Arkansas State Highway Department for water content. Values for the aggregate were 4.0 and 4.7 percent, and those of the mix ranged from 5.1 to 6.4 percent. The emulsion content was slightly higher (7.3 percent or 4.9 percent residual asphalt content) because the mixture laid the previous day appeared slightly deficient in coating after one day of curing.

An inspection of the pavement on the following day showed the pavement to be in reasonably good shape—even those sections laid prior to a brief rainstorm. There was no rutting, although some areas, especially near intersections, exhibited some signs of raveling, but nothing of major concern. There were no indications of bleeding because of the relatively high void content, but surface particles appeared to be susceptible to scouring by traffic. Overall, the results of this job were considered to be very satisfactory. Apparently, the higher water contents of the mixes in the field did not have detrimental effects on the initial pavement performance.

*Tests on Field Samples.* Eight samples of mix from the Arkansas job (including immediately after mixing, before entering paver, after laydown, and after being stockpiled for one day) were shipped to Institute Headquarters for extraction analysis. Results of this analysis are given in Table 23. The average

**Table 22. Summary of tests on field samples from Harrisonburg, Virginia, project.**

Water Contents of Mineral Aggregate, Percent Dry Aggregate

0.79 0.78 0.71 0.84

Water Contents of Mixture (Truck Samples), Percent Dry Aggregate

2.66 2.59 3.04 3.17

Water Contents of Mixture (Road Samples), Percent Dry Aggregate

2.23 1.53 1.28 3.65 4.03

Residual Asphalt Content (Truck Samples), Percent Dry Aggregate

2.82 2.88 3.61 2.38 3.02 Avg. 2.94

Residual Asphalt Content (Road Samples), Percent Dry Aggregate

3.40 3.85 4.53 4.41 3.79 Avg. 4.00

Wet Density (Dry Density), lb per cu ft

| | | | | | |
|---|---|---|---|---|---|
| 128.3 | 131.7 | 144.9 | 148.6 | 136.6 | 135.4 |
| (126.5) | (130.6) | - | - | - | - |

AGGREGATE GRADATION ON PERCENT PASSING

| Sieve Size | Truck Samples | | | Mix Samples | | | Avg. | Lab. Grad. |
|---|---|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 83.7 | 94.7 | 85.1 | 93.0 | 90.4 | 93.4 | 90.1 | 92.1 |
| 1/2 in. | 44.5 | 69.6 | 56.9 | 73.9 | 71.4 | 74.2 | 65.1 | 74.5 |
| 3/8 in. | 33.1 | 50.3 | 41.7 | 61.9 | 56.3 | 58.8 | 50.4 | 60.2 |
| No. 4 | 19.1 | 26.3 | 26.6 | 35.0 | 33.5 | 33.8 | 29.1 | 36.2 |
| No. 8 | 13.2 | 17.4 | 20.8 | 22.0 | 22.0 | 21.6 | 19.5 | 24.3 |
| No. 16 | 7.5 | 9.7 | 14.7 | 11.9 | 11.8 | 11.6 | 11.2 | 13.9 |
| No. 30 | 4.8 | 6.3 | 11.8 | 7.5 | 7.5 | 7.5 | 7.6 | 8.3 |
| No. 50 | 3.3 | 4.4 | 10.2 | 5.0 | 5.1 | 5.1 | 5.5 | 5.1 |
| No. 100 | 2.4 | 3.2 | 8.5 | 3.5 | 3.6 | 3.6 | 4.1 | 3.4 |
| No. 200 | 1.8 | 2.5 | 3.9 | 2.7 | 2.8 | 2.8 | 2.8 | 2.3 |

**Table 23. Summary of tests on field samples from Saline County, Arkansas, project obtained during construction in July 1981.**

Water Contents of Mineral Aggregate, Percent Dry Aggregate

4.0 4.7

Water Contents of Mixture, Percent Dry Aggregate

5.1 5.6 5.4 6.4

Residual Asphalt Content, Percent Dry Aggregate

(Sample taken immediately after mixing)

4.63 4.20 4.62 Avg. 4.48

Residual Asphalt Content, Percent Dry Aggregate

(Sample taken from truck before mix entered paver, after laydown, or after stockpiling of mix for one day)

4.72 4.15 3.61 4.53 4.48 Avg. 4.30

Aggregate Gradation, Percent Passing

| Sieve Size | Immediately after Mixing | | | Before Entering Paver, after Laydown, or after Stockpiling | | | | | Avg. | Lab. Grad. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 99.7 | 100.0 | 99.4 | 100.0 | 99.9 | 99.8 |
| 1/2 in. | 96.5 | 97.8 | 96.9 | 96.3 | 95.5 | 92.6 | 94.0 | 94.6 | 95.5 | 93.6 |
| 3/8 in. | 87.0 | 89.2 | 84.0 | 86.8 | 79.4 | 76.6 | 79.1 | 83.6 | 83.2 | 75.3 |
| No. 4 | 65.5 | 70.0 | 59.7 | 66.1 | 56.0 | 52.4 | 55.8 | 60.2 | 60.7 | 50.6 |
| No. 8 | 48.0 | 51.8 | 44.7 | 48.6 | 42.3 | 38.6 | 41.4 | 44.1 | 44.9 | 38.3 |
| No. 16 | 35.1 | 38.1 | 33.8 | 36.0 | 32.4 | 29.4 | 32.3 | 32.9 | 33.8 | 30.0 |
| No. 30 | 26.7 | 29.2 | 26.3 | 27.5 | 25.3 | 23.0 | 26.1 | 25.5 | 26.2 | 23.5 |
| No. 50 | 19.3 | 21.4 | 18.7 | 19.7 | 18.2 | 16.6 | 18.9 | 18.1 | 18.9 | 16.8 |
| No. 100 | 10.2 | 11.8 | 9.0 | 10.0 | 9.0 | 8.3 | 9.0 | 8.5 | 9.5 | 7.3 |
| No. 200 | 4.8 | 4.5 | 4.2 | 4.6 | 4.3 | 4.0 | 4.1 | 3.9 | 4.3 | 3.4 |

residual asphalt content of the samples was 4.4 percent with a standard deviation of 0.4 percent and a range of 3.6 to 4.7 percent. This average value was close to the target values of 4.7 to 4.9 percent, especially considering that some of the asphalt remained on the sides of the container after shipping. However, the average gradation of the extracted aggregate was considerably finer (10.1 percent more passing the No. 4 sieve) than the laboratory gradation for the 75-25 blend. Although some of this was due to the degrading effects of mixing, it does indicate that blending of the aggregate at the asphalt plant, in spite of careful calibration, was not entirely accurate.

An important consideration when paving with emulsions is the effect of the environmental conditions on mix composition which affects compaction and curing. In many instances, the water content of the mix is directly governed by the water content in the uncovered aggregate stockpiles because, unlike with hot-mixes, the aggregate is normally not heated prior to or during the mixing process. In Arkansas, the laboratory target value for water content of this mix was 2.9 percent, but measured values were in the 5.1 to 6.4 percent range, which includes the effects of heat from the drum burner. Compounding this problem is the fact that the water content is generally not uniform throughout the stockpiles, can change due to the effects of sun and rain, and can vary as new loads of aggregates are delivered.

In late September of 1981, approximately 2 to 3 months after construction, cylindrical cores (using water) and rectangular blocks (without using water to enable determination of in-situ water contents) were cut from all sections. Three cores (one from between the wheelpaths, one from the outside wheelpath, and one from the inside wheelpath) and one block were cut from the pavement of each of the four combinations of emulsion and aggregate, resulting in a total of 16 samples.

The twelve cores shipped to the Institute from Arkansas were first measured for bulk specific gravity and then tested for Marshall stability. Extractions were then run to determine residual asphalt contents and aggregate gradations. All pertinent properties were computed using the same formulas as for laboratory specimens. The values were grouped according to emulsion-aggregate combination; i.e., average of three specimen values for each of the four combinations.

In addition, the four blocks (sawed without using water) were analyzed for water content, residual asphalt content, and aggregate gradation.

Because all four emulsion-aggregate combinations were tested in the laboratory, comparisons were possible between laboratory specimens and all sixteen of the field samples. The field data, along with comparisons to laboratory specimen data, are given in Table 24.

The field cores were tested for Marshall stability and fairly good agreement was found between core stabilities (corrected for height) and those of "cured" laboratory specimens; i.e., the highest stabilities were for mixes with MS-2M. Although MS-2M mixes showed much more susceptibility to water in the laboratory, the cores apparently were not affected by the environmental effects in the field.

Cores containing CSS-1 for both aggregate blends had slightly higher dry densities than those with MS-2M, which is the opposite of what occurred in the laboratory. In other words, the percent of laboratory density was much higher for CSS-1 cores than for MS-2M cores.

**Table 24. Summary of tests on cores and blocks from Saline County, Arkansas, project obtained in September 1981.**

Water Content, Percent Dry Aggregate

| Mix Composition | Cores | | | Avg. | Blocks |
|---|---|---|---|---|---|
| MS-2M & 75-25 | 0.38 | 0.37 | 0.67 | 0.47 | 0.14 |
| MS-2M & 65-25-10 | 1.10 | 0.92 | 0.79 | 0.94 | 0.94 |
| CSS-1 & 75-25 | 2.01 | 1.00 | 1.33 | 1.45 | 0.20 |
| CSS-1 & 65-25-10 | 1.33 | 3.04 | 1.67 | 2.01 | 1.82 |

Residual Asphalt Content, Percent Dry Aggregate

| Mix Composition | Cores | | | Avg. | Blocks |
|---|---|---|---|---|---|
| MS-2M & 75-25 | 4.54 | 4.93 | 4.15 | 4.54 | 4.96 |
| MS-2M & 65-25-10 | 4.89 | 5.04 | 5.36 | 5.10 | 4.76 |
| CSS-1 & 75-25 | 5.04 | 5.23 | 5.21 | 5.16 | 5.18 |
| CSS-1 & 65-25-10 | 5.11 | 5.27 | 4.79 | 5.06 | 5.12 |

Aggregate Gradation, Percent Passing

| Sieve Size | MS-2M & 75-25 | CSS-1 & 75-25 | Lab. Grad. | MS-2M & 65-25-10 | CSS-1 & 65-25-10 | Lab. Grad. |
|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 99.8 |
| 1/2 in. | 96.1 | 96.6 | 94.5 | 94.0 | 93.8 | 94.4 |
| 3/8 in. | 82.8 | 85.4 | 75.5 | 80.5 | 82.6 | 78.4 |
| No. 4 | 61.0 | 63.9 | 50.7 | 60.7 | 62.7 | 56.8 |
| No. 8 | 45.9 | 46.9 | 38.1 | 47.0 | 48.6 | 45.5 |
| No. 16 | 35.3 | 35.3 | 29.5 | 36.8 | 37.8 | 37.2 |
| No. 30 | 27.7 | 27.5 | 23.3 | 29.2 | 29.7 | 29.9 |
| No. 50 | 20.1 | 20.0 | 15.8 | 21.6 | 21.9 | 21.7 |
| No. 100 | 10.7 | 10.3 | 6.4 | 11.4 | 12.0 | 10.4 |
| No. 200 | 5.2 | 5.2 | 2.4 | 5.3 | 6.0 | 4.9 |

Comparison of Dry Density and Marshall Stability of Pavement Cores with Laboratory Specimens Having Comparable Residual Asphalt Contents

A. Dry Density, lb per cu ft

| Mix Composition | Lab. Specimens 50 blow | Lab. Specimens 5,000 lb | Cores | Cores % of 50 blow | Cores % of 5,000 lb |
|---|---|---|---|---|---|
| MS-2M & 75-25 | 138.7 | 136.9 | 131.7 | 95.0 | 96.2 |
| | | | 131.6 | 94.9 | 96.1 |
| | | | 134.8 | 97.2 | 98.5 |
| | | | Avg. 132.7 | 95.7 | 96.9 |
| MS-2M & 65-25-10 | 136.4 | - | 135.9 | 99.6 | - |
| | | | 130.5 | 95.7 | - |
| | | | 132.7 | 97.3 | - |
| | | | Avg. 133.0 | 97.5 | - |
| CSS-1 & 75-25 | 130.1 | 132.8 | 131.9 | 101.4 | 99.3 |
| | | | 136.7 | 105.1 | 102.9 |
| | | | 134.9 | 103.7 | 101.6 |
| | | | Avg. 134.5 | 103.4 | 101.3 |
| CSS-1 & 65-25-10 | 128.2 | - | 133.5 | 104.1 | - |
| | | | 132.2 | 103.1 | - |
| | | | 136.0 | 106.1 | - |
| | | | Avg. 133.9 | 104.4 | - |

B. Average Marshall Stability, lb

| Mix Composition | Lab. Specimens Cured | Lab. Specimens Immersed | Cores |
|---|---|---|---|
| MS-2M & 75-25 | 2365 | 880 | 4771 |
| MS-2M & 65-25-10 | 2160 | 817 | 7181 |
| CSS-1 & 75-25 | 1252 | 1381 | 3538 |
| CSS-1 & 65-25-10 | 1917 | 1869 | 4135 |

Extractions were run on the cores and blocks, and residual asphalt contents ranged from 4.2 to 5.4 percent. Both 75-25 and 65-25-10 cores were finer in gradation than the laboratory specimen gradations. However, the difference between the 65-25-10 core gradations and the corresponding laboratory gradation was much less than the difference between the 75-25 core gradations and the corresponding laboratory gradation. This wide difference involving the 75-25 blend was also evident with mix samples taken prior to laydown, which would indicate a possible problem with aggregate blending at the asphalt plant when using the 75-25 blend.

In order to monitor the effects of winter weather and sustained traffic, cores and water-content blocks were again cut from the pavements in late April 1982, approximately 9 months after construction of the four pavement sections. A total of 12 cores (3 from each section) and four blocks (1 from each section) were cut from approximately the same locations and shipped to the Institute for analysis.

An inspection of the test sections during the April coring showed them all to be in reasonably good condition with no visible signs of major distress with any of the four emulsion-aggregate combinations, in spite of inundations of the pavements by water during the weeks preceding the coring.

The laboratory tests that were run on the previous pavement samples were repeated on the April 1982 cores and blocks. These data, along with comparisons to laboratory specimen data, are given in Table 25.

When comparing properties of the two sets of cores, there was a decrease in average residual asphalt content for all combinations except CSS-1 with the 65-25-10 aggregate blend. There was no particular pattern with regard to increases or decreases in dry densities, although densities between the wheelpaths were lower for all combinations except MS-2M and 75-25 blend. Average values for percentage of laboratory specimen density remained roughly the same, ranging from 95.7 to 97.5 percent for MS-2M and from 101.3 to 104.4 percent for CSS-1 mixes.

Voids showed slight increases in most cases. As before, field samples with MS-2M had higher voids values than corresponding laboratory specimens, while voids of CSS-1 field samples were lower than such values for laboratory specimens.

The water contents of the 1982 blocks (0.94 to 3.10 percent) were higher than those of 1981 (0.14 to 1.82 percent), but the relative values were comparable; i.e., the highest values in both years were recorded for the mixes containing the 65-25-10 aggregate blend.

Strength testing of laboratory specimens had shown that mixes with MS-2M emulsion were considerably more water susceptible than those with CSS-1. Marshall testing of the 1982 cores with MS-2M showed decreases in average Marshall stabilities of approximately 2,100 lb for the 75-25 blend and 2,600 lb for the 65-25-10 blend as compared to 1981. On the other hand, CSS-1 cores had approximately the same average stability for the 75-25 blend and an increase of about 1,000 lb for the 65-25-10 blend. These changes with time tend to support the importance of a water sensitivity test in the mix design.

Sieve analysis on extracted aggregate from the 1982 cores showed higher average percentages passing most sieve sizes for both aggregate blends, especially the middle sieve sizes—No. 8 to ⅜ in. This could indicate a possible degradation through the action of traffic during the interval between field sampling in 1981 and 1982.

**Table 25. Summary of tests on cores and blocks from Saline County, Arkansas, project obtained in April 1982.**

Water Content, Percent Dry Aggregate*

| Mix Composition | Cores | | | Avg. | Blocks |
|---|---|---|---|---|---|
| MS-2M & 75-25 | 0.93 | 0.45 | 0.60 | 0.66 | 0.99 |
| MS-2M & 65-25-10 | 1.60 | 1.02 | 0.93 | 1.18 | 2.50 |
| CSS-1 & 75-25 | 0.48 | 0.53 | 0.44 | 0.48 | 0.94 |
| CSS-1 & 65-25-10 | 0.64 | 1.14 | 1.00 | 0.93 | 3.10 |

Residual Asphalt Content, Percent Dry Aggregate*

| Mix Composition | Cores | | | Avg. | Blocks |
|---|---|---|---|---|---|
| MS-2M & 75-25 | 4.35 | 4.47 | 3.97 | 4.26 | 4.26 |
| MS-2M & 65-25-10 | 4.20 | 4.61 | 3.92 | 4.24 | 4.15 |
| CSS-1 & 75-25 | 4.78 | 4.66 | 4.75 | 4.73 | 4.55 |
| CSS-1 & 65-25-10 | 5.76 | 5.06 | 5.71 | 5.51 | 4.92 |

Aggregate Gradation, Average Percent Passing*

| Sieve Size | MS-2M & 75-25 | CSS-1 & 75-25 | Lab. Grad. | MS-2M & 65-25-10 | CSS-1 & 65-25-10 | Lab. Grad. |
|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 99.2 | 99.8 |
| 1/2 in. | 97.0 | 97.8 | 94.5 | 91.4 | 95.1 | 94.4 |
| 3/8 in. | 86.2 | 86.5 | 75.5 | 78.5 | 86.0 | 78.4 |
| No. 4 | 62.6 | 64.4 | 50.7 | 59.2 | 66.2 | 56.8 |
| No. 8 | 48.1 | 48.5 | 38.1 | 47.0 | 51.9 | 45.5 |
| No. 16 | 36.2 | 36.1 | 29.5 | 36.8 | 39.9 | 37.2 |
| No. 30 | 28.4 | 28.3 | 23.3 | 29.4 | 31.2 | 29.9 |
| No. 50 | 20.8 | 20.9 | 15.8 | 21.8 | 22.9 | 21.7 |
| No. 100 | 11.5 | 11.2 | 6.4 | 12.1 | 12.2 | 10.4 |
| No. 200 | 5.8 | 6.1 | 2.4 | 6.3 | 5.9 | 4.9 |

Comparison of Dry Density and Marshall Stability
of Pavement Cores with Laboratory Specimens
Having Comparable Residual Asphalt Contents*

A. Dry Density, lb per cu ft

| Mix Composition | Lab. Specimens 50 blow | Lab. Specimens 5,000 lb | Cores | Cores % of 50 blow | Cores % of 5,000 lb |
|---|---|---|---|---|---|
| MS-2M & 75-25 | 138.7 | 136.9 | 131.8 | 95.0 | 96.3 |
| | | | 132.3 | 95.4 | 96.6 |
| | | | 132.5 | 95.5 | 96.8 |
| | | | Avg. 132.2 | 95.3 | 96.6 |
| | | | 1981 (132.7) | (95.7) | (96.9) |
| MS-2M & 65-25-10 | 136.4 | - | 133.6 | 97.8 | - |
| | | | 125.4 | 91.9 | - |
| | | | 134.5 | 98.5 | - |
| | | | Avg. 131.2 | 96.2 | - |
| | | | 1981 (133.0) | (97.5) | - |
| CSS-1 & 75-25 | 130.1 | 132.8 | 138.2 | 106.2 | 104.1 |
| | | | 132.5 | 101.8 | 99.8 |
| | | | 137.2 | 105.5 | 103.3 |
| | | | Avg. 136.0 | 104.5 | 102.4 |
| | | | 1981 (134.5) | (103.4) | (101.3) |
| CSS-1 & 65-25-10 | 128.2 | - | 138.8 | 108.3 | - |
| | | | 131.0 | 102.2 | - |
| | | | 134.7 | 105.1 | - |
| | | | Avg. 134.8 | 105.1 | - |
| | | | 1981 (133.9) | (104.4) | - |

B. Average Marshall Stability, lb

| Mix Composition | Lab. Specimens Cured | Lab. Specimens Immersed | Cores 1981 | Cores 1982 |
|---|---|---|---|---|
| MS-2M & 75-25 | 2365 | 880 | 4771 | 2651 |
| MS-2M & 65-25-10 | 2160 | 817 | 7181 | 4530 |
| CSS-1 & 75-25 | 1262 | 1381 | 3538 | 3471 |
| CSS-1 & 65-25-10 | 1917 | 1869 | 4185 | 5130 |

*For comparisons to the properties of pavement cores obtained in September 1981, see Table 24.

*Comments on Performance.* The results of the field project in Saline County, Arkansas, contrast sharply with those of the Harrisonburg, Virginia, project. Successful pavements, at least on a short-term basis, were achieved in Arkansas using all four emulsion-aggregate combinations. Mix designs run for both projects had indicated that success could be achieved in both cases, and yet the actual results in the field of the Harrisonburg project were far from satisfactory.

Again, this leads to the conclusion that good construction techniques are important when using emulsions. In Arkansas, there was better quality control through the use of separate aggregate stockpiles and three cold feed bins. A longer mixing time resulted in better coating of the larger aggregate particles. With regard to paving procedures, the use of a self-propelled paver such as the "Trac-Paver" in Arkansas is preferred over a Jersey spreader. Better uniformity is achieved and no equipment tracks are left in the freshly laid mix. In Harrisonburg, a dozer was used to push the Jersey spreader which resulted in immediate compaction of the mix in the dozer's wheelpaths. Also, better results are achieved when normal traffic is kept off the mix for as long as possible, even after compaction with a steel-wheel roller. All of these factors had a deciding effect on the quality of the pavements constructed in the Arkansas and Harrisonburg, Virginia, projects.

### *Chesapeake, Virginia, Field Project*

*Details of Construction.* This extensive project, utilizing over one million gallons of emulsion, involved the use of a Midland paver to overlay numerous secondary roads in the City of Chesapeake. The overlay consisted of approximately 1.5 in. of emulsion mix comprised of CMS-2 and a granite meeting the Virginia No. 78 coarse aggregate gradation. However, because of the low amount of fine material in the aggregate (only 29 percent passing the No. 4 sieve), this material did not meet the requirements for dense-graded mix. The Chesapeake Department of Public Works agreed to place a half-mile trial section (approximately 500 tons of mix) using a denser graded aggregate mixed with CMS-2. To achieve the desired gradation, 60 percent of No. 8 granite (slightly coarser than No. 78 with top size of ½ in.) was blended with 40 percent concrete sand. Gradation of mineral aggregate and properties of emulsion are generalized in Tables 20 and 21.

Modified UI and AI method mix designs were run prior to construction (see Tables 17 and 18, and Figures 32 and 40). Tests indicated that optimum water content for mixing and compaction was comprised only of the water in the emulsion and the natural water content of the aggregate. Thus, no added mixing water was necessary for these mixes. Four residual asphalt contents, namely 1.5, 2.5, 3.5, and 4.5 percent, were investigated. Based on the consideration of stabilities and dry densities of both cured and vacuum saturated specimens, 3.5 percent was selected as the initial value for field construction, which translates into 12.2 gal of emulsion per ton of mix.

Construction of the half-mile test section took place in early September 1981. The surface course of one lane of this 2-lane road was paved using a mixture of CMS-2 and the No. 78 granite. The temperature of the emulsion in the tanker was approximately 140°F, and the emulsion content was 14 to 16 gal per ton which resulted in a watery mix; some runoff of fluids occurred on curved sections. The initial compaction was accomplished with several passes of a tandem steel-wheel roller within 15 min after laydown of mixture. This was followed by a light application of fine uncoated aggregate (screenings) using a whirling spreader. Then several additional passes of the roller finished the compaction process.

The adjacent lane was later paved using the denser 60-40 blend of No. 8 granite and concrete sand. For the most part, the target emulsion content was 12 to 13 gal per ton (or 3.4 to 3.8 percent residual content based on aggregate weight). Because this denser blended material holds more fluid, there was none of the runoff observed with the No. 78 mix. Although the No. 8 granite-sand mix exhibited less coating and took longer to cure, it showed more stability after initial compaction (approximately 15 to 30 min after laydown). The quality of this mix was judged to be quite satisfactory and there were no problems with segregation or the mixing operation in the Midland paver. There was initial concern by the contractor that the lower emulsion content would not provide adequate adhesion between the overlay and the underlying surface; however, this proved not to be a problem. After an application of the screenings, the mix was rolled once more.

*Tests on Field Samples.* During construction, eight samples of the mix and four samples of the aggregate were obtained and brought back from Chesapeake for laboratory testing. Results of these tests are given in Table 26. The water contents of the aggregate, which was sampled at approximately 1-hour intervals, ranged from 3.8 to 4.2 percent. These high water contents were due primarily to heavy rain the night before construction and poor drainage around the stockpile. According to the laboratory mix design, for best results the aggregate's water content should have been less than 1 percent. Water contents of the mix samples

**Table 26. Summary of tests on field samples from Chesapeake, Virginia, project obtained during construction in September 1981.**

Aggregate Water Contents, Percent Dry Aggregate

3.80 4.03 4.18 4.18 Avg. 4.05

Mix Water Contents, Percent Dry Aggregate

4.13 4.20 6.02 4.06 3.61 4.62 4.12 3.80 Avg. 4.32

Mix Residual Asphalt Contents, Percent Dry Aggregate

2.53 3.06 2.87 2.97 3.22 3.39 3.18 3.16 Avg. 3.05

Aggregate Gradation, Percent Passing

| Sieve Size | | | | | Avg. | Grad. |
|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 99.3 | 99.2 | 100.0 | 100.0 | 99.6 | 100.0 |
| 1/2 in. | 98.4 | 98.4 | 98.8 | 99.3 | 98.7 | 99.1 |
| 3/8 in. | 87.5 | 90.1 | 88.7 | 88.7 | 88.8 | 89.1 |
| No. 4 | 55.4 | 54.6 | 56.0 | 50.6 | 54.2 | 54.4 |
| No. 8 | 42.4 | 41.9 | 43.3 | 38.0 | 41.4 | 41.7 |
| No. 16 | 32.4 | 32.4 | 33.5 | 29.4 | 31.9 | 32.2 |
| No. 30 | 20.1 | 20.2 | 20.8 | 18.5 | 19.9 | 19.9 |
| No. 50 | 9.1 | 9.4 | 9.5 | 8.8 | 9.2 | 9.2 |
| No. 100 | 3.6 | 4.0 | 3.9 | 3.8 | 3.8 | 3.8 |
| No. 200 | 1.7 | 2.2 | 2.1 | 2.1 | 2.0 | 2.1 |

Extracted Sample Gradation, Percent Passing

| Sieve Size | | | | | | | | | Avg. | Lab. Grad. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 99.6 | 98.5 | 99.8 | 99.1 | 99.3 | 99.7 | 99.4 | 99.6 | 99.4 | 99.1 |
| 3/8 in. | 90.4 | 90.0 | 89.3 | 89.3 | 87.8 | 87.5 | 88.8 | 88.2 | 88.9 | 89.1 |
| No. 4 | 53.9 | 55.4 | 51.8 | 54.4 | 53.6 | 54.2 | 54.0 | 53.6 | 53.9 | 54.4 |
| No. 8 | 40.4 | 41.8 | 38.5 | 41.4 | 41.0 | 41.2 | 41.3 | 41.8 | 40.9 | 41.7 |
| No. 16 | 31.1 | 32.3 | 29.4 | 32.2 | 32.0 | 32.0 | 32.0 | 32.7 | 31.7 | 32.2 |
| No. 30 | 19.7 | 20.4 | 18.2 | 20.5 | 20.5 | 20.3 | 20.3 | 20.7 | 20.1 | 19.9 |
| No. 50 | 9.6 | 9.7 | 8.3 | 10.2 | 10.2 | 9.8 | 9.8 | 9.9 | 9.7 | 9.2 |
| No. 100 | 4.3 | 4.2 | 3.0 | 4.9 | 4.8 | 4.4 | 4.4 | 4.3 | 4.3 | 3.8 |
| No. 200 | 2.5 | 2.4 | 2.6 | 2.5 | 2.9 | 2.6 | 2.6 | 2.5 | 2.6 | 2.1 |

ranged from 3.6 to 6.0 percent. These values were all at least 1.5 percent greater than the 2.2 percent water content selected as optimum in the laboratory.

Although the target values for residual asphalt contents were in the 3.4 to 3.8 percent range, the range of values from extraction of field samples was only 2.9 to 3.4 percent, with an average of 3.1 percent and a standard deviation of only 0.2 percent, indicating good mixing by the Midland paver. There was very good agreement between the aggregate gradations of the extracted samples and the gradation used for laboratory design purposes. This indicates a minimal amount of aggregate degradation resulting from the mixing process.

The Chesapeake field mixes contained on the average approximately 8.8 percent total fluids (asphalt plus water) which is 2.8 percent higher than the 6.0 percent fluids content of the laboratory specimens having 3.5 percent residual asphalt content, the target value for the field. Yet, the field mixes averaged only 3.1 percent residual asphalt content, thus containing more water as a percentage of total fluids. This, no doubt, facilitated mixing and laydown by the Midland paver and enabled the asphalt to be more thoroughly distributed throughout the mix. In spite of the low asphalt contents, the pavement exhibited no signs of raveling.

Three weeks after construction, densities were obtained using the sand-cone method (ASTM Method D 1556). Four samples were taken at each of two selected sites approximately 200 ft apart—two from between the wheel paths, one from the inside wheelpath, and one from the outside wheelpath. These eight samples were each approximately 6 in. in diameter and 1½ in. in depth. Wet densities were determined in the field, and the samples were returned to the laboratory for determining water contents, dry densities, residual asphalt contents, voids, and aggregate gradations.

An inspection of the pavement at that time showed it to be in very good condition. There were no signs of rutting or raveling. When obtaining the sand-cone density samples, it was noted that the lower pavement layer had not cured out; there was noticeable moisture and the mix was still pliable. It should be noted that this overlay was compacted by a steel-wheel roller within a half-hour after laydown and no attempt was made to aerate the mix.

After wet densities were determined in the field, the material dug from the pavement was returned to the laboratory for further tests. Extractions were run to determine residual asphalt contents and aggregate gradations. Water contents, dry densities, total voids, air voids, and voids in the mineral aggregate (VMA) were computed using the same equations as for laboratory specimens. Comparisons were also made to laboratory specimens having comparable residual asphalt contents. The data providing these comparisons are given in Table 27.

**Table 27. Summary of tests on sand-cone density samples from Chesapeake, Virginia, project obtained in September 1981.**

Water Content, Percent Dry Aggregate

| | | | | | |
|---|---|---|---|---|---|
| Site 1 | 0.46 | 0.31 | 0.27 | 0.23 | Avg. 0.32 |
| Site 2 | 0.79 | 0.40 | 0.56 | 0.79 | Avg. 0.64 |

Overall Average 0.46

Residual Asphalt Content, Percent Dry Aggregate

| | | | | | |
|---|---|---|---|---|---|
| Site 1 | 3.78 | 3.25 | 3.66 | 3.30 | Avg. 3.50 |
| Site 2 | 3.42 | 3.21 | 2.92 | 3.21 | Avg. 3.19 |

Overall Average 3.34

Aggregate Gradation, Average Percent Passing

| Sieve Size | Site 1 | Site 2 | Overall Average | Lab. Grad. |
|---|---|---|---|---|
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 99.3 | 98.9 | 99.1 | 99.1 |
| 3/8 in. | 88.8 | 89.3 | 89.0 | 89.1 |
| No. 4 | 51.8 | 57.0 | 54.4 | 54.4 |
| No. 8 | 37.7 | 43.9 | 40.8 | 41.7 |
| No. 16 | 29.0 | 34.2 | 31.6 | 32.2 |
| No. 30 | 19.2 | 22.3 | 20.8 | 19.9 |
| No. 50 | 10.3 | 11.6 | 10.9 | 9.2 |
| No. 100 | 5.2 | 5.6 | 5.4 | 3.8 |
| No. 200 | 3.2 | 3.3 | 3.2 | 2.1 |

Comparison of Dry Density (lb per cu ft) of Sand-Cone Density Samples with Laboratory Specimens Having Comparable Residual Asphalt Contents

| Lab. Specimens | | | | | |
|---|---|---|---|---|---|
| 50 blow | 5,000 lb | | | % of 50 blow | % of 5,000 lb |
| 132.5 | 131.6 | Site 1 Density Samples | 124.3 | 93.8 | 94.4 |
| | | | 121.7 | 91.8 | 92.5 |
| | | | 125.2 | 94.5 | 95.1 |
| | | | 130.7 | 98.6 | 99.3 |
| | | Avg. | 125.5 | 94.7 | 95.3 |
| | | Site 2 Density Samples | 127.0 | 95.8 | 96.5 |
| | | | 136.2 | 102.8 | 103.5 |
| | | | 127.8 | 96.4 | 97.1 |
| | | | 133.8 | 101.0 | 101.7 |
| | | Avg. | 131.2 | 99.0 | 99.7 |
| | | Overall Avg. | 128.3 | 96.8 | 97.5 |

Considerable differences in average property values were measured for mixes at test sites 1 and 2. Site 2 samples had higher water content (0.6 vs 0.3 percent), lower residual asphalt content (3.2 vs 3.5 percent), higher dry densities (131.2 vs 125.5 lb/ft$^3$) and finer gradation than samples at site 1. The combined averages for all eight samples (sites 1 and 2) were reasonably close to properties of laboratory specimens with comparable residual asphalt content. For instance, 96.8 percent of laboratory density in the field gives good support for the use of 50-blow compaction with the Marshall hammer. Considering that both sites were laid with supposedly the same mix, it is surprising that there were such differences between the two sites. Very likely, variability in material properties and construction practices (such as segregation in the aggregate stockpile or timing of compaction) contributed to these differences.

In early June of 1982 (approximately 9 months after construction), density measurements by the sand-cone method and sampling of mixture were repeated. Eight samples were taken in close proximity to the locations of the previous sampling. As before, wet densities were determined in the field, and the samples were returned to the laboratory for further testing and analysis.

Inspection of the pavement at the time of sampling showed it still to be in very good condition. There were no signs of rutting or raveling, although some alligator cracking on one curved section was observed. The pavement was fully cured out to a depth of approximately ¾ in., but was still moist for the lower ¾ in. of the lift.

The tests that were performed on the 1981 density samples were repeated on the 1982 samples. This allowed for comparisons between the two sets of field samples as well as comparisons with laboratory specimens. The test data are given in Table 28.

As with samples obtained in 1981, there were again noticeable differences in properties between test sites 1 and 2 which were approximately 200 ft apart. The average water content of the 1982 samples was lower (0.3 vs 0.5 percent), but the average was higher again at site 2 (0.5 percent) than at site 1 (0.2 percent). The average residual asphalt content was approximately the same at both sites (2.9 percent) and represented a decrease of about 0.5 percent from the 1981 average. There was an overall increase in average dry density of 2.8 lb/ft$^3$ (131.1 vs 128.3), but an increase of only 0.3 lb/ft$^3$ at site 2, while the increase at site 1 was 5.3 lb/ft$^3$. The overall average was approximately 99 percent of laboratory density—an increase of about 2 percent over 1981.

**Table 28. Summary of tests on sand-cone density samples from Chesapeake, Virginia, project obtained in June 1982.**

Water Content, Percent Dry Aggregate*

| | | | | | |
|---|---|---|---|---|---|
| Site 1 | 0.25 | 0.14 | 0.13 | 0.13 | Avg. 0.16 |
| Site 2 | 0.87 | 0.32 | 0.75 | 0.18 | Avg. 0.53 |
| | | | | | Overall Average 0.35 |

Residual Asphalt Content, Percent Dry Aggregate*

| | | | | | |
|---|---|---|---|---|---|
| Site 1 | 2.87 | 2.91 | 2.92 | 2.96 | Avg. 2.92 |
| Site 2 | 2.84 | 3.33 | 2.83 | 2.57 | Avg. 2.89 |
| | | | | | Overall Average 2.90 |

Aggregate Gradation, Average Percent Passing*

| Sieve Size | Site 1 | Site 2 | Overall Average | Lab. Grad. |
|---|---|---|---|---|
| 3/4 in. | 99.8 | 100.0 | 99.9 | 100.0 |
| 1/2 in. | 99.3 | 99.6 | 99.4 | 99.1 |
| 3/8 in. | 89.1 | 91.0 | 90.1 | 89.1 |
| No. 4 | 51.1 | 58.6 | 54.8 | 54.4 |
| No. 8 | 37.9 | 45.5 | 41.7 | 41.7 |
| No. 16 | 29.3 | 35.4 | 32.3 | 32.2 |
| No. 30 | 19.7 | 23.4 | 21.5 | 19.9 |
| No. 50 | 10.9 | 12.4 | 11.7 | 9.2 |
| No. 100 | 5.7 | 6.3 | 6.0 | 3.8 |
| No. 200 | 3.5 | 3.7 | 3.6 | 2.1 |

Comparison of Dry Density (lb per cu ft) of Sand-Cone Density Samples with Laboratory Specimens Having Comparable Residual Asphalt Contents*

| Lab Specimens | | Site 1 Density Samples | | | |
|---|---|---|---|---|---|
| 50 blow | 5,000 lb | | | % of 50 blow | % of 5,000 lb |
| 132.5 | 131.6 | | 128.2 | 96.8 | 97.4 |
| | | | 129.8 | 98.0 | 98.6 |
| | | | 133.1 | 100.5 | 101.1 |
| | | | 132.2 | 99.8 | 100.5 |
| | | Avg. | 130.8 | 98.8 | 99.4 |
| | | Site 2 Density Samples | | | |
| | | | 130.6 | 98.6 | 99.2 |
| | | | 127.4 | 96.2 | 96.8 |
| | | | 133.3 | 100.6 | 101.3 |
| | | | 134.5 | 101.5 | 102.2 |
| | | Avg. | 131.5 | 99.2 | 99.9 |
| | | Overall Avg. | 131.1 | 98.9 | 99.6 |

*For comparisons to the properties of density samples obtained in September 1981, see Table 27.

The most striking difference between the two test sites was with regard to aggregate gradations of the extracted samples. Those from site 2, which was paved first, were considerably finer than the samples from site 1. For example, there was a 7.6 percent difference in the average amount of material passing the No. 8 sieve. This, again, indicates a segregation problem with the single aggregate stockpile used for the job. The overall average gradation was only slightly finer than that for 1981, indicating that traffic had little degrading effect on the aggregate.

*Comments on Performance.* As with Arkansas, this was also for the most part a successful project. There was efficient mixing with the Midland paver which also left no tracks in the pavement during laydown. The aggregate was a well-graded siliceous material that was combined with a cationic emulsion. Laboratory tests had shown no problems with water-sensitivity with this particular emulsion-aggregate combination, and the relatively low emulsion content of this mix indicated that success is possible without the need for 100 percent coating. In effect, a question may be raised as to whether 100 percent coating is necessary for good performance of emulsified asphalt paving mixtures. Admittedly, these are short-term service observations and there is a need to monitor the long-term effects of sustained traffic loadings and environmental exposure.

### *Schuyler County, New York, Field Project.*

*Details of Construction.* This 1.5-mile long project involved an overlay of an asphalt concrete pavement on State Route 79 near Mecklenburg, New York. This 2-lane, each 12 ft wide, undivided highway contained steep grades on certain sections. The emulsion for the job was HFMS-2Gh. For the binder course, limestone with 1-in. top size, and for the surface course, limestone with a small amount of gravel for improved skid resistance having top size of ⅜ in., were used. Mixing was accomplished by using a Barber-Greene portable continuous pugmill mixer having a relatively short mixing time. The aggregate was blended using a 4-bin cold-feed system. The emulsion temperature in the storage tank was approximately 140°F, resulting in a 90 to 100°F mix temperature. The mix was transported to the paving site in dump trucks and laid using a pneumatic-tired Blaw-Knox paver. For this project, mixing was done by a private contractor, whereas transporting and paving were performed by State personnel.

Construction took place in mid-August of 1982. Following the placement of a preleveling course, the binder course was laid in two lifts. The first lift was laid 1¾ in. thick and compacted to 1¼ in. The second lift was placed at least one day later than the first, resulting in a total compacted binder thickness of 2 to 2¼ in. The emulsion content for the binder course was 15.5 gal per ton of aggregate, or roughly 4.6 percent residual asphalt. The surface course was laid 1½ in. thick and compacted to 1 in. The emulsion content for the surface course was 18 gal per ton, or approximately 5.4 percent residual asphalt. No added mixing water was used with either mix.

An 8 to 10-ton steel-wheel tandem roller was used for compaction, which began at least 15 min after laydown to allow for a loss of some volatiles in order to avoid a situation where flushing and bleeding would tend to bring fines to the pavement surface. A longer than 15-min curing period would have been preferable, but traffic necessitated early compaction. Fast-moving traffic, however, had little observable effect on the freshly compacted mix.

Some minor problems were observed during construction, including a lack of coating on the larger particles of the binder course, a tendency for the paver wheels to shove the underlying emulsion mix on steep grades, and a build-up of the surface course mix in front of the screed resulting in an uneven surface behind the paver. However, none of these problems was of major concern. It should be noted that according to New York State DOT personnel raveling had become a problem on a similar pavement constructed in 1980, which was surprising considering the high emulsion content being used. It could have been a result of the poor coating on larger aggregate particles due to the short mixing time of the portable pugmill mixer.

Modified UI and AI method mix designs were run in the laboratory for both the surface and binder courses using 50-blow Marshall compaction and a 10,000-lb static load (see Tables 17 and 18, and Figures 37, 38, 43, and 44). Four residual asphalt contents, in 1 percent increments, were investigated in each case and included the target value used in the field. Tests had indicated that no added mixing water was needed for optimum coating and that immediate compaction after mixing resulted in optimum specimen properties. The field values for the binder and surface courses, respectively, were considerably higher than the trial values derived from the CKE method (4.6 and 5.4 percent vs 3.2 and 3.9 percent).

The results of the designs were, for the most part, inconclusive for both mixes. Marshall stabilities, $R_t$-values and C-values of vacuum-saturated specimens generally decreased with increasing residual asphalt content. With the binder course, there was a considerable drop in dry density of vacuum-saturated specimens above 3.2 percent residual asphalt content and a substantial drop in percent retained Marshall stability with residual asphalt content of 5.2 percent. With the surface course, there was a considerable decrease in dry density of vacuum-saturated specimens with 6.0 percent residual asphalt content. Thus, the field value for the binder course might have been at least 1 percent too high, while that for the surface course was reasonably accurate based on the laboratory designs. It is interesting to note that no mix designs were run by the contractor for these mixes. Instead, the field values for emulsion content were selected on the basis of experience with this mixture type.

*Tests on Field Samples.* Ten samples of the mix (five of the binder course and five of the surface course) were obtained during construction for extraction tests. The results of these tests are provided in Table 29.

The average field values for residual asphalt content of both the binder and surface course were very close to the target values. Also, there was reasonably close agreement between the aggregate gradations of the field samples and those of laboratory specimens, although surface course samples from the field were somewhat finer. This would help to explain the rather high emulsion content used for this mix.

**Table 29. Summary of tests on field samples from Schuyler County, New York, project obtained during construction in August 1982.**

Water Content, Percent Dry Aggregate*

| | | | | | |
|---|---|---|---|---|---|
| Site 1 | 0.25 | 0.14 | 0.13 | 0.13 | Avg. 0.16 |
| Site 2 | 0.87 | 0.32 | 0.75 | 0.18 | Avg. 0.53 |
| | | | | | Overall Average 0.35 |

Residual Asphalt Content, Percent Dry Aggregate*

| | | | | | |
|---|---|---|---|---|---|
| Site 1 | 2.87 | 2.91 | 2.92 | 2.96 | Avg. 2.92 |
| Site 2 | 2.84 | 3.33 | 2.83 | 2.57 | Avg. 2.89 |
| | | | | | Overall Average 2.90 |

Aggregate Gradation, Average Percent Passing*

| Sieve Size | Site 1 | Site 2 | Overall Average | Lab. Grad. |
|---|---|---|---|---|
| 3/4 in. | 99.8 | 100.0 | 99.9 | 100.0 |
| 1/2 in. | 99.3 | 99.6 | 99.4 | 99.1 |
| 3/8 in. | 89.1 | 91.0 | 90.1 | 89.1 |
| No. 4 | 51.1 | 58.6 | 54.8 | 54.4 |
| No. 8 | 37.9 | 45.5 | 41.7 | 41.7 |
| No. 16 | 29.3 | 35.4 | 32.3 | 32.2 |
| No. 30 | 19.7 | 23.4 | 21.5 | 19.9 |
| No. 50 | 10.9 | 12.4 | 11.7 | 9.2 |
| No. 100 | 5.7 | 6.3 | 6.0 | 3.8 |
| No. 200 | 3.5 | 3.7 | 3.6 | 2.1 |

Aggregate Gradation--Surface Course, Percent Passing

| Sieve Size | | | | | | Avg. | Lab. Grad. |
|---|---|---|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/8 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| No. 4 | 80.5 | 80.6 | 80.5 | 81.3 | 80.1 | 80.6 | 78.7 |
| No. 8 | 44.6 | 44.5 | 45.7 | 45.3 | 46.5 | 45.3 | 46.1 |
| No. 16 | 18.4 | 17.5 | 18.1 | 17.1 | 19.3 | 18.1 | 17.3 |
| No. 30 | 10.4 | 9.6 | 9.9 | 9.5 | 10.7 | 10.0 | 8.6 |
| No. 50 | 7.1 | 6.6 | 6.9 | 6.6 | 7.3 | 6.9 | 5.5 |
| No. 100 | 5.5 | 5.1 | 5.5 | 5.2 | 5.7 | 5.4 | 3.8 |
| No. 200 | 4.6 | 4.2 | 4.6 | 4.3 | 4.8 | 4.5 | 3.1 |

In mid-October, approximately 2 months after construction, cores were taken from the State Route 79 overlay. Four cores, one from between the wheelpaths and one from a wheelpath for both lanes, were taken at each of two sites approximately one-half mile apart for a total of eight cores. At the laboratory, the fused surface and binder courses were separated and each was tested for density, voids, and Marshall stability and subjected to extraction tests. The results of the tests, plus comparisons to the properties of comparable laboratory specimens, are given in Table 30.

As with the mix samples obtained during construction, the average values for the residual asphalt content of both the binder and surface course were close to the target values in the field. Average gradations of the core aggregates were somewhat higher than those of the mix samples, especially in the middle sieve sizes, indicating the degrading effects of compaction and traffic. Dry densities of the cores were in the 93 to 95 percent range of laboratory densities, indicating the advisability of using 50 blows of the Marshall hammer and a 10,000-lb static load for laboratory compaction. Marshall stabilities of the cores were considerably higher than those of cured laboratory specimens for the surface course but only slightly higher for the binder course. These results, plus the fact that several of the binder course cores literally collapsed overnight while stored at room temperature, indicate that the emulsion content for the binder

**Table 30. Summary of tests on cores from Schuyler County, New York, project obtained in October 1982.**

Binder Course, Residual Asphalt Content, Percent Dry Aggregate

4.40 5.64 4.57 Avg. 4.87

Surface Course, Residual Asphalt Content, Percent Dry Aggregate

5.27 5.10 5.65 5.09 Avg. 5.28

Aggregate Gradation, Average Percent Passing

| Sieve Size | Binder Course | Lab. Grad. | Surface Course | Lab. Grad. |
|---|---|---|---|---|
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 97.0 | 92.8 | 100.0 | 100.0 |
| 1/2 in. | 87.5 | 79.0 | 100.0 | 100.0 |
| 3/8 in. | 78.6 | 66.2 | 99.8 | 100.0 |
| No. 4 | 58.9 | 50.6 | 81.2 | 78.7 |
| No. 8 | 41.6 | 37.9 | 49.3 | 46.1 |
| No. 16 | 19.6 | 16.9 | 22.1 | 17.3 |
| No. 30 | 11.3 | 9.2 | 12.6 | 8.6 |
| No. 50 | 7.7 | 5.8 | 8.6 | 5.5 |
| No. 100 | 5.9 | 4.0 | 6.7 | 3.8 |
| No. 200 | 4.9 | 2.9 | 5.5 | 3.1 |

Comparison of Dry Density and Marshall Stability of Pavement Cores with Laboratory Specimens Having Comparable Residual Asphalt Contents

A Dry Density, lb per cu ft

| | Lab. Specimens | | Cores | | |
|---|---|---|---|---|---|
| Mix Composition | 50 blow | 10,000lb | | % of 50 blow | % of 10,000 lb |
| Binder Course | 138.2 | 140.4 | 133.1 | 96.3 | 94.8 |
| | | | 131.7 | 95.3 | 93.8 |
| | | | 131.0 | 94.8 | 93.3 |
| | | | 129.9 | 94.0 | 92.5 |
| | | | 134.7 | 97.5 | 95.9 |
| | | | Avg. 132.1 | 95.6 | 94.1 |
| Surface Course | 130.0 | 133.4 | 124.0 | 95.4 | 93.0 |
| | | | 125.0 | 96.2 | 93.7 |
| | | | 125.4 | 96.5 | 94.0 |
| | | | 129.3 | 99.5 | 96.9 |
| | | | 124.4 | 95.7 | 93.3 |
| | | | 122.0 | 93.8 | 91.4 |
| | | | 125.2 | 96.3 | 93.9 |
| | | | 126.0 | 96.9 | 94.5 |
| | | | Avg. 125.2 | 96.3 | 93.9 |

B. Average Marshall Stability, lb

| | Lab Specimens | | |
|---|---|---|---|
| Mix Composition | Cured | Immersed | Cores |
| Binder Course | 1103 | 879 | 1473 |
| Surface Course | 1262 | 1169 | 2510 |

course may have been too high. Also, it is reasonable to assume that the binder course was less cured-out than the surface course after only 2 months of service. The problem of differential curing in the field is one of the major factors in the difficulty of applying laboratory results to field conditions.

*Comments on Performance.* The mixing operation for this project was interesting in that a sophisticated 4-bin cold-feed system was used in conjunction with a portable pugmill mixer having a short mixing time. Thus, the accuracy of the aggregate feed system was somewhat negated by the lack of thorough mixing associated with this type of mixer. The sieve analyses on field samples of the binder course had shown considerable variation in the percentages passing the large sieve sizes, and coating had been a problem with the larger aggregate particles. Considering the problems with the Harrisonburg project, which involved the use of a portable pugmill mixer, and the comments concerning raveling on 2-year old emulsion pavements in New York, the effectiveness of this type of mixing for dense-graded emulsion mixes may be questionable.

Doubts had existed as to the feasibility of coring only 2 months after construction. However, no problems were encountered during the coring operation, though the ambient temperature was in the low 50's. Had the temperature at the time of coring been higher, the results may have been less successful, as indicated by the collapse of several cores at normal room temperature. No visible signs of distress in the pavement were evident at the time of coring. After the pavement has been subjected to the severe winter weather of New York, its condition may be considerably different, especially with regard to the structural adequacy of the binder course.

CHAPTER THREE

# INTERPRETATION, APPRAISAL, APPLICATION

## ANALYSIS OF LABORATORY DESIGNS

### Dense-Graded Mixes

The test data and experience accumulated from the twelve mix designs (six for each method) conducted using the University of Illinois and The Asphalt Institute methods with dense-graded aggregate mixes indicate that the methods' ability to adequately determine optimum emulsion and water contents is primarily a function of the specific emulsion-aggregate combination being investigated. In some instances, graphs obtained by plotting residual asphalt content against density or strength characteristics resulted in well-defined peaks which provided definitive values for the selection of mixture composition. However, with the majority of other emulsion-aggregate combinations, there was either a continuous increase or decrease, or a random pattern, in specimen property values with increasing residual asphalt content, thus making the selection of "optimum" conditions for the mix mostly a matter of judgment. With these types of test results, the effectiveness of the design criteria of both the UI and AI methods is quite limited. It is evident that these two published methods have merit; however, based on the data developed in this research, they do not have universal applicability and must be used only on a comparative basis with previous experience. This limitation is similar to that of the Marshall and Hveem designs used for hot-applied paving mixtures.

In addition to the inadequacy of the reference methods with regard to pinpointing optimum mix components, two other aspects of the design procedures prompted the investigation of modifications. First, the methods for trial emulsion content determination, specimen compaction, and curing-water exposure of the two methods are considerably different and result in strength tests being conducted on specimens that are comprised of the same components but have dissimilar densities, voids, emulsion contents, and water contents. These differences make comparisons between the two methods virtually impossible. Secondly, the reference methods take a considerable length of time to complete. Considering that these design procedures are used primarily for designing mixes for secondary roads, a desirable objective would be to shorten the time needed to complete the designs.

All of these concerns point toward the need for modifications of one or both of these methods.

The major goals of the modification phase of this research were to adjust the procedures so that specimens having comparable properties could be tested following a shorter conditioning period. An attempt was made to: (1) provide agreement in the procedures for determining trial emulsion contents; (2) standardize the curing-water exposure procedures for the two methods; and (3) modify the levels of compactive effort in order to achieve comparable densities between Marshall and Hveem specimens, to reduce aggregate degradation during compaction, and to obtain densities in closer agreement with those of actual pavements.

As described and discussed in Chapter Two, the effects of various levels of compactive effort and curing-water exposure procedures were extensively investigated. The rigorous review of the reference methods and the analyses of the laboratory investigations scrutinizing various modifications to individual procedural steps of both design methods has resulted in the following recommendations:

A. *Suggested Modifications to University of Illinois Design Method*

1. The use of the Centrifuge Kerosene Equivalent (CKE) method to determine the trial residual asphalt content is preferred in place of an empirical equation based on aggregate gradation. Such an equation with aggregate lacking fines results in negative values for the residual asphalt content.
2. Mixing enough material to prepare only one specimen each time instead of batching enough for three or six identical specimens is preferable. Preparation and storage of loose mixture for multiple specimens enhances the progression of water evaporation which affects the compaction process.
3. Batch weights for the coating test should be the same as for specimens prepared for the compaction and strength tests. This would save time and effort needed to calculate aggregate blends.
4. For more effective aeration during the coating test, flat pans instead of mixing bowls should be used.
5. Oven drying of loose mixture prepared for the coating test should not be allowed. Such drying results in agglomeration of the mixture or nonuniform distribution of moisture.
6. Sixty seconds for premixing aggregate and water is sufficient. Two minutes mixing for that purpose is too long.
7. Mixing of wetted aggregate and emulsion should be accomplished in 1 min instead of 5 min. Mixing time should be shortened to 30 sec if segregation of asphalt-fines mixture from coarse aggregate is noticed.
8. The use of oven for drying back of loose mixture should not be permitted. It promotes nonuniform drying and causes premature breaking of the emulsion. To aerate loose mixture, use of a fan, as described in ASTM coating test, is preferable.
9. Using 50 blows of the Marshall hammer on each specimen end for compaction instead of 75 blows is suggested. Because of degradation, even 50 blows compactive effort may be too high with some aggregates.
10. For compaction testing, examine the water content established as optimum for mixing plus 1 and 2 percent drybacks. The examination of water contents greater than that established in the coating test is not practical.

11. For the compaction test, besides Marshall stability, dry density of specimens should also be determined. Such values could be used conjunctively to determine optimum water content for compaction.

12. Curing of specimens for the strength test phase should be changed from 3 days in mold to 1 day in mold followed by 1 day out of mold in oven at 100°F.

13. Changing of water exposure procedure from 2 days capillary soaking for each specimen end to 1-hour vacuum saturation followed by 1-hour immersion (AI method procedure) is recommended. Shortening of curing-water exposure procedures as recommended would provide considerably greater flexibility in the design procedures.

14. For the calculation of water content at testing, the specimens should be weighed before instead of after the Marshall stability measurement. Using this weight will minimize the error since some moisture and material may be lost during handling and stability measurements.

15. Apparent specific gravity of aggregate instead of bulk specific gravity should be used to compute voids of compacted specimens. This would result in more realistic air voids values.

16. The design criteria of 2 to 8 percent of total voids should be ignored. Nearly all specimens had total voids in excess of 8 percent, even when using bulk specific gravity of the aggregate in the calculation.

17. If no peak in residual asphalt content vs immersed stability or other properties is developed, the optimum emulsion content should be established based on the best combination of such properties as Marshall stability of both cured and immersed specimens, percent retained stability and dry density, with particular attention to the effects of water on specimen properties.

B. *Suggested Modifications to The Asphalt Institute Design Method*

1. Batches for the mixing test should be the same as for the compaction and strength tests.

2. The time for blending water, aggregate, and emulsion with a mechanical mixer should be 1 min instead of 30 sec. Mixing time may be shortened to 30 sec if segregation in the mixture is noticed.

3. For the compaction test, specimens should be cured for 1 day in the mold and then extruded. Dry densities should be determined by displacement in water instead of by just height and mass measurements.

4. The double-plunger static load should be reduced from 40,000 to 10,000 lb. Such a reduction would result in more reasonable specimen densities and also minimize crushing of mineral aggregates.

5. For the strength test, at least four residual asphalt contents should be examined. These asphalt contents should be distributed in equal increments above and below a base residual asphalt content that is derived from the initial emulsion content which is equal to 1.4 times the CKE oil ratio.

6. Holding water content and not total fluids content constant for compaction in the strength test appears to be a more reasonable and convenient approach. Water contents are established in the mixing and compaction tests which are conducted using a fixed emulsion content. By keeping the water content constant in the strength test, the only variable is residual asphalt content. With constant fluids content, however, both asphalt and water contents are variables.

7. For fully cured specimens, curing for 1 day in mold at room temperature followed by 1 day out of the mold in oven at 100°F should be used. This replaces the 3-day cure in mold plus 4 days of vacuum desiccation. Such change saves time and provides specimens with equivalent properties.

8. There is no need to measure resilient modulus, $M_R$, of fully cured specimens. $M_R$ is used for pavement thickness design rather than for the establishment of mixture composition. However, $M_R$ would be measured if such information is needed for designing pavement thickness.

9. No changes in water exposure procedures are recommended. After being fully cured, the specimens are exposed to 1 hour of vacuum saturation followed by 1 hour of immersion at room temperature.

10. An optimum emulsion content is established on the basis of the best combination of specimen properties, instead of selecting a minimum content which meets the rather tenuous mix design criteria of the reference method. Tests indicate that these criteria are met even by specimens having unreasonably low emulsion contents. Stability, density, and maximum resistance to water should be emphasized when establishing an optimum emulsion content.

In spite of the inclusion of these recommended modifications, mix design tests made using the revised methods (see Chapter Two) did not result in easily identifiable optimum mix components for most emulsion-aggregate combinations. Test data lead to the conclusion that the selection of the optimum emulsion and water contents cannot be based on just one property such as peak Marshall stability on water-immersed specimens as specified in the UI method. A judgment has to be made regarding the relative importance of individual properties such as the level of stability and attainable density and voids. However, because of the need for information on adequate mixture durability, the emphasis should be placed on the effects of water on those properties. For example, often mixtures of lower stability but exhibiting higher water resistance should be selected over high stability mixtures having low resistance to water.

Other factors must also be considered when selecting emulsified asphalt mixtures. These include environmental conditions in the field, construction techniques, and availability of equipment. The ultimate decision may have to depend on engineering judgment based on economics and previous experiences with similar materials and processes.

## Open-Graded Mixes

The Asphalt Institute design method for open-graded mixes is considerably less complicated than either of the two design methods for dense-graded mixes. Primarily, the open-graded mix design involves subjective judgments regarding coating and workability of trial mixes comprised of emulsion and water contents that vary in fixed increments. There are two actual tests in the design procedure, namely the runoff test for loose mixes and the washoff test for compacted specimens. As the names of the tests imply, the first indicates whether a maximum fluids content has been exceeded and the other reflects on the degree of water sensitivity by simulating the effects of rainfall on a recently laid pavement. These tests are directed more toward eliminating unsuitable mixes rather than for the establishing of optimum mix components.

As shown in Table 8 of Chapter Two, these two tests were run on a variety of emulsion-aggregate combinations and wide variability in the tests results was indicated. Because of the nature of the runoff test, it was not possible to investigate any modifications to that test. With the washoff test, the curing time and the level of compactive effort could be subjected to variation and evaluation. However, the 24-hour cure in the mold appeared to be appropriate for simulating a pavement in the early stages of curing, and, thus, no modification to the curing period was investigated. On the other hand, the use of the 40,000-lb double-plunger static load was judged to be excessive especially when considering the degrading effects that this load had on the aggregate in dense-graded mix specimens. It should be noted, however, that reduction of the compactive load had no noticeable effect on the results of the washoff test. Tests indicated that reduction of the static load to 10,000 lb results in more reasonable densities and decreased degradation of open-graded aggregate.

Generally, the tests results lead to the conclusion that the selection of emulsion and water contents for a given aggregate type and gradation is rather subjective in nature. The runoff and washoff tests results can only serve as general guidelines in the selection of mixture composition. The ultimate decision will depend primarily on visual judgments regarding coating of aggregate and workability of the mixture. Other factors such as environmental and traffic conditions must also be considered.

## APPLICABILITY OF LABORATORY DESIGNS OF DENSE-GRADED AGGREGATE MIXES TO FIELD CONSTRUCTION

Four field projects were studied in an attempt to determine if mixes designed in the laboratory could be effectively used in actual pavement construction. These projects involved the use of a wide variety of emulsified asphalts and mineral aggregates, mixing techniques, and laydown operations. Table 19 in Chapter Two summarizes the pertinent details of each project. These four projects involved a wide variation in geographic location and climatic conditions, and, thus, could serve as suitable contrasts for studying the effects of environmental conditioning on a short-term basis.

On the basis of laboratory designs, the Institute made recommendations regarding target residual asphalt contents for the projects in Harrisonburg, Virginia; Saline County, Arkansas; and Chesapeake, Virginia. The actual values in the field were generally equal to or slightly higher than the recommended values. No recommendation was made for the Schuyler County, New York, project, but laboratory testing performed after construction pointed to lower residual asphalt contents than those used in the field for both the binder and surface courses. Though water contents for mixing were established in the laboratory, it was generally not feasible to follow the suggested value in the field because water contents of the aggregate stockpiles were subject to fluctuating environmental influences and the available mixing equipment either prohibited the use of added mixing water or included a water-feed that could not be closely regulated.

Three of the projects resulted in the successful construction of pavements. Only the Harrisonburg project could not be constructed as planned because of numerous problems encountered. Yet the laboratory designs, especially with regard to the primary criteria of adequate stability and resistance to water sensitivity, had indicated that successful pavements could be achieved with all four projects.

A key question may be raised as to whether a laboratory mix design is critical for the construction and performance of an emulsion pavement. As was noted earlier, it is extremely difficult to develop a mix design method that simulates what occurs in the field. All mixture proportion elements in the laboratory are far better controlled than comparable field operations. For instance, laboratory mixing is more effective in distributing the asphalt throughout the aggregate due to the small batch size, the longer mixing time, and higher input of mixing effort. It is interesting to note that the Harrisonburg project, which was unsuccessful, and the Schuyler County project which, based on experience with similar mixes, had indicated a potential for raveling, involved the use of portable pugmill mixers having very short mixing times as compared to those of the dryer-drum and Midland paver used for the Saline County and Chesapeake jobs, respectively.

Another critical element is the time for initiating compaction of the freshly laid mix. In many cases, this is controlled by extraneous factors such as the need for traffic to use the roadway (as in Harrisonburg and Schuyler County) or restrictions on time for completing construction. One possible solution to this dilemma is to stockpile the mix prior to laydown; i.e., let the mix initially cure at a location away from the actual paving site as was done with some of the mixes in Saline County. It is not uncommon to have only the upper portion of a compacted emulsion pavement adequately "cured out" while the lower portions remain moist for extended periods after laydown. This again points to the difficulty of comparing laboratory specimens to in-situ pavements. Obviously a 2½-in. × 4-in. cylindrical specimen, even when left in the mold, will cure at room conditions more uniformly than any pavement layer will.

Another point to consider with laboratory specimens is the mode of compaction and the degree of aggregate degradation. Tests on field samples indicated that although comparable densities to those obtained in the laboratory (using the revised methods) were being achieved, the amount of aggregate degradation was considerably less. This is well illustrated in Table 31. Crushing of the aggregate in the confined space of a mold to form interlocking particles contributes more to achieving laboratory density than is the case with a relatively unconfined field mix where particle realignment is the major factor controlling density. The results of strength tests on laboratory specimens may, therefore, be more of an indication of this particle interlock (which is a function of aggregate type) than the ability of the emulsion to effectively bond the aggregate which is the more dominant mechanism in the field.

As discussed in Chapter Two, emulsion mixtures are considerably more complex than either asphalt concrete or paving mixtures with cutback asphalt. They are comprised of mineral aggregate, asphalt, chemical emulsifiers, water and, in some instances, solvents. An added complication is that the water content of this multicomponent system does not remain constant during or after construction. It varies as a function of environmental conditions and specimen properties such as density and voids. It is questionable whether design methods that were adapted from existing methods for hot-mix asphalt concrete (which reaches a "steady-state" condition very soon after com-

**Table 31. Comparison between laboratory and field aggregate gradations and degradation due to compaction.**

Saline County, Arkansas
(MS-2M & Gravel/Sand)

| | Laboratory | | | Field | | |
|---|---|---|---|---|---|---|
| Sieve Size | Uncompacted Batch | 50 blow | 5,000 lb | Loose Mix | After 3 Months | After 9 Months |
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 99.4 | 99.9 | 100.0 | 100.0 |
| 1/2 in. | 94.5 | 95.1 | 94.0 | 95.5 | 96.1 | 97.0 |
| 3/8 in. | 75.5 | 80.8 | 79.6 | 83.2 | 82.8 | 86.2 |
| No. 4 | 50.7 | 56.1 | 54.9 | 60.7 | 61.0 | 62.6 |
| No. 8 | 38.1 | 42.8 | 40.8 | 44.9 | 45.9 | 48.1 |
| No. 16 | 29.5 | 32.8 | 31.6 | 33.8 | 35.3 | 36.2 |
| No. 30 | 23.3 | 21.0 | 25.7 | 26.2 | 27.7 | 28.4 |
| No. 50 | 15.8 | 16.3 | 19.1 | 18.9 | 20.1 | 20.8 |
| No. 100 | 6.4 | 8.5 | 9.6 | 9.5 | 10.7 | 11.5 |
| No. 200 | 2.4 | 4.5 | 4.6 | 4.3 | 5.2 | 5.8 |

Chesapeake, Virginia
(CMS-2 & No. 8 Granite/Sand)

| | Laboratory | | | Field | | |
|---|---|---|---|---|---|---|
| Sieve Size | Uncompacted Batch | 50 blow | 5,000 lb | Loose Mix | After 1 Month | After 9 Months |
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 99.9 |
| 1/2 in. | 99.1 | 98.8 | 98.5 | 99.4 | 99.1 | 99.4 |
| 3/8 in. | 89.1 | 90.0 | 90.4 | 88.9 | 89.0 | 90.1 |
| No. 4 | 54.4 | 59.1 | 56.9 | 53.9 | 54.4 | 54.8 |
| No. 8 | 41.7 | 43.9 | 43.0 | 40.9 | 40.8 | 41.7 |
| No. 16 | 32.2 | 34.4 | 33.5 | 31.7 | 31.6 | 32.3 |
| No. 30 | 19.9 | 23.7 | 21.9 | 20.1 | 20.8 | 21.5 |
| No. 50 | 9.2 | 12.8 | 11.2 | 9.7 | 10.9 | 11.7 |
| No. 100 | 3.8 | 6.0 | 5.1 | 4.3 | 5.4 | 6.0 |
| No. 200 | 2.1 | 3.3 | 2.8 | 2.6 | 3.2 | 3.6 |

Schuyler County, New York
(Binder Course: HFMS-2Gh & Limestone)

| | Laboratory | | | Field | |
|---|---|---|---|---|---|
| Sieve Size | Uncompacted Batch | 50 blow | 10,000 lb | Loose Mix | After 2 Months |
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 92.8 | 94.2 | 92.0 | 94.2 | 96.4 |
| 1/2 in. | 79.0 | 82.4 | 80.7 | 81.3 | 85.7 |
| 3/8 in. | 66.2 | 71.0 | 68.9 | 70.7 | 76.8 |
| No. 4 | 50.6 | 54.1 | 54.2 | 52.6 | 57.6 |
| No. 8 | 37.9 | 42.0 | 42.3 | 34.8 | 40.5 |
| No. 16 | 16.9 | 21.7 | 23.1 | 15.0 | 19.3 |
| No. 30 | 9.2 | 12.5 | 14.0 | 8.6 | 11.2 |
| No. 50 | 5.8 | 8.3 | 9.4 | 5.8 | 7.7 |
| No. 100 | 4.0 | 6.1 | 6.9 | 4.4 | 5.9 |
| No. 200 | 2.9 | 4.9 | 5.4 | 3.6 | 4.9 |

Schuyler County, New York
(Surface Course: HFMS-2Gh & Gravel/Limestone)

| | Laboratory | | | Field | |
|---|---|---|---|---|---|
| Sieve Size | Uncompacted Batch | 50 blow | 10,000 lb | Loose Mix | After 2 Months |
| 1 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/4 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2 in. | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/8 in. | 100.0 | 100.0 | 99.4 | 100.0 | 99.8 |
| No. 4 | 78.7 | 81.0 | 81.1 | 80.6 | 81.2 |
| No. 8 | 46.1 | 52.8 | 57.3 | 45.3 | 49.3 |
| No. 16 | 17.3 | 24.5 | 29.3 | 18.1 | 22.1 |
| No. 30 | 8.6 | 13.5 | 17.0 | 10.0 | 12.6 |
| No. 50 | 5.5 | 8.8 | 11.2 | 6.9 | 8.6 |
| NO. 100 | 3.8 | 6.5 | 8.2 | 5.4 | 6.7 |
| No. 200 | 3.1 | 5.2 | 6.4 | 4.5 | 5.5 |

paction) can be successfully applied to this more complex system. Considering the problems with compaction and curing-water exposure procedures, and the inability of these methods to consistently establish optimum emulsion and water contents, it may be suggested that an entirely different approach to the design of emulsion mixes be investigated.

On the basis of the results of the field study, it would appear that a precise laboratory design (even if obtainable) is not critical for achieving a successful pavement with emulsion mixes. At best, such a design can serve only as a general guideline for an initial job-mix formula with adjustments being made in the field following an evaluation of mix quality. Of greater importance is the degree of quality control associated with the construction operation. The selection of a suitable emulsion, an accurate aggregate feed system, adequate proportioning and mixing of ingredients, and properly timed compaction leading to sufficient densification of mixture are of key importance. The experience of the design and construction personnel with emulsion mixes is needed and may be a determining factor for achieving a successful pavement.

CHAPTER FOUR

# CONCLUSIONS AND SUGGESTED RESEARCH

## CONCLUSIONS

The major objectives of this research project were to evaluate and, if necessary, modify the University of Illinois and Asphalt Institute mix design methods for dense-graded emulsion mixtures and to determine the applicability of these methods with regard to designing mixes for actual use in the field. In addition, a laboratory evaluation of The Asphalt Institute mix design method for open-graded emulsion mixtures was undertaken. The following general conclusions have been developed as a result of the research described in this report. Specific information about each of the conclusions may be found in the appropriate section of the report.

1. The University of Illinois and The Asphalt Institute design methods for dense-graded mixes, as published in the FHWA manual (*1*), are lengthy and cumbersome, and the sequence of individual procedural steps is difficult to follow.
2. Both methods are time consuming. About 2-weeks time is required to complete either of the two methods. Additionally, design tests must be initiated on certain weekdays to avoid testing on weekends.
3. There are considerable differences between the methods with regard to trial emulsion content determination, specimen compaction, and curing-water exposure procedures, and this incompatibility can result in dissimilar designs for the same emulsion-aggregate combination.
4. Neither method is satisfactory for establishing optimum emulsion and water contents for different emulsion-aggregate systems. The data generated in this research project indicate that the ability of mix design methods utilizing Marshall and Hveem equipment to establish optimum properties for dense-graded emulsion mixes is a function of the specific emulsion-aggregate combination being investigated and thus these methods do not have universal applicability. Furthermore, the design criteria are either overly restrictive (UI method) or insufficiently selective (AI method) and, therefore, are inadequate for establishing optimum mixture composition.
5. Modifications in these methods are needed and have been recommended in order to shorten them, to make them more compatible with each other, and to achieve specimen densities and voids that are in closer agreement to those obtained in the field.
6. The recommended revisions to the reference methods, however, do not consistently result in the determination of identifiable optimum emulsion and water contents.
7. On the basis of the study of four field projects involving the use of a variety of dense-graded emulsion mixes, it appears that mix design is not a critical factor in achieving a successful pavement. Of greater importance is the degree of quality control associated with the construction operation especially with regard to aggregate feed, proportioning of ingredients, mixing time, and timing of compaction.
8. The Asphalt Institute design method for open-graded emulsion mixes is predominantly subjective in nature, with greatest emphasis placed on judgments regarding the coating and workability of trial mixes. Test data indicate that the results of the runoff and washoff tests are primarily a function of the specific emulsion-aggregate combination being investigated. A reduction in level of compactive effort for washoff test specimens is needed to achieve more reasonable densities.

## SUGGESTED RESEARCH

One of the main conclusions of this research is that the use of Marshall and Hveem equipment in the University of Illinois and Asphalt Institute methods to design emulsion mixes does not produce consistently effective, definitive, or comparable results. Even after implementation of a number of modifications, the two methods do not agree sufficiently well in the establishment of compositional characteristics of the mixture. Thus, it is evident that a uniform and unifying alternative is needed. Additionally, a literature review indicates that there is a lack of in-depth knowledge on the properties and behavior of various emulsion mixes or pavements containing such mixes. This suggests that additional research is needed not only to provide improvements in design procedures, but also to enhance or complement the existing knowledge of emulsified asphalt paving mixes. To achieve these goals, the research plans could be divided into short- and long-term efforts as follows:

### A. *Short-Term Research Aimed to Improve Compositional Design*

1. A study and the development of standard preliminary test or tests establishing the suitability and compatibility of a given emulsion and mineral aggregate. Such tests should provide answers to initial questions such as whether an anionic or a cationic emulsion should be used with a given aggregate and whether or not the emulsion should contain solvents. These tests, involving relatively small quantities of materials, could be used for initial indication of water needed to coat the aggregate and the ability of the aggregate to retain that coating. Tests would be conducted on different aggregate-emulsion combinations to assess their compatibility and to determine the retention tenacity of asphalt particles to aggregate surfaces.

The utility of such tests is supported by the experience gained in the field tests of this research. For most of the field tests, the aggregate and emulsion were specified prior to running the mix design tests. Thus, the sole purpose of the mix design tests was to establish optimum compositional conditions for an in-advance selected emulsion-aggregate system. Better results may have been obtained using emulsions of different grade and source. A good example of this was the use of CSS-1h for the Harrisonburg, Virginia, project as noted in the field verification section of Chapter Two. The encountered problems could have been eliminated or, at least minimized, by the use of a different emulsion.

2. The development of a convenient and expedient method to establish a preliminary emulsion content for a given emulsion-aggregate system. Possibly, this method could be similar to the Centrifuge Kerosene Equivalent (CKE) test. However, in place of kerosene, water or even an asphalt emulsion should be used in these determinations. Measurement of the amount of water retained by the aggregate should provide a rough estimate of the demand for emulsion by different aggregates. The CKE test was devised for estimating the preliminary contents of either asphalt cement or cutback asphalt, materials which are entirely different from aqueous asphalt emulsions. Thus, the applicability of the original CKE test for emulsion-containing systems may be questioned and an alternative test should be rigorously evaluated.

3. The substantial aggregate degradation resulting from the use of impact compaction by the Marshall hammer or excessive static loads applied by means of a double-plunger device indicates the need for a different compaction methodology. Gyratory or vibratory modes of compaction appear to be promising. An evaluation of different compactive efforts should be undertaken to establish whether laboratory densities comparable to field densities can be achieved and whether aggregate degradation would be minimized with those compaction methods.

B. *Long-Term Applied Research Aimed to Supplement Knowledge of Emulsion-Aggregate Systems*

1. A comprehensive laboratory study evaluating the effects and influences of basic variables, such as emulsion type, residual asphalt content, mixing conditions and time, mode of compaction and strength determination of emulsion-aggregate systems, is needed to provide further practical knowledge of such systems. At least two mineral aggregates that differ considerably in their granulometric and mineralogical characteristics should be included in this study. The tests would be performed on both cured out and water-exposed specimens in order to determine the water sensitivity of such mixtures.

It is anticipated that such a comprehensive study, besides enhancing the general knowledge of emulsion-aggregate systems, would also lead to a better and more rational methodology of compositional design for such system.

2. Detailed information on the field performance of pavements composed of various emulsions and aggregates is lacking and is needed. Such information could be accumulated from either well-documented regular construction projects or from test roads especially designed for the purpose of gathering such information. This long-term research would require one central agency for accumulating test and performance data and several other agencies for cooperating in the design, construction, and monitoring of the performance of emulsion mix pavements.

Specially designed test roads would have a specific aim to evaluate and compare the effects of different emulsion types and varying amounts of residual asphalt content on pavement performance. These special test roads could also be used to compare the performance of emulsion mixes with hot-mixed asphalt concrete pavements containing the same aggregates.

3. A study evaluating the economic advantages of emulsion mixes and comparing these advantages with other construction types is needed. Such a study would provide information on conditions and situations in which the use of emulsified asphalt would be beneficial and justified.

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# APPENDIX A

## UNIVERSITY OF ILLINOIS AND THE ASPHALT INSTITUTE DESIGN METHODS FOR DENSE-GRADED MIXES

### UNIVERSITY OF ILLINOIS METHOD (DENSE-GRADED BASE COURSES)

#### Part I—Tests on Aggregate

1. Sieve analysis (and gradation for mixes).
2. Specific gravity and absorption of fine aggregate (ASTM C 128).
3. Specific gravity and absorption of coarse aggregate (ASTM C 127).
4. Natural water content of air-dried aggregate (ASTM D 2216).
5. Using specific gravities of fine and coarse aggregate, compute the bulk specific gravity of air-dried aggregate based on relative percentages of aggregate retained on and passing the No. 4 sieve in the specified gradation.

#### Part II—Tests on Emulsified Asphalt (ASTM D 244)

1. Residue by distillation at 500°F to determine the relative percentages of residual asphalt, water, and oil distillate.
2. Viscosity at 77°F.
3. Settlement test.
4. Tests on asphalt residue:
    a. Penetration at 77°F.
    b. Ductility at 77°F.
    c. Specific gravity.
    d. Solubility in trichloroethylene.
    e. Viscosity at 140°F and 275°F.

### Part III—Determination of Trial Residual Asphalt Content, R, Using Empirical Formula Based on Gradation of Aggregate

1. $R = 0.00138\ AB + 6.358 \log_{10} C - 4.655$

   where: $R$ = residue by dry weight of aggregate, %;
   $A$ = aggregate retained on No. 4 sieve, %;
   $B$ = aggregate passing No. 4 sieve and retained on No. 200 sieve, %; and
   $C$ = aggregate passing No. 200 sieve, %.
2. The trial residual asphalt content derived from this formula should be rounded to the nearest ½ percent and that value is the actual percentage used for the preparation of specimens.
3. The trial emulsion content is then computed by dividing the trial residual asphalt content by the percent asphalt cement contained in the emulsion (as determined by the distillation test in Part II of this procedure). This emulsion content is to be used for all specimens prepared for the coating and compaction tests.

### Part IV—Coating Test (To Determine the Optimum Mixing Water Content, as Percent of Dry Aggregate Weight)

- *Background*
  1. Aggregate weight for each batch should be approximately 2,000 g. The material of different size should be weighed out and blended to meet the weight and gradation requirements.
  2. Initially, the added mixing water content for the first batch should be 0 percent when using an anionic emulsion and 3 percent when using a cationic emulsion. Subsequent batches will have increased added mixing water contents (in increments of 1 percent) until the batches become soupy or segregate on standing.
- *Procedure*
  3. Each batch is prepared by first placing the aggregate in the mixing bowl of a mechanical mixer. The mixing water (if any) is then added in a thin stream. The aggregate and water are mixed until the water is thoroughly blended (30 sec should be adequate). The amount of asphalt emulsion (percent by dry weight of aggregate) as determined from the "trial emulsion content" calculated in Part III is then added in a thin stream and the batch is mixed for approximately 5 min.
  4. The mixture is then allowed to air dry (with the aid of an electric fan) or dried in an oven at 230 ± 10°F.
  5. Steps (3) and (4) are repeated with an additional increment of 1 percent mixing water for successive batches until the mixture becomes fluid or segregates on standing. (Mixtures at ½ percent increments may be batched later to help clarify the optimum mixing water content.)
  6. Total mixing water contents are computed for each mixture by adding the percent water from the added emulsion, the natural water content of the aggregate, and the added mixing water content.
  7. The appearance of the "surface dry" mixtures is rated by visually estimating the total aggregate surface area that is coated with asphalt. The percent coating for each total mixing water content is recorded.
  8. Aggregate coating in excess of 50 percent is considered acceptable. If none of the mixtures attains 50 percent coating, the emulsion is rejected for that particular aggregate.
  9. All subsequent mixtures should be prepared at the minimum total mixing water content giving optimum coating and not resulting in a fluid or segregated mix.

### Part V—Compaction Test (To Determine Optimum Water Content at Compaction)

- *Background*
  1. Trial water contents at compaction are to be selected (at increments of 1 percent) which give at least 50 percent coating and result in mixtures that are not overly fluid. If a trial compaction water content is less than the minimum total mixing water content for optimum coating determined in the coating test, the mixture should first be mixed at the optimum mixing water content and then aerated back.
  2. Three specimens are prepared for each trial water content, with five water contents normally being sufficient for this test.
- *Procedure*
  3. Blend approximately 3,600 g of aggregate (approximately 1,200 g for each specimen) to meet the established gradation requirement.
  4. Addition of mixing water and aeration:
     a. If the trial water content at compaction is less than the minimum mixing water content for optimum coating established in the coating test:
        (1) Enough water should be added (in a slow stream) to obtain optimum mixing water content. The aggregate and water should be mixed for 2.0 ± 0.5 min or until the water is thoroughly dispersed.
        (2) The emulsion is then added in a thin stream to moisten the aggregate using the same amount of emulsion for all mixtures as established in Part III. Mixing time can last up to 5 min.
        (3) The mixture is then aerated to achieve a lower water content for compaction. The mixture should be transferred to an aeration pan and the material distributed so that it is less than 1 in. deep. The weight of the pan and mixture is recorded, and the weight loss needed to achieve the desired water content is calculated. The mixture is placed in an oven at 200 ± 5°F and then stirred and weighed every 15 ± 5 min until the weight is within 20 g of the required water loss. At that point, the pan is removed from the oven and cooled (with the aid of a fan if desired) until the necessary weight loss is attained. The mixture is then ready for compaction.
     b. If the trial water content for compaction is equal to or greater than the minimum mixture water content for optimum coating:
        (1) The aggregate, water, and emulsion are mixed as previously described with enough added mixing water to achieve the desired water content for compaction without the need for transferring

the mixture to an aeration pan and heating in an oven. In other words, the mixture is ready for compaction immediately after mixing.

5. One-third of the mixture is poured into each of three standard Marshall compaction molds. Each of the three specimens is compacted using 75 blows of the compaction hammer on each face of the specimen.
6. This process is repeated until three specimens have been compacted for each of the trial water contents at compaction.
7. The specimens are then cured in the mold resting on their edges to allow equal ventilation of the faces for 24 hours at 72 ± 3°F.
8. The specimens are then extruded and tested for Marshall stability. The trial water content having the highest average Marshall stability is considered to be the optimum total water content for compaction. If it is greater than the optimum mixing water content established in the coating test, there will be no difference between the water content at mixing and at compaction. If it is less than the optimum mixing water content, there will be a difference and drying back will be necessary for all subsequent mixtures.

### Part VI—Variation of Residual Asphalt Content

- *Background*
  1. The total water contents at mixing and at compaction have been fixed by the coating test and the compaction test. Although the natural water content of the aggregate is fixed, the percent water from the added emulsion will vary as the residual asphalt content is increased. Thus, the added mixing water (and any necessary dry-back) will vary as the residual asphalt content is increased in order to maintain constant water contents at mixing and at compaction.
  2. Six specimens are prepared for each of five trial residual asphalt contents: two contents below the trial residual asphalt content established in Part III, two above, and one at the trial content. Three specimens are to be compacted in standard Marshall forming molds and the other three in specially threaded molds (for attachment to perforated brass plates).
- *Procedure*
  3. For each residual asphalt content, blend approximately 7,200 g of aggregate (approximately 1,200 g per specimen) to meet the established gradation requirement. Place the aggregate in a mixing bowl.
  4. Compute the amount of emulsion that needs to be added based on the selected residual asphalt content for a set of six specimens.
  5. Determine the percent water from the added emulsion. Knowing this and the natural water content of the aggregate, the percent added mixing water can be determined in order to achieve the optimum total mixing water content established in the coating test.
  6. From these percentages, the weights of added mixing water and emulsion can be calculated.
  7. The ingredients should be mixed, dried back if the total water content compaction is less than the total water content at mixing, and compacted in the same manner as for the compaction test, except that three of the specimens should be compacted in standard Marshall forming molds and the other three in specially threaded molds.
  8. All six specimens are allowed to cure in the mold (resting on their edges for equal ventilation of both faces) for 3 days (72 hours) at 72 ± 3.0°F and then extruded.
  9. Prior to testing, the specimens' bulk specific gravities (BSG) are measured according to ASTM D 2726 (i.e., weight in air, weight in water, and weight SSD after 3 to 5 min of immersion). Also, the thickness of the cured specimens is measured for adjusting Marshall stabilities to those of standard 2.5-in. thick specimens.
  10. Three specimens are then tested for Marshall stability and flow. After testing, the failed specimens are broken apart, placed in tared pans, weighed, and then placed in an oven at 200 ± 10°F. After 24 hours, the dry mixtures are weighed for determining their oven-dry weights and calculating water contents "at testing."
  11. The three specimens in the specially threaded molds, after 3 days of air curing, are pushed flush to one end of their molds by the extrusion jack. Brass plates are screwed on the ends, and the flush ends are placed in a water bath at a depth of 1 in. and at a temperature of 72 ± 3.0°F, with the specimen faces out of the water and covered to prevent evaporation. After 48 hours, the specimens are removed from the water, pushed flush to the opposite end of the mold and then replaced in the bath with the flush end immersed for another 48 hours.
  12. After a total of 4 days of capillary soak, the specimens are extruded from their molds and measured for BSG (ASTM D 2726—weight SSD and weight in water) and thickness. They are then tested for Marshall stability and flow.
  13. The failed specimens are broken apart, weighed, and oven-dried to determine water contents "at testing."

### Part VII—Determination of Optimum Asphalt Content

From the water content and BSG data developed during the testing of specimens, dry BSG, total voids, air voids, and voids-in-mineral aggregate (VMA) of both "cured" and "soaked" specimens can be computed as well as moisture absorption as a result of water exposure. From the stability measurements on "cured" and "soaked" specimens, percent stability loss as a result of water exposure can also be computed.

The optimum residual asphalt content is chosen that provides maximum soaked stability as long as it provides for adequate stability, moisture absorption, percent loss of stability, total voids, and aggregate coating (i.e., meets the requirements listed in Appendix B).

## THE ASPHALT INSTITUTE METHOD (DENSE-GRADED MIXES)

### Part I—Selection of Aggregates and Emulsified Asphalts

1. Aggregates meeting the requirements for processed dense-

graded or semiprocessed, crusher, pit or bank run aggregates should be used.

2. Either slow-setting (SS) or medium setting (MS) emulsions meeting the requirements of ASTM D 977 or D 2397 standard specifications should be used.

### Part II—Trial Asphalt Emulsion Content

1. The Centrifuge Kerosene Equivalent (CKE) method is used to determine the trial asphalt emulsion content.
   a. The surface area of the aggregate in square feet per pound is calculated by multiplying the percent passing a given sieve size by "surface area factors" and then adding all calculated fractional surface areas.
   b. Using 100 g of material passing the No. 4 sieve, the CKE is determined for fine aggregate.
   c. Using 100 g of material passing the $\frac{3}{8}$-in. sieve but retained on the No. 4 sieve, the oil surface capacity is determined for the course aggregate.
   d. After correcting for specific gravities greater than 2.70 or less than 2.60, these values (along with the surface area) are plotted on a series of charts in "A Basic Asphalt Emulsion Manual" (*2*) in order to establish a CKE oil ratio.
   e. The trial emulsion content is equal to 1.4 × CKE oil ratio, and is adjusted to a 60 percent residue as follows:

$$\begin{array}{l}\text{Correct}\\ \text{Emulsion}\\ \text{Content}\end{array} = \frac{(1.4 \times \text{CKE Oil Ratio}) \times 60}{\text{Emulsion Residue, \%}}$$

### Part III—Mixing Test, Determination of Optimum Fluids Content at Mixing

1. The natural moisture content of the aggregate is determined according to the ASTM D 2216 test method.
2. The aggregate, whose batch weight is based on "nominal maximum particle size" chart on page 8 of the FHWA manual (*1*), is added to a mixing bowl. Enough water is added and mixed with the aggregate to dampen it. The weight of added water is recorded and its percentage based on dry weight of aggregate is calculated.
3. The asphalt emulsion, in an amount as determined by the "correct emulsified asphalt content" of Part II, is added to the damp aggregate and mixed with a mechanical mixer for approximately 30 sec.
4. Based on coating, workability, and "job conditions" (i.e., the type of equipment, the availability of water at the job site), the mix is judged as satisfactory or unsatisfactory. If the mix is judged to be unsatisfactory, the added mixing water content is increased in fixed increments until a satisfactory mix is obtained.
5. The total fluids content at mixing of the satisfactory mix is computed by adding percentages of the asphalt emulsion, added mixing water and natural water content of the aggregate. It is expressed as weight percent of dry aggregate. This optimum fluids content at mixing is used for establishing weight proportions of subsequent batches.

### Part IV—Optimum Fluids Content for Compaction

1. Mixtures at the optimum fluids content at mixing as developed in Part III are prepared using batch weights of approximately 1,200 g each.
2. At least three batches are prepared at the optimum fluids content. One is compacted immediately by using approximately 20 tamps at 250 psi of a kneading compactor followed by a 40,000-lb double-plunger static load, and the others are allowed to dry to two different lower fluids contents prior to compaction. At least three points are needed to establish an optimum fluids content.
3. After compaction of each batch, the height H of the specimen while still in the mold is measured and recorded to the nearest 0.01 in.
4. The specimens are then extruded from the mold and weight $W_w$ is determined. The specimen is dried to a constant weight in an oven at 230 ± 9°F, cooled to room temperature, and again weighed to determine dry weight, $W_d$.
5. Calculations:

$$\text{Dry density in pcf} = W_d/H \times 0.303$$

$$\text{or dry density in g/cm}^3 = W_d/H \times 0.0048561$$

$$\text{water content, \%} = \frac{W_w\text{-}W_d}{W_d} \times (100 \times A)$$

   where A = residual asphalt content (percent of dry aggregate weight).
6. A plot is made of dry density vs fluids content at compaction. The fluids content resulting in highest dry density is optimum for compaction.

### Part V—Strength Testing (Variation in Residual Asphalt Content)

This test differs depending on whether the mix is intended for a base, temporary surface, or permanent surface courses.

1. If the mix is intended for use as a base course or temporary surface course:
   a. Duplicate specimens are prepared at each of three trial asphalt emulsion contents—1.1, 1.4, and 1.7 times the CKE oil ratio adjusted to a 60 percent residue. Each specimen batch is to be mixed at the fluids content (asphalt plus water) determined in the Mixing Test (Part III) and then dried back (if necessary) to achieve the optimum fluids content for compaction determined in Part IV. Each specimen is then compacted using the light kneading compaction followed by a double plunger static load.
   b. Three of the six specimens (one at each of the trial asphalt emulsion contents) are cured in the mold by placing them in a horizontal position at a temperature of 73 ± 5°F for 24 hours.
   c. The heights of the specimens, while still in the mold, are measured.
   d. After extrusion, the bulk specific gravities of the specimens are measured according to ASTM D 1188 by lightly dusting the surface with zinc stearate instead of coating the specimen with paraffin.
   e. The bulk volumes of the compacted mixes and the volumes of air voids, asphalt, and aggregate are calculated according to the following equations:

$$V_a = 100 - (V_b + V_{sa})$$

$$V_b = \frac{W_b}{G_b} \cdot \frac{100}{V_{mb}}$$

$$V_{sa} = \frac{W_s}{G_{sa}} \cdot \frac{100}{V_{mb}}$$

$$V_{mb} = \frac{W_m}{G_{mb}}$$

$$W_b = \frac{W_e R_e}{100}$$

where:

$V_a$ = volume of air, % of total mix;
$V_b$ = volume of asphalt in mix, % of total mix;
$V_{sa}$ = volume of aggregate, by apparent specific gravity % of total mix;
$V_{mb}$ = bulk volume of compacted mix;
$W_b$ = weight of asphalt;
$G_b$ = specific gravity of asphalt;
$W_s$ = weight of dry aggregate;
$W_m$ = weight of dry compacted mix;
$G_{mb}$ = bulk specific gravity of dry compacted mix;
$G_{sa}$ = aggregate apparent specific gravity;
$W_e$ = weight of emulsified asphalt; and
$R_e$ = percent residue of emulsified asphalt, expressed as a whole number.

f. The specimens are tested for "early resistance R-value" using the Hveem stabilometer at a temperature of 73 ± 5°F.

g. The same specimens are then tested for "cohesive resistance" using the cohesiometer, also at a temperature of 73 ± 5°F. The resistance $R_t$-value is computed by the equation: $R_t = R + 0.05C$.

h. After testing, the failed specimens are weighed in a tared pan, dried to constant weight in an oven at 230 ± 9°F, cooled to room temperature, and weighed again. From these weights, a water content "at testing" is determined.

i. The remaining three specimens are allowed to cure in the mold in a horizontal position at a temperature of 73 ± 5°F for 3 days (72 hours) instead of 1 day (24 hours).

j. These specimens are then extruded from the mold and vacuum desiccated using Drierite for 4 days. The vacuum should be applied to obtain a residual pressure of 10 to 20 mm of Hg.

k. If needed, the specimens are measured for resilient modulus. At this time, the heights of the specimens are measured, the weights $A_b$ of the specimens are recorded and their bulk specific gravities are determined according to ASTM D 1188. Volume calculations are made using the same equations as shown previously.

l. To simulate the effect of prolonged exposure to subsurface water, these same specimens are placed in the desiccator, covered with water, and saturated under vacuum, with residual pressure of 100 mm of Hg for 1 hour. After the vacuum is slowly released, the specimens are allowed to soak in water for an additional hour.

m. The specimens' height, weight in water, and SSD weight, $A_w$, are determined.

n. The specimens are then tested for resistance R-value and cohesiometer C-value, both at 73 ± 5°F. Again, the resistance $R_t$-value is computed according to the equation $R_t = R + 0.05C$.

o. After the cohesiometer test, the specimen is weighed in a tared pan. Then, after drying to constant weight in an oven at 230 + 9°F and cooled to room temperature, specimen weight, $A_d$, is determined. From these weights, a water content at testing is calculated and also the percent moisture "pick-up," P, during vacuum saturation is computed using the equation:

$$P = \frac{A_w - A_b}{A_d} \times 100$$

2. If the mix is intended for use as a permanent surface course:

a. Only one specimen is prepared at each of the three trial asphalt emulsion contents obtained by multiplying the CKE oil ratio adjusted to a 60 percent residue by factors of 1.1, 1.9, and 1.7. These three specimens are mixed at the optimum fluids content established in the Mixing Test, dried back (if necessary), and compacted using the light kneading compaction followed by a 10,000-lb double-plunger static load.

b. The specimens are allowed to cure in the mold in a horizontal position at a temperature of 73 ± 5°F for 3 days.

c. The specimens are extruded from the mold and vacuum desiccated with Drierite for 4 days.

d. The resilient modulus values of the specimens are measured. At this time, the heights of the specimens are recorded and their bulk specific gravities are determined by following the ASTM D 1188 standard test. Volume calculations are made using the same equations as before.

e. These specimens, because they are intended to simulate cores from a permanent surface course, are not subjected to vacuum saturation. Instead, the specimens are tested immediately for stabilometer S-value, at a temperature of 140 ± 5°F. Prior to testing, the specimens are placed in an oven at 140 ± 5°F for 2 hours since this is the temperature at which the S-value is established.

f. The specimens are then tested for cohesiometer C-value, also at 140 ± 5°F using a heated cabinet of the cohesiometer device.

g. After the cohesiometer test, the specimen is dried to constant weight in an oven at 230 ± 9°F, and water content "at testing" is calculated.

3. Determination of the optimum emulsion content required to satisfy the criteria given in Appendix B cannot be less than 1.1 times the CKE oil ratio selected.

## COMPARISON OF UNIVERSITY OF ILLINOIS AND ASPHALT INSTITUTE DESIGN METHODS FOR EMULSIFIED ASPHALT PAVING MIXTURES

| | UNIVERSITY OF ILLINOIS | THE ASPHALT INSTITUTE |
|---|---|---|
| *1. Tests on Materials* | Tests for aggregate properties.<br>Tests for emulsified asphalt properties. | Tests for aggregate properties including CKE method.<br>Tests for emulsified asphalt properties. |
| *2. Trial Emulsion Content* | Compute the trial residual asphalt content, R, according to the following empirical formula:<br>$R = 0.00138\ AB + 6.358 \log C - 4.655$<br>A = retained on No. 4 sieve, %<br>B = pass No. 4 sieve and on No. 200 sieve, %<br>C = passing No. 200 sieve, %<br>Round R to the nearest ½ percent for trial residual asphalt content; divide by the percent residual asphalt in the emulsion to determine trial emulsion content. | After determining the CKE oil ratio by means of the CKE method, compute the trial asphalt emulsion content as 1.4 × CKE oil ratio, adjusted to a 60 percent asphalt residual. |
| *3. Coating Test* | Using the trial residual asphalt, prepare a batch using approximately 200 g of aggregate without added mixing water if emulsion is anionic and 3 percent added mixing water if the emulsion is cationic. Prepare additional batches by increasing the added mixing water content in fixed increments. Continue until the mixtures become soupy or segregated. Record the percent coating vs total water content (added water + water in emulsion + moisture in aggregate) for each batch. The minimum total water content giving the highest percent coating is considered optimum for mixing. | Add enough water to darken the aggregate. Record the weight of added water. Add the emulsion using the trial emulsion content. Record the total weight of fluids (emulsion + added water + moisture in aggregate). After mixing, rate the mixture according to coating and workability. If unsatisfactory, increase the water content in fixed increments until a satisfactory mix is obtained. Record the fluids content of this satisfactory mix as the minimum fluids content required for adequate mixing. |
| *4. Compaction Test* | Using the same trial residual asphalt content, prepare three specimens at each total water content which gave at least 50 percent coating but was not overly fluid or segregated.<br>Compact specimens using 75 blows of the Marshall hammer. After cure in the mold for 1 day, extrude specimens and test for BSG, Marshall stability and flow, and water content. The mix with the highest average Marshall stability has the optimum total water content for compaction. | Using the same trial emulsion content, prepare at least three batches at the minimum fluids content for mixing established in the Coating Test.<br>Compact one batch, using the kneading compactor and 40,000-lb double-plunger static load, immediately after mixing. Dry back a second batch 1 percent and a third batch 2 percent before compaction. Record the height of compacted specimen in the mold. Extrude from the mold, record the specimen's weight, and calculate the density based on the specimen dimensions. Determine water contents and dry densities. Plot dry density vs fluids content at compaction. Indicate highest dry density mix optimum fluids content for compaction. |

| UNIVERSITY OF ILLINOIS | THE ASPHALT INSTITUTE |
|---|---|
| *5. Strength Test* | |
| Select five trial residual asphalt contents at 1 percent increments: two below, two above, and one at the trial residual asphalt content established in Part II and prepare six specimens at each of these asphalt contents using the optimum total water contents for mixing and compaction established in the Coating and Compaction Tests. | (A) *Mix for Base Course or Temporary Surface.*<br>Prepare two specimens at each of the three trial emulsions contents: 1.1, 1.4, and 1.7 × CKE oil ratio, adjusted to 60 percent residue. Mix each batch at the minimum fluids established in the Mixing Test, dry back if needed to get optimum fluids content at compaction. |
| Allow three of the specimens at each asphalt content to cure in the mold for 3 days at room conditions and then test them for BSG, Marshall stability and flow, and moisture content. | For "early cure" strength, allow one specimen at each trial emulsion content to cure in the mold for 1 day at room conditions. Test for BSG, R-value at 73 ± 5°F, C-value at 73 ± 5°F, and water content. |
| Cure remaining specimens in the mold for 3 days at room conditions and then subject them to a capillary soak (in water at depth of 1 in.) in the mold for 4 days at room temperature, turning the specimens on their opposite ends after the first 2 days. Extrude and test soaked specimens for BSG, Marshall stability and flow, and water content. | Cure remaining three specimens in the mold for 3 days at room conditions. Extrude and vacuum desiccate with Drierite for 4 days. Then vacuum saturate for 1 hour and soak without vacuum for another hour at room temperature. Test for BSG, R-value at 73 ± 5°F, C-value at 73 ± 5°F, and water content. |
| | (B) *Mix for Permanent Surface.*<br>Prepare one specimen at each of three trial emulsion contents; 1.1, 1.4, and 1.7 CKE oil ratio, adjusted to 60 percent residue. Mix each batch at the minimum fluids content established in the Coating Test, dry back (if needed) to obtain the optimum fluids content at compaction. |
| | Cure specimens in the mold for 3 days at room conditions. Extrude and vacuum desiccate with Drierite for 4 days. Test for BSG, S-value at 140 ± 5°F, and water content. |
| *6. Determination of Optimum Emulsion Content* | |
| The optimum residual asphalt content is that which provides maximum soaked stability but is adjusted either up or down depending on moisture absorption, percent loss of stability, total voids, and coating of aggregate. If one or more of the properties do not meet the minimum criteria requirements given in Appendix B, the mix is considered inadequate. | The minimum required emulsion content is the lowest percent necessary to satisfy the criteria requirements in Appendix B, but it cannot be less than 1.1 × CKE oil ratio, adjusted to 60 percent residue. |

# APPENDIX B

## EMULSIFIED ASPHALT-AGGREGATE MIXTURE DESIGN CRITERIA

UNIVERSITY OF ILLINOIS METHOD

| Test Property | Minimum | Maximum |
|---|---|---|
| STABILITY, lb (N) at 72°F (22.2°C)<br>Paving Mixtures | 500 (2,224) | -- |
| TOTAL VOIDS (%)<br>Compacted Mix (not required for sand mix) | 2 | 8 |
| STABILITY LOSS (%)<br>After 4 days soaking at 72°F (22.2°C) | -- | 50 |
| ABSORBED WATER (%)<br>After 4 days soaking at 72°F (22.2°C) | -- | 4 |
| AGGREGATE COATING (%) | 50 | -- |

THE ASPHALT INSTITUTE METHOD

| Test Property | | Base or Temporary Surface | Permanent Surface |
|---|---|---|---|
| RESISTANCE $R_t$-VALUE at 73±5°F (23±2.8°C) | Early Cure[a] | 70 min. | N.A. |
| | Fully cured and water immersed[b] | 78 min. | N.A. |
| STABILOMETER S-VALUE at 140±5°F (60±2.8°C) | | N.A. | 30 min. |
| COHESIOMETER C-VALUE at 73±5°F (23±2.8°C) | Early Cure[a] | 50 min.[c] | N.A. |
| | Fully cured and water immersed[b] | 100 min.[c] | N.A. |
| COHESIOMETER C-VALUE at 140±5°F (60±2.8°C) | | N.A. | 100 min. |
| AAGGREGATE COATING (%) | | 50 min. | 75 min. |

[a] Cured in mold for total of 24 hours at temperature of 73±5°F (23±2.8°C).

[b] Cured in mold for total of 72 hours at temperature of 73±5°F (23±2.8°C) vacuum dessicated for 4 days followed by water immersion for one hour under vacuum and one hour without vacuum.

[c] Applicable to temporary wearing surface only.

N.A. Not Applicable

NOTE: Besides meeting the above requirements, the mix must be reasonably workable (i.e., not too stiff or sloppy).

# APPENDIX C

## PROCEDURAL AND DESIGN CRITERIA FOR THE ASPHALT INSTITUTE DESIGN METHOD FOR OPEN-GRADED MIXES

1. *Selection of Trial Emulsion Contents*
   a. Select trial emulsion contents from ranges specified for each type of aggregate gradation:
      coarse —4.5 to 6.5%
      medium—5.0 to 7.0%
      fine —6.0 to 8.0%
2. *Mixing Test*
   a. For a given emulsion content, add enough water to just darken the aggregate (the amount of which is a function of nominal maximum particle size). Then add the selected amount of emulsion and mix for 30 sec using a mechanical mixer. Immediately pour or spoon the mixture into an 850-μm (no. 20) mesh wire screen funnel that has been positioned over a tared quart container. Allow the mix to drain for 30 min. Remove the mix from the funnel and judge it for coating and workability. Place the container with the runoff in a 230 ± 9°F oven and dry to a constant weight. Determine the final weight and compute the runoff as:

$$\text{Runoff, \%} = \frac{\text{Final Weight} - \text{Fared Weight}}{\text{Batch Aggregate Weight}} \times 100$$

   If the three components (coating, workability, and runoff) are judged to be unsatisfactory, increase the water content in fixed increments until a satisfactory mix is obtained.
   b. The process is repeated for each trial emulsion content. The objective is to determine the maximum emulsified asphalt content that can be used within the range that meets the mix design requirements (Note: The mixing fluids content (asphalt and water) for open-graded mixes is assumed to be at optimum for compaction.)
3. *Mix Curing and Resilient Modulus Testing*
   a. Prepare two specimens at the emulsion and water content established as optimum in the mixing test. Compact them using the Triaxial Institute kneading compactor followed by a 40,000-lb double-plunger static load.
   b. One specimen is cured for 72 hours in the mold at room conditions and then vacuum desiccated (with a residual pressure of 10 to 20 mm of Hg) for four additional days. This specimen is then tested for diametral resilient modulus, $M_R$. (The $M_R$ is not part of the actual mix design since criteria have not been established. It may be used for establishing pavement layer thickness.)
   c. The second specimen is cured for 24 hours in the mold at room conditions and subjected to the washoff test. This involves placing the specimen, while still in its mold, on a 5-in. square No. 20 mesh wire screen supported by a pedestal, and then pouring 200 cm$^3$ of water over the sample and collecting the washoff in a tared container. After allowing the specimen to drain for 30 min, the washoff is dried to constant weight in an oven at a temperature of 230 ± 9°F. The residue weight after drying is computed as the "residual asphalt washoff." The percent washoff is computed as:

$$\text{Washoff, \%} = \frac{\text{Wt. of Residual Asphalt Washoff}}{\text{Wt. of Aggregate in Specimen}} \times 100$$

4. *Design Criteria*
   a. To be acceptable, the mix must satisfy the design criteria given as follows:

| | Base or Temporary Surface | Permanent Surface |
|---|---|---|
| Coating (%) | 50.0 min. | 75.0 min. |
| Runoff (%) | 0.5 max. | 0.5 max. |
| Washoff (%) | 0.5 max. | 0.5 max. |
| Combined runoff and washoff (%) | 0.5 max. | 0.5 max. |

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