SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-82/5

CHARACTERIZATION OF COLD-RECYCLED ASPHALT MIXTURES

Mang Tia

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-82/5

CHARACTERIZATION OF COLD-RECYCLED ASPHALT MIXTURES

Mang Tia

Interim Report

CHARACTERIZATION OF COLD-RECYCLED ASPHALT MIXTURES

TO:	H. L. Michael, Director Joint Highway Research Project	February 2, 1982
		Project: C-36-21D
FROM:	L. E. Wood, Research Engineer Joint Highway Research Project	File: 2-8-4

Attached is an Interim Report, "Characterization of Cold-Recycled Asphalt Mixtures" which is part of the HPR Research Project titled "An Investigation of Recycling Bituminous Pavement". Mr. Mang Tia, Graduate Instructor in Research on our staff, has authored the report and conducted the study under the direction of Professor Leonard E. Wood.

This report presents the results of a detailed laboratory study on the long-term behavior of cold-recycled asphalt mixtures and on the feasibility of using the gyratory testing machine for the design of cold-recycled asphalt mixtures. The results indicate that the gyratory testing machine can be used to determine the optimum binder content of a cold-recycled mix.

This report is offered as fulfillment of Task I of the Project and is submitted to review and acceptance by DOH and FHWA.

Respectfully submitted,

L E Wood/HLM.

Leonard E. Wood
Research Engineer

LEW:ms

cc: A. G. Altschaeffl
J. M. Bell
W. L. Dolch
R. L. Eskew
G. D. Gibson
W. H. Goetz
M. J. Gutzwiller
G. K. Hallock
J. F. McLaughlin
R. D. Miles
P. L. Owens
G. T. Satterly
C. F. Scholer
K. C. Sinha
C. A. Venable
L. E. Wood
E. J. Yoder
S. R. Yoder

Interim Report

CHARACTERIZATION OF COLD-RECYCLED ASPHALT MIXTURES

by

Mang Tia
Graduate Instructor in Research

Joint Highway Research Project

Project No.: C-36-21D

File No.: 2-8-4

Prepared as a Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Highways

and the

U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, Indiana
February 2, 1982

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JHRP-82/5		

4. Title and Subtitle
CHARACTERIZATION OF COLD-RECYCLED ASPHALT MIXTURES

5. Report Date
February 2, 1982

6. Performing Organization Code

7. Author(s)
Mang Tia

8. Performing Organization Report No.
JHRP-82-5

9. Performing Organization Name and Address
Joint Highway Research Project
Civil Engineering Building
Purdue University
West Lafayette, Indiana 47907

10. Work Unit No.

11. Contract or Grant No.
HPR-1(19) Part II

12. Sponsoring Agency Name and Address
Indiana Department of Highways
State Office Building
100 North Senate Avenue
Indianapolis, Indiana 46204

13. Type of Report and Period Covered
Interim Report
Laboratory Phase

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Part of the Study titled "An Investigation of Recycling Bituminous Pavements".

16. Abstract
In this study, the long-term behavior of the cold-recycled asphalt mixtures was investigated. The scope of the study covered two types of pavement material, three levels of oxydized condition of the old binder and one type of virgin aggregate. The added softening agents included a high-float asphalt emulsion AE-150, a foamed asphalt, and the rejuvenating agents, Reclamite, Mobilsol and DUTREX 739.

Specimens of the recycled mixes were compacted with the gyratory machine, and gyratory indices were obtained during the compaction process. The Resilient Modulus, Hveem Stabilometer R-Value and Marshall parameters were obtained on the compacted recycled mixes. The Water Sensitivity Test was used to evaluate the resistance of the recycled mixes to water.

The results of the study indicated that most of the rejuvenating action of the added agents on the old binder took place during the compaction process. The binders of the recycled mixes which underwent the initial softening during the compaction process generally increased in stiffness with increasing curing time.

The results indicated that the gyratory indices could be used to determine the optimum binder content of a recycled mix.

The structural performance of these recycled mixes was compared to that of an asphalt concrete using a linear elastic multilayer analysis. A mix design for cold recycled asphalt mixtures was recommended from the results of this study.

17. Key Words
Cold recycling; gyratory testing machine; Resilient Modulus; Virgin Binder; Rejuvenating Agent; Curing; Compactive Effort; Testing Temperature

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	290	

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation to his major professor, Prof. Leonard E. Wood for the guidance in the research work, the long hours of discussion, the critical review of the manuscript, and the encouragement and advice during the entire study. He is especially grateful to Prof. Donn E. Hancher for his special guidance and advice throughout the entire study, and his review of the manuscript. He wishes to convey his gratitude to Prof. Virgil E. Anderson for his advice on the design of experiment and the statistical analysis, and his review of the manuscript. He wishes to thank Prof. Eldon J. Yoder for his valuable advice and his review of the manuscript.

The author wishes to express his appreciation to the Indiana Department of Highways and the Federal Highway Administration, U.S. Department of Transportation for their financial support of this research.

He would like to convey his appreciation to K. E. McConnaughay, Inc. for supplying the asphalt emulsion and the rejuvenating agents, to American Oil Co. for supplying the asphalt cement, and to Shell Development Co. for supplying the rejuvenating agent. The valuable assistance given by the Research and Training Center, West Lafayette, is appreciated. Appreciation is extended to Mr. Wayne Carbiener for his assistance in the laboratory work, to Mr. Michael Paulson for his drafting work, to Mr. Emmette Black for the photographs, and to Mrs. Cathy Ralston for typing the manuscript.

Finally, special thanks go to the author's wife, Maria, for her encouragement and support in all aspects of this study.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

Figure LIST OF FIGURES (Continued) Page

Figure LIST OF FIGURES (Continued) Page

LIST OF FIGURES (Continued)

Figure	LIST OF FIGURES (Continued)	Page

LIST OF FIGURES (Continued)

LIST OF SYMBOLS

GEPI - Gyratory Elasto-Plastic Index

GSI - Gyratory Stability Index

GCI - Gyratory Compactibility Index

M_R - Resilient Modulus

ν - Poisson's Ratio

S_M - Marshall Stability

I_M - Marshall Index

R-Value - Hveem Stabilometer Resistance Value

HIGHLIGHT SUMMARY

Increased interest in improving the quality of the cold-recycled paving mixtures has made it necessary to better understand the behavior of these mixes and to develop a suitable mix design method. In this study, the long-term behavior of the cold-recycled asphalt mixtures was investigated through nine experimental designs. The scope of the study covered two types of pavement material, three levels of oxydized condition of the old binder and one type of virgin aggregate. The added softening agents included a high-float asphalt emulsion AE-150, a foamed asphalt, and the rejuvenating agents, Reclamite, Mobilsol and DUTREX 739.

Specimens of the recycled mixes were compacted with the gyratory machine, and gyratory indices were obtained during the compaction process. The resilient modulus, Hveem Stabilometer R-Value and Marshall parameters were obtained on the compacted recycled mixes. The Water Sensitivity Test was used to evaluate the resistance of the recycled mixes to water.

The results of the study indicated that most of the rejuvenating action of the added binder on the old binder took place during the compaction process. The binders of the recycled mixes which underwent

the initial softening during the compaction process generally increased in stiffness with increasing curing time.

The results indicated that the gyratory stability index and the gyratory elasto-plastic index could be used to determine the optimum binder content of a recycled mix. However, they could not be used to estimate the resilient modulus or the Marshall stability of the mix.

A higher compactive effort generally produced a higher resilient modulus and Marshall stability of the recycled mix. When the binder content is too high, a higher compactive effort generally produces a lower Hveem R-value.

The structural performance of these recycled mixes was compared to that of an asphalt concrete using a linear elastic multilayer analysis.

A mix design procedure for cold recycled asphalt mixtures was recommended from the results of this study.

CHAPTER 1

INTRODUCTION

One of the major problems confronting the transportation agencies in the United States today is the maintenance and rehabilitation of the existing highway systems with the decreased level of funding. Since 1975, the overall condition of the highway systems has been declining, as a result of the fact that the actual expenditure on pavement rehabilitation has not been able to meet up with the cost needed to preserve the conditions of the existing roadways. In 1981, the needed expenditure to restore the highway systems to their 1980 levels was estimated to be $14.5 billion, while the projected expenditure was only $7.5 billion [1]. If the present trend remains unchanged, the overall condition of the highway systems will continue to deteriorate. One of the ways to ease this crisis is through the more effective and more efficient utilization of the available resources. Methods of pavement rehabilitation have to be prudently selected and planned so that more can be accomplished for every dollar spent. Asphalt pavement recycling is a rehabilitation method which has been shown to be economical as well as effective, if done properly. Besides the substantial savings in cost, the benefits of pavement recycling include conservation of asphalt and aggregate resources, reduction in fuel consumption, preservation of pavement geometries, and reduction in environmental pollution. Pavement recycling is a promising rehabilitation alternative that can help ease the present crisis of deteriorating highway systems.

Asphalt pavement recycling is the technique of putting the existing pavement material back into use. The fundamental concept of asphalt pavement recycling lies in upgrading the deteriorated aggregates by the addition of virgin aggregates and softening the hardened old asphaltic binders by the addition of rejuvenating agents. Basically, it involves (1) removing the old pavement material from the road, (2) mixing it when necessary with additional virgin aggregate, a virgin binder or a softening agent, and (3) repaving it. This process can be done either hot or cold (i.e. with or without the application of heat). The advantages of the cold process as compared to the hot process are the less fuel consumption, the simpler construction equipment, and thus the lower construction cost. However, the finished product of the cold recycling process is generally not as stable as that produced by the hot process. Thus, at present, cold-mix recycling is used only on low volume roads. More work still remains to be done to improve the quality of the cold recycled mixture, so that it could be used on interstate highways and other high volume roads. Such a breakthrough would mean eventual replacement of hot recycling by cold recycling and a drastic reduction of pavement rehabilitation cost.

Increased interest in improving the quality of the cold recycled paving mixtures has made it necessary to understand the behavior of these mixes more fully, and to develop a suitable mix design method as a means of proportioning the ingredients in the recycled mixtures. The difficulty encountered in designing a cold recycled mixture lies in the fact that it behaves differently from a conventional virgin mix. Conceptually, in an old pavement material, an aggregate piece is surrounded by a hardened layer of binder. During the recycling process, a thin film of virgin binder or softening agent is established. This thin film of virgin binder or softening agent will have a rejuvenating effect on the old binder material. The rejuvenating action that takes place is dependent on time, temperature and additional traffic compaction. If too much of the old binder material is "activated" through the rejuvenating action, the mix will have too rich an asphalt content, and problems such as instability and bleeding will occur. (Bleeding is the upward movement of asphalt in a pavement, creating a film of asphalt on the surface). If not enough virgin asphalt or softening agent is added, the mix will be too lean in asphalt content, and it will not have the desirable durability and flexibility. In the design for a cold recycled mix, it is very important to be able to predict the long term behavior from short term laboratory results.

The purpose of this study was to investigate a method that would allow a decision to be made from short term results concerning proportioning of ingredients in cold recycled asphalt paving mixtures. In a previous study on cold-mix recycling by the author [2], it was found that the potential problem of instability of a recycling mixture could be detected when the mixture was subjected to a high compactive effort with the gyratory compactor. It was thought that the compactive effort of the gyratory machine forced the old binder and the virgin binder or softening agent to act as one. Thus, the rejuvenating action was expedited. Based on this hypothesis, the gyratory machine was used to compact the recycled mixes and to evaluate their performance. The study has the following objective:

1. To evaluate the feasibility of using the Gyratory Machine for designing cold recycled asphalt paving mixtures.
2. To study the properties of cold recycled asphalt paving mixtures under the effect of time, additional compaction and temperature.
3. To evaluate the effectiveness of the different cold recycled mixes using the different softening agents.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Background on Asphalt Pavement

2.1.1 Definition

Traditionally, airport or highway pavements have been classified in two categories - the rigid pavement and the flexible pavement. These two types of pavements differ in the way they distribute the loads over the subgrade [3] . The rigid pavement is usually composed of Portland cement concrete. Because of its rigidity (high modulus of elasticity), the rigid pavement distributes the load over a relatively large area of the subgrade. The flexible pavement usually consists of an asphalt surface course over a base course, a subbase course and a compacted subgrade. The loads are distributed from the surface to the subgrade through a series of flexible layers. The terms, Rigid Pavement and Flexible Pavement, have been commonly used to denote Portland cement concrete pavement and asphalt pavement respectively. Today, an asphalt pavement may have a stiffness comparable to that of a Portland cement concrete pavement. This is especially true for a full-depth asphalt pavement, which approaches the rigid condition. The Asphalt Institute defines the asphalt pavements as "Pavements consisting of a surface course of mineral aggregate coated and cemented together with asphalt cement on supporting courses such as asphalt bases, crushed stone, slag or gravel; or on Portland cement concrete, brick, or block pavement" [4] . This definition for asphalt pavements will be used throughout this report.

2.1.2 Designs of Asphalt Pavements

The two primary functions of a pavement structure are (1) to provide a safe and comfortable riding surface, and (2) to act as a protective layer for the subgrade below. Pavement structures are designed for specified traffic loads and expected life. Methods for the design of asphalt pavements may be classified in two groups - the empirical method and the analytical method.

Empirical methods of pavement design have been developed from experiences and road tests. The most common empirical design methods include the AASHTO [5] , the Asphalt Institute [6] , the National Crushed Stone Association [7] and the California [8] methods of design.

In an analytical design method, a suitable elastic or viscoelastic model is used to represent the pavement structure. Using the model, the stresses, strains and deformations in the pavement structure are calculated for the designed traffic loads. The composition and thicknesses of the layers are selected so that the stresses, strains and deformations do not exceed the capabilities of any of the materials in the pavement. The two common analytical design methods are the multilayer elastic and the finite element design methods [3, 9, 10]. Various computer programs have been developed and used, such as the BISTRO (Bitumen Structures in Roads) program developed by the Shell Company and the Chevron program developed by the Chevron Oil Company.

2.2 Tests for Bituminous Mixtures

Conventional tests to characterize bituminous paving mixtures are mostly empirical or semi-empirical, and most of these tests have been standardized. However, in the last decade, a great amount of effort has been put in developing test methods to measure the fundamental properties of the bituminous mixtures. These fundamental properties, such as the dynamic elastic modulus and the Poisson's ratio, are essential input parameters for the analytical pavement design method. This section reviews some of the common empirical, semi-empirical and fundamental test methods used today.

2.2.1 Marshall Test

The concept of the Marshall test was first formulated by Bruce Marshall [11] . The Marshall test and design procedures were further developed by the U.S. Corps of Engineers through extensive correlation studies. The test procedures have been standardized by the American Society for Testing and Materials and designated as ASTM D1559.

In the standard Marshall test, test specimens of 2.5 inches (64 mm) in height and 4 inches (102 mm) in diameter are tested at 140^{o}F (60^{o}C). Specimens are loaded to failure diametrically through semicircular testing heads at a constant speed of 2 inches (51 mm) per minute. The two values measured in the loading test are (1) the stability, which is the load required to fail the specimen, and (2) the flow, which is the vertical deformation required to produce failure. A density and voids analysis is also performed, and the percent air voids and the percent voids in mineral aggregate (VMA) of the specimens are calculated. Design criteria have been recommended for these four variables.

Some researchers have investigated the relationship between the Marshall stability and flow and other fundamental properties. Goetz and McLaughlin [12, 13] stated that the Marshall test is a form of confined test, in which the confinement is due to the curved shape of the testing head. They also demonstrated that a good correlation existed between the Marshall flow values and the angle of internal friction. Metcalf [14] analyzed the stress condition of a specimen in a Marshall test, and showed that the bearing capacity of a bituminous mixture could be related to the Marshall stability and flow. The Marshall stiffness (calculated as stability/flow) was found to correlate well with rut depth [15, 16] .

Several researchers have modified the Marshall test to test cold paving mixtures at room temperature instead of the standard 140°F (60°C) [17, 18]. Gadallah [18] recommended using the Marshall Index (defined as the slope of the linear portion of the load deformation trace of the Marshall test) in addition to the conventional Marshall variables to characterize a paving mixture.

2.2.2 Hveem Stabilometer Test

The Hveem stabilometer test is a part of the Hveem method of designing paving mixtures, which was developed under the direction of Francis N. Hveem, formerly Materials and Research Engineer for the California Division of Highway [11] . The test procedures have been standardized by the ASTM and designated as ASTM D1561.

In the standard test procedures, Marshall size specimens are tested in the stabilometer at 140°F (60°C) with a head speed of .05 inch (1.27 mm) per minute. The Hveem stabilometer is a semi-triaxial testing device containing a fluid around a flexible diaphragm. A test specimen is loaded in the stabilometer at a constant head speed and the lateral pressure developed is registered in the stabilometer fluid. The stabilometer value, which indicates the relative stability of a mixture is calculated from the following empirical equation:

$$S = \frac{22.2}{[P_h D_2/(P_v - P_h)] + .222}$$

where P_v = Vertical pressure, 400 psi (2.76 MPa)

P_h = Horizontal pressure when P_v is 400 psi (2.76 MPa)

D_2 = Displacement of specimen

The standard stabilometer test has been commonly used to evaluate the performance of hot asphalt paving mixtures and there have been good correlation of the stabilometer values with the field performance [19]. Recently, the stabilometer test has been used to test cold asphalt mixtures at room temperature [2].

2.2.3 Stabilometer Resistance (R-Value) Test

The R-Value test is used by the California Division of Highways for the evaluation of base course materials. The R-Value obtained is an essential input parameter in the California method of pavement design [8].

Marshall size specimens are tested in the stabilometer at room temperature. The test procedure is similar to that of the Hveem stabilometer test, with the exception that the vertical pressure is applied only to 160 psi (1.10 MPa). The R-Value is calculated by the following empirical formula:

$$R = 100 - \frac{100}{(2.5/D_2)(P_v/P_h - 1) + 1}$$

where P_v = Vertical pressure, 160 psi (1.10 MPa)

P_h = Horizontal pressure when P_v is 160 psi (1.10 MPa)

D_2 = Displacement of specimen

Both the R-Value and the Hveem test were developed on the basis that the stability of a paving material depends on how much of the vertical load will be transmitted laterally. A higher transmitted lateral pressure will produce a lower R or S value, indicating a less stable mixture.

Iida [20] has analyzed the vertical stress of a specimen in the stabilometer test using the Maxwell and the Burgers viscoelastic models. His results showed that the S value measured with the standard procedure at 140°F (60°C) was highly correlated with the tangential modulus of elasticity, and the R and S values measured at room temperature were correlated with the modulus of elasticity alone. It is noted that the horizontal stresses, which are directly related to the R and S values, are very complex functions of the properties of the stabilometer fluid, the loading rate and the viscoelastic properties of the test specimen, and have not been analyzed in detail by any researcher. Due to the empirical nature of the test method, the correlation of the R and S values with field performance is much more meaningful than a stress analysis of the test specimen.

2.2.4 Indirect Tensile Test

The indirect tensile test is a simple and common method used to determine the tensile strength of concrete or bituminous mixtures. The test involves loading a cylindrical specimen diametrically at a constant speed until splitting failure occurs. Both the vertical and horizontal deformations are recorded during the loading process. The tensile strength, S_t, can be calculated by the following equation:

$$S_t = \frac{2\ P_{max}}{\pi\ h\ d}$$

where P_{max} = Maximum load at failure

h = Specimen height

d = Specimen diameter

The other variables obtained from this test are the Poisson's ratio, the tensile stiffness and the total tensile strain at failure [21].

2.2.5 Creep Test

Bituminous mixtures are viscoelastic materials, whose stress-strain characteristics are time-dependent. The creep test is used to determine the viscoelastic properties of bituminous mixtures. Basically, it involves applying a constant stress to a specimen and observing its deformation as a function of time. The most common variable obtained from the creep test is the creep compliance, J(t), which is given as:

$$J(t) = \varepsilon(t)/\sigma_o$$

where $\varepsilon(t)$ = Strain at time t

σ_o = Constant stress aplied

Viscoelastic models are generally used to describe the stress-strain characteristics of bituminous mixtures. The most common models used are the Maxwell model and the Burgers model, illustrated in Figure 2.1. The Maxwell model consists of a spring in series with a dashpot. The Burgers model is made up of two springs and two dashpots. When the Burgers model is used to analyze the time-dependent deformation in the creep test, the creep compliance, J(t), can be calculated to be:

$$J(t) = \frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2}(1 - e^{-E_2 t/\eta_2})$$

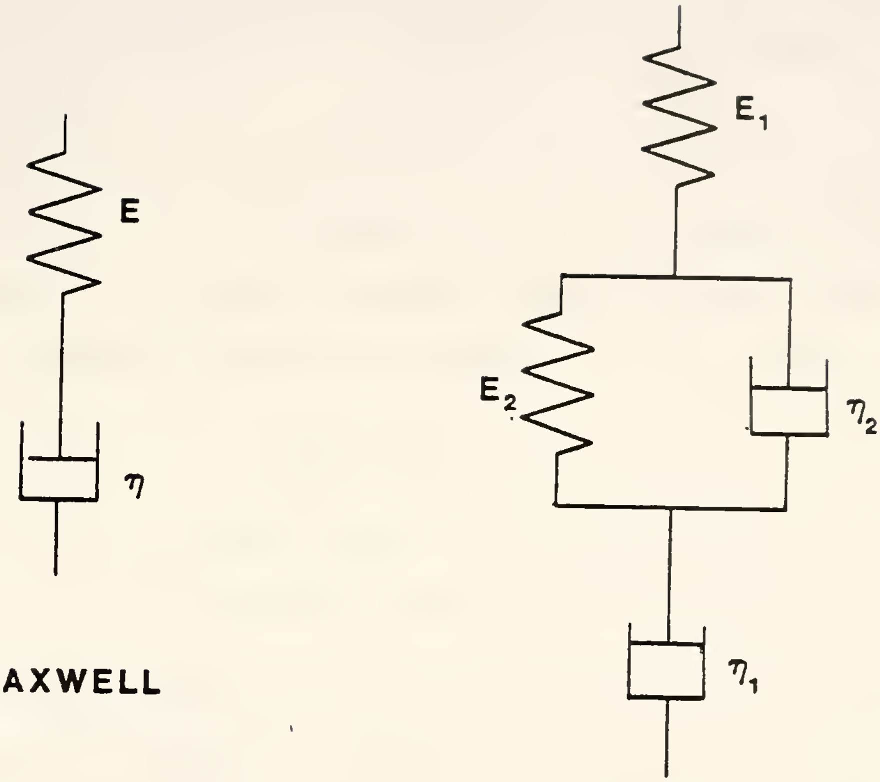
The constants (E_1, E_2, η_1 and η_2) can be found through curve fitting, using graphical procedure [22, 23] or nonlinear least-square regression analysis [20].

The sample sizes and applied pressures used by the different researchers vary. A convenient and effective way to run the creep test is to use standard Marshall size specimens and constant applied pressures of 5 and 10 psi (34.5 and 69.0 kPa) [20].

The results of the creep test have been used to measure the degree of asphalt hardening in asphaltic mixtures and as input parameters to the viscoelastic analysis of pavement design [20, 23, 24].

2.2.6 Resilient Modulus Test

The two material properties needed as input parameters to the linear elastic layered pavement analysis are the elastic modulus (E)



MAXWELL

BURGERS

FIGURE 2.1 VISCOELASTIC MODELS

and the Poisson's ratio (ν). Since a bituminous mixture is a viscoelastic material, its stress-strain characteristic (described by E) is time-dependent. The "idealized" E used for the linear elastic layered model will depend on how it is defined and the test method used to measure it.

The most common "idealized" E value used in the linear elastic layered model is the resilient modulus M_R. The resilient modulus is defined as the ratio of the applied stress to the recoverable strain when a repeated dynamic load is applied. It can be expressed as:

$$M_R = \sigma/\varepsilon_r$$

where σ = Applied stress

ε_r = Recoverable strain

The test method is based on the fact that when a viscoelastic material is loaded for a short duration of time, its response is mainly elastic. The test involves applying cyclic pulse loads of short duration to the test specimens and recording the instantaneous deformations through the use of strain gages or linear differential transformers (LVDTs). The resilient moduli are then calculated from the induced stresses and the measured strains. The resilient modulus is essentially the instantaneous elastic modulus of a viscoelastic material.

The conventional resilient modulus test is conducted in a triaxial device. Specimens are usually 4 inches (10.16 cm) in diameter and 8 inches (20.32 cm) in height. Repetitive pulse loads of constant magnitude are applied on the flat surfaces of the specimens, and the deformations are measured using LVDTs [3, 25]. The main disadvantage of this test method is that it is too complicated or expensive for routine control or mix design purposes.

A simpler test method is the diametral resilient modulus test developed by Schmidt [26]. In this method, standard Marshall size specimens are used. A vertical pulse load of 0.1 second duration is applied diametrally on the test specimen every 3 seconds, and the corresponding horizontal deformation is recorded. The derivation of the equation for calculating M_R from the applied load and the induced deformation was based on the analytical work of Timoshenko and Goodier [27] on an elastic thin disk. By assuming the specimen to be linearly elastic and in a plane stress condition, the resilient modulus of the specimen can be calculated to be:

$$M_R = P(\nu + \frac{4}{\pi} - 1)t\ d_h$$

where P = Applied load

ν = Poisson's ratio

t = Thickness of specimen

d_h = Horizontal displacement

Schmidt suggested the use of 0.35 as the Poisson's ratio. It is noted that the Poisson's ratio can be obtained if both the vertical deformation and the horizontal deformation are recorded [21, 28].

In this study, the resilient modulus was calculated from the vertical deformation rather than the horizontal deformation as suggested by Schmidt. The theoretical basis and the testing procedure for this method of measuring M_R are presented in detail in Chapter 5.

2.2.7 Fatigue Test

When a paving mixture is subjected to a large number of cyclic loads, the stiffness (or elastic modulus) of the material will tend to decrease and cracks or complete fracture may eventually occur. This phenomenon is known as fatigue, and controls the service life of a pavement material.

A fatigue test generally involves applying a cyclic load or deformation to a test specimen and observing the number of cycles it takes to produce failure or certain percentages of reduction in stiffness. The two types of controlled cyclic testing are (1) the controlled stress, and (2) the controlled strain. Monismith and Deacon [29] introduced the mode factor to differentiate between the controlled stress and the controlled strain tests quantitatively. It is defined as:

$$MF = \frac{|A| - |B|}{|A| + |B|}$$

where MF = Mode factor

A = Percentage change in stress due to a fixed percent reduction in stiffness

B = Percentage change in strain due to a fixed percent reduction in stiffness

The mode factor approaches -1 for controlled stress and +1 for controlled strain, and is somewhere between -1 and +1 for mixed mode. Monismith and Deacon stated that the controlled strain mode of testing is applicable to thin layers of pavement structure (2 inches or less) and the controlled stress mode is applicable to thick layers (greater than 6 inches). A mode factor between -1 and +1 is applicable to layers of 2 to 6 inches in thickness. It is also known from experience that the controlled stress fatigue test usually produces a conservative estimate of the fatigue life.

The different test methods used to produce the cyclic stresses or strains in the specimen include the following:

(1) Flexural test

(2) Indirect tension test

(3) Direct tension test

(4) Torsion test

2.3 Recycled Asphalt Pavement

The last five years has seen recycling of asphalt pavements evolve from an experimental state to an economically preferred and functionally satisfactory process. A great number of reports have been written on successful recycling projects in the United States and in other parts of the world (see References 30-47). A number of laboratory studies have also been conducted on the performance of the recycled asphalt mixtures (see References 2, 20, 48-58). This section reviews some background information on the recycling process, the mix design methods and the behavior of recycled asphalt mixtures.

2.3.1 The Recycling Process

The recycling of asphalt pavements is the process of re-using a deteriorated asphalt pavement material in a functionally new pavement. An existing asphalt pavement material usually contains a hardened asphaltic binder and a deteriorated aggregate, and has lost its desirable characteristics such as stability, flexibility and durability. The fundamental process of asphalt pavement recycling involves the addition of rejuvenating agents to soften the hardened old asphaltic binders, and the addition of virgin aggregates to upgrade the deteriorated aggregates. Basically, it involves (1) removing the old pavement material from the road, (2) remixing it, when necessary with additional virgin aggregate, a virgin binder or a rejuvenating agent, and (3) recompacting it. The process can be carried out either hot or cold, i.e., with or without the application of heat.

There are a wide variety of procedures by which asphalt pavements can be recycled. These procedures vary according to the type of equipment used, the type of pavement material to be recycled, the physical location where the process takes place, and the functional purpose of the end-product. Recycling procedures are generally divided into three categories [30]. They are (1) Surface Recycling, which involves the in-place recycling of the surface of a pavement, (2) In-Place Surface and Base Recycling, which involves the in-place recycling of both the surface course and the base course of a pavement, and (3) Central Plant Recycling, in which the processing of the recycled pavement material is done at a central plant.

Some of the materials that have been used as the added binders to the recycled asphalt mixtures include some soft asphalt cements, asphalt emulsions, cutbacks, foamed asphalts and various rejuvenating agents. Rejuvenating agents are chemicals consisting mainly of aromatic hydrocarbons that can soften the old hardened asphaltic binder when mixed with it. Some of the commercially available rejuvenating agents include Reclamite, Mobilsol, Dutrex, Paxole and Cyclogen.

2.3.2 Mix Design Methods for Recycled Asphalt Pavements

The mix design for a recycled asphalt material basically involves the determination of the kind and amount of virgin asphalt (or rejuvenating agent) and virgin aggregate to be added to the recycled material. Various design procedures have been proposed by different agencies and researchers for both the cold and the hot recycled asphalt mixtures. Most of these proposed design procedures are similar in the general approaches and differ only in the details. A design method usually consists of the following general steps:

1. The old pavement to be recycled is evaluated. This usually involves the extraction and recovery of the asphaltic binder and aggregate, and the determination of the properties of the recovered asphalt and aggregate.
2. Determination is made on the amount of additional aggregate needed to meet the required gradation.
3. The type and amount of softening agent to be added is selected through the use of viscosity blending charts. (Viscosity blending charts show the relationships between the concentration of the softening agents and the viscosity of the blend consisting of the old asphaltic binder and the softening agent.)
4. The recycled mixtures are prepared and tested, and the optimum proportioning of ingredients is then determined from the test results.

Conventional tests for bituminous mixtures are generally used to evaluate the recycled mixtures. They include the Marshall stability, the Hveem stabilometer (S and R Values), the resilient modulus, the indirect tension, the permanent deformation, the fatigue and the creep compliance tests. The water sensitivity test and the freeze-thaw test have been used to measure the susceptibility of the recycled mixes to water and freezing and thawing.

2.3.3 Behavior of Recycled Asphalt Mixtures

A recycled asphalt mix generally consists of a blend of old and virgin aggregates, and a blend of old and virgin binders. In a hot recycled mix, the blending of the old binder and the virgin binder (or rejuvenating agent) is relatively more homogeneous. In a cold recycled mix, the virgin binder or rejuvenating agent tends to adhere to the old material (old aggregate coated with old binder), and to form a thin film around it. The diffusion of the virgin binder or rejuvenating agent into the old binder is a function of time, temperature and additional traffic compaction [2, 20]. This diffusion process can greatly influence the behavior of a recycled material, and thus a knowledge of its long-term behavior is very important in designing a recycled mix.

The time-dependent diffusion process of the virgin binder (or rejuvenating agent) into the old binder is also present in the hot recycled asphalt mixtures. Carpenter and Wolosick [53] studied this diffusion phenomenon in a hot recycled material, made from an old pavement material with the addition of a rejuvenating agent, Paxole 1009. The recycled material was tested over a long period of time, by means of the resilient modulus, creep compliance, permanent deformation and

Marshall tests. Their resilient modulus and permanent deformation test results indicated that the recycled material showed a softening followed by a hardening effect. The softening effect was explained by the diffusion of the rejuvenating agent into the old asphalt cement. When this diffusion process reached the balance point where the viscosity of the outer layer began to increase due to the continuing diffusion, the recycled material would appear to harden again. It is noted, however, that their creep compliance and Marshall test results showed no variation with time. Carpenter and Wolosick claimed that the creep compliance and the Marshall tests were not sensitive enough to detect the softening effect caused by the diffusion process. They further validated this diffusion process through the use of an incremental extraction process. In the incremental extraction process, the binder in the outer layer was extracted by immersing the recycled mix in trichloroethylene for three minutes, and the remaining binder was extracted by further washing with trichloroethylene. Both the binders in the inner and outer layers were recovered using the Abson method. Their results indicated that the outer and the inner layers were not of the same consistency for some time after mixing, but were approaching the same consistency with time, as the diffusion process continued.

Iida [20] studied the long-term behavior of cold recycled asphalt mixtures using the creep test. His results showed that the initial softening effect of a virgin binder or rejuvenating agent was apparent in the first few days after mixing, and that this softening effect was indicated by a drop in the creep compliance value of the recycled mixture.

The literature reviewed above would indicate that a recycled mix behaves differently from a virgin mix. Thus a thorough understanding of the long-term behavior of the recycled asphalt mixtures is needed before any mix design method can be applied to the recycled materials effectively.

CHAPTER 3

EQUIPMENT AND MATERIAL

3.1 Equipment

The major pieces of equipment used in this study include the gyratory testing machine, the resilient modulus test equipment, the Hveem stabilometer and compression machine, the Marshall testing equipment and the Foamix asphalt dispenser. They are described in the following sections.

3.1.1 Gyratory Testing Machine

The gyratory testing machine was used for compaction and testing of the recycled mixtures. Figure 3.1 shows the gyratory machine used in this study. This machine was developed by the U.S. Army Engineer Waterways Experiment Station [59]. The gyratory machine compacts a specimen by a kneading process. Figure 3.2 shows the cross section through the gyratory mechanism. A specimen in a mold is held by a mold chuck and a constant ram pressure. The mold and the mold chuck is set at a fixed angle (initial angle of gyration) by two fixed rollers. As the two fixed rollers rotate, a shear strain is constantly applied to the mixture in the mold, and as a result the mixture is compacted by a gyratory kneading mechanism. A ram pressure of 200 psi (1.38 MPa) and an initial gyratory angle of 1 degree were used.

The gyrograph recorder plots the shear displacement (gyratory angle) of the specimen during the compaction. A recording of the

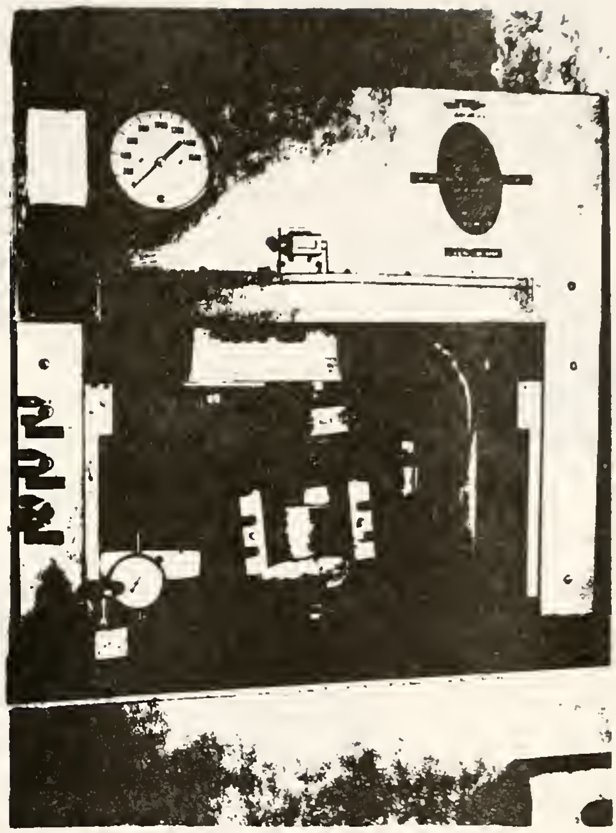
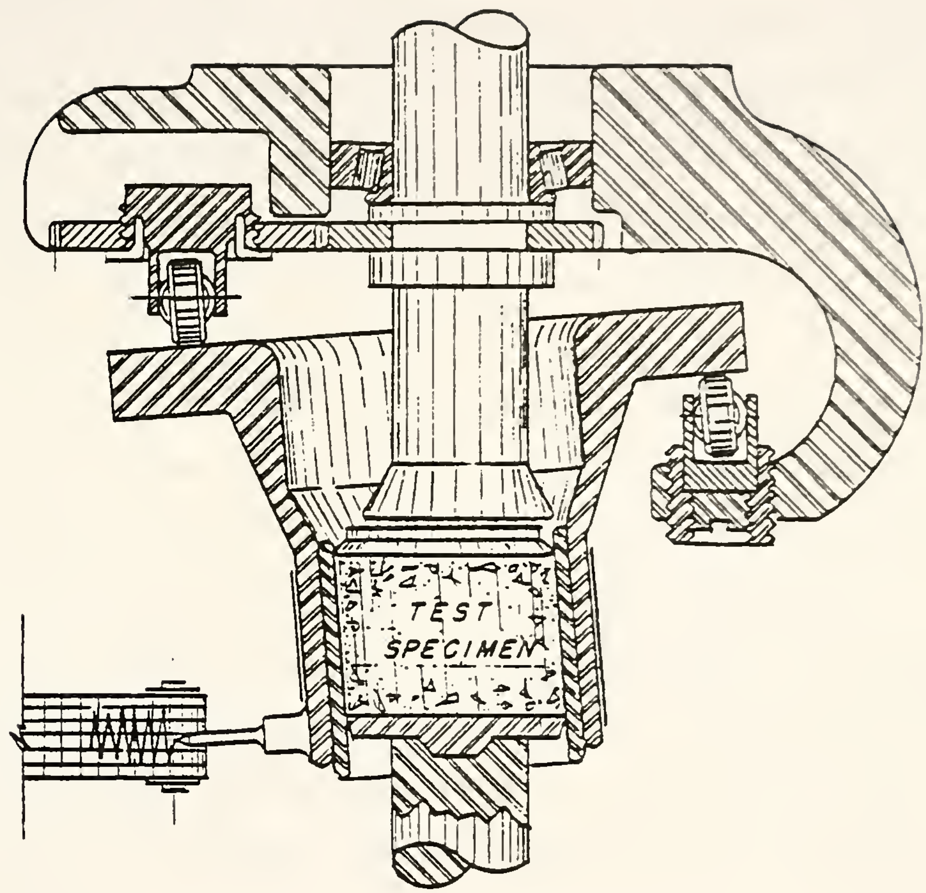


FIGURE 3.1 GYRATORY TESTING MACHINE



(AFTER CORPS OF ENGINEERS)

FIGURE 3.2 CROSS SECTION THROUGH THE GYRATORY MECHANISM gyratory angle is known as the gyrograph and is used to obtain the gyratory indices. Figure 3.3 presents two typical gyrograph bands.

3.1.2 Resilient Modulus Test Equipment

The diametral resilient modulus test proposed by Schmidt [26] was modified and used in this study. The resilient modulus test equipment is shown in Figure 3.4. It consisted mainly of a loading frame, a diaphragm air cylinder, a solenoid valve system, a compressed air source, three DC LVDTs, a two-channel chart recorder, and a DC voltage source for the DC LVDTs.

The compressed air source in the laboratory was connected to the diaphragm air cylinder through the solenoid valve. Every 3 seconds, the electrically activated selonoid valve would open for a duration of 0.1 second, causing a pulse of compressed air to pass to the air cylinder and creating a pulse load on the test specimen. The magnitude of the pulse load was a function of the pressure of the compressed air, which was controlled by a pressure regulator. The pressure of the compressed air was adjusted so that pulse loads of 50 lb. (222.4 NT) were generated.

The vertical deformation of the test specimen was measured by two LVDTs, as illustrated in Figure 3.5. The horizontal deformation of the specimen was measured by the diametral extensometer, as illustrated in Figure 3.6. The output voltages of the LVDTs were plotted on the chart recorder.

3.1.3 Hveem Stabilometer and Compression Machine

The Hveem stabilometer and compression machine, shown in Figure 3.7, were used for the R-Value test in this study. The Hveem

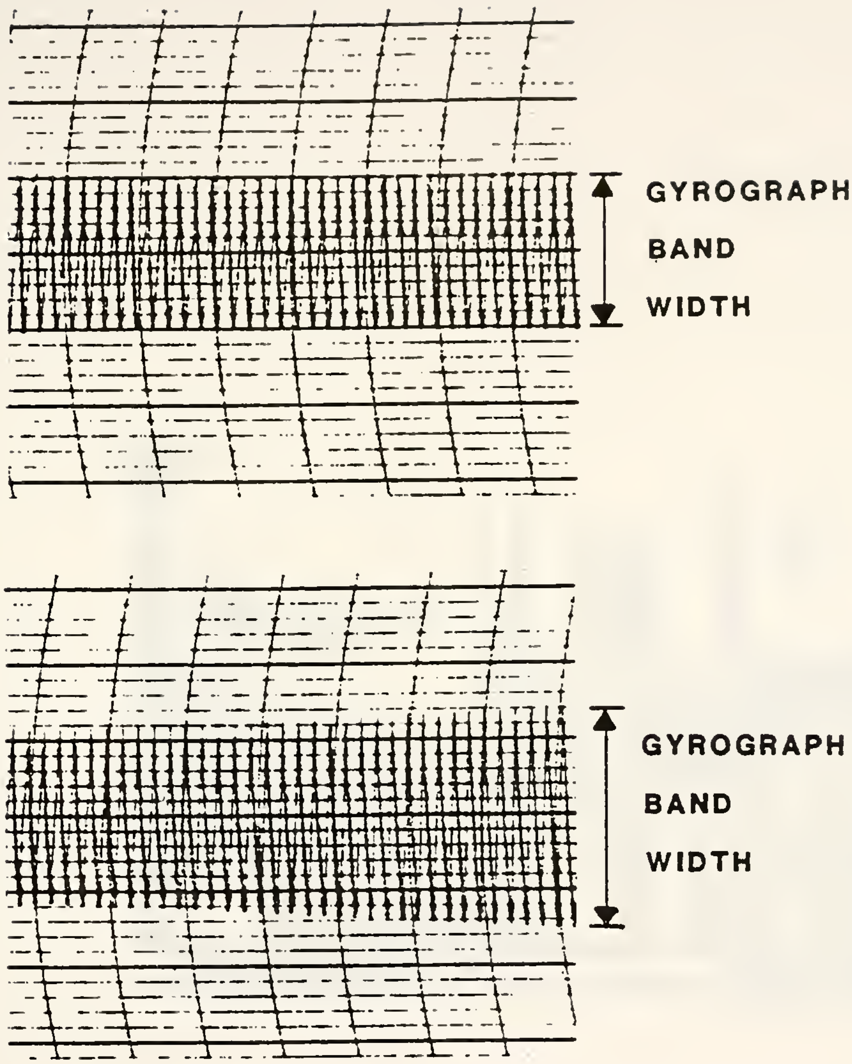


FIGURE 3.3 TYPICAL GYROGRAPH BANDS

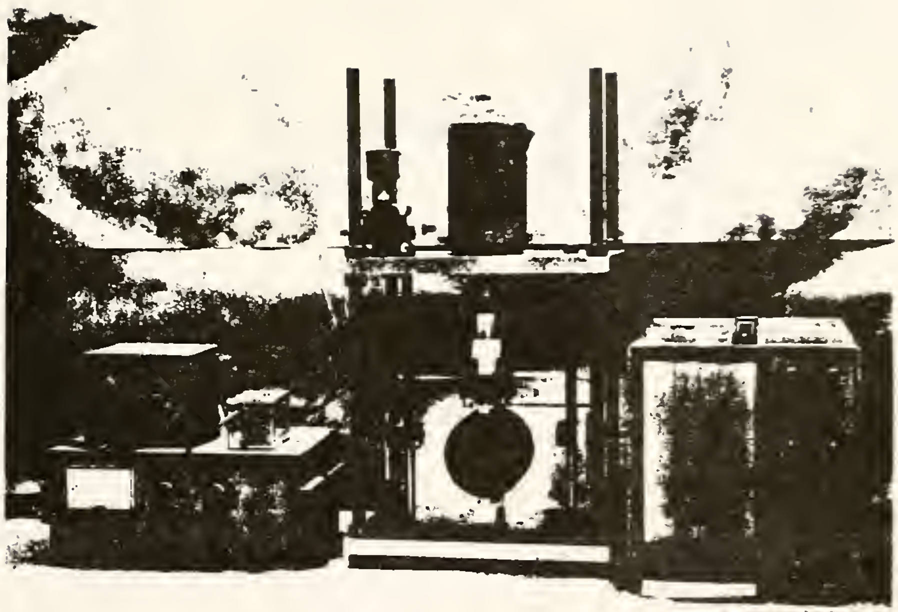


FIGURE 3.4 RESILIENT MODULUS TEST EQUIPMENT

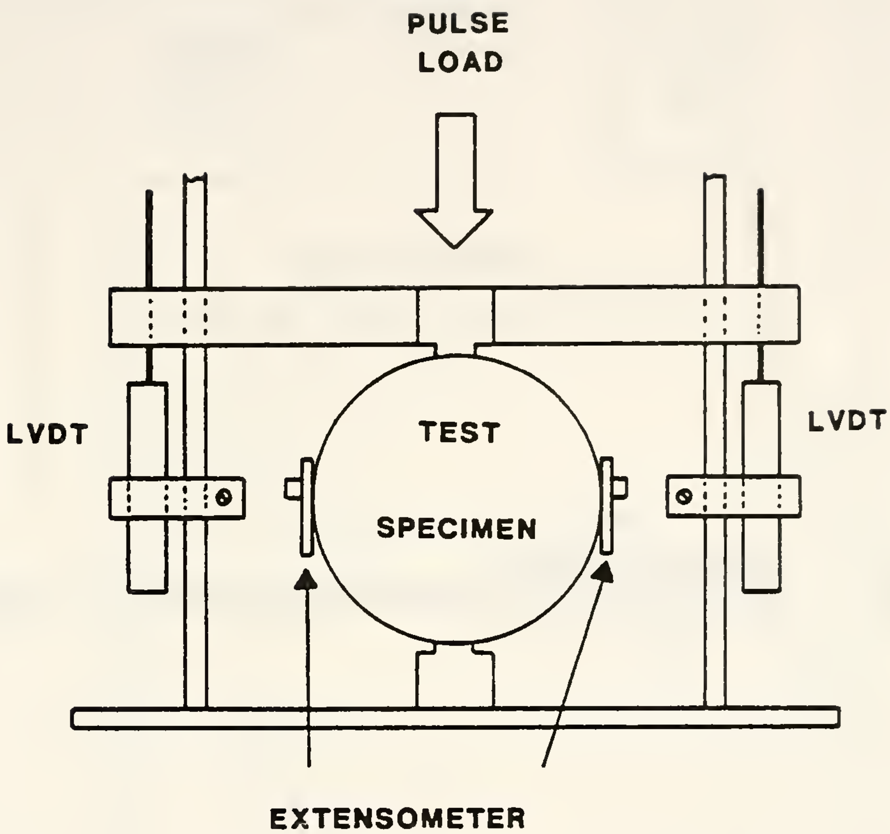


FIGURE 3.5 VERTICAL DEFORMATION MEASURING DEVICE IN RESILIENT MODULUS TEST

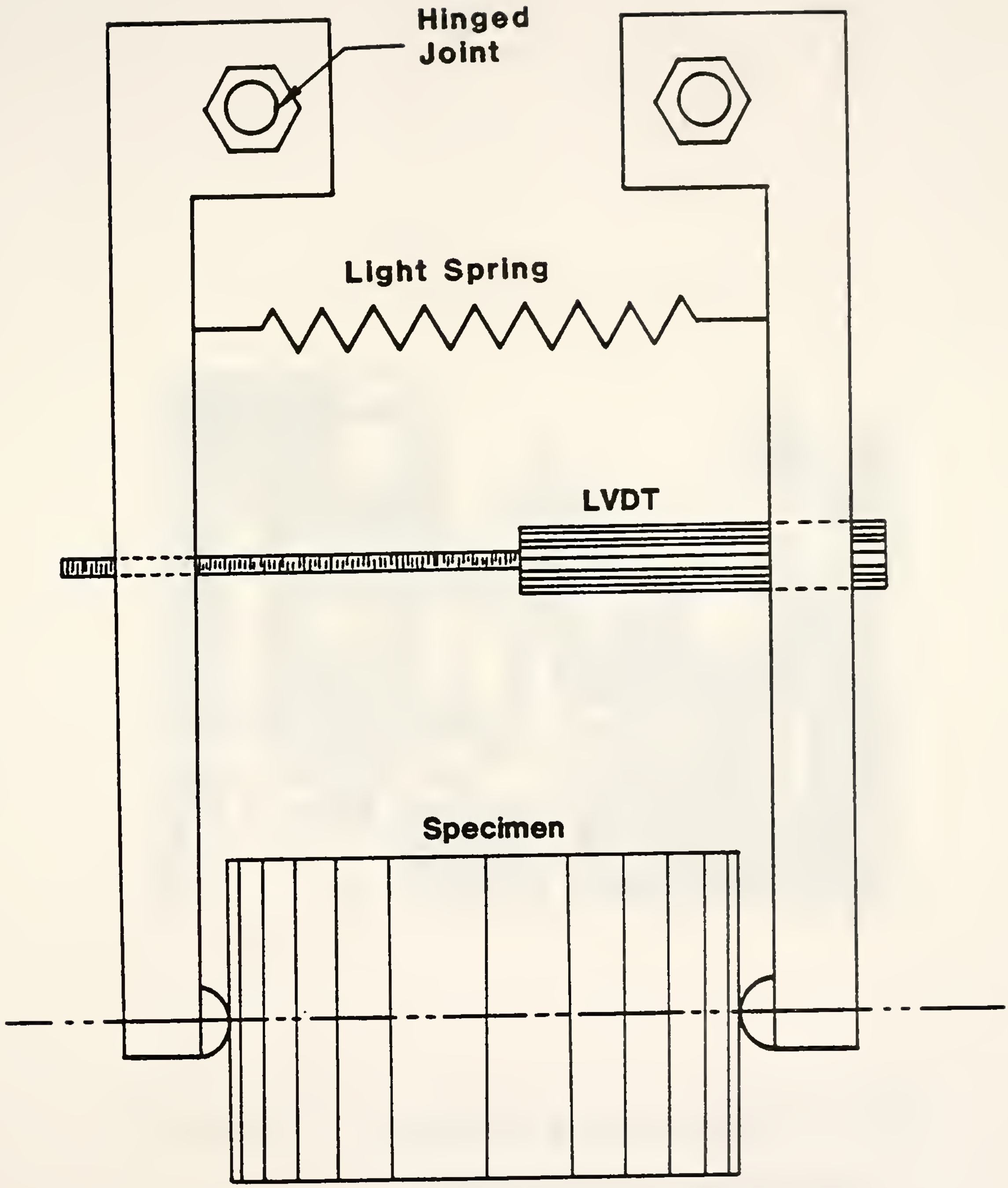


FIGURE 3.6 DIAMETRAL EXTENSOMETER

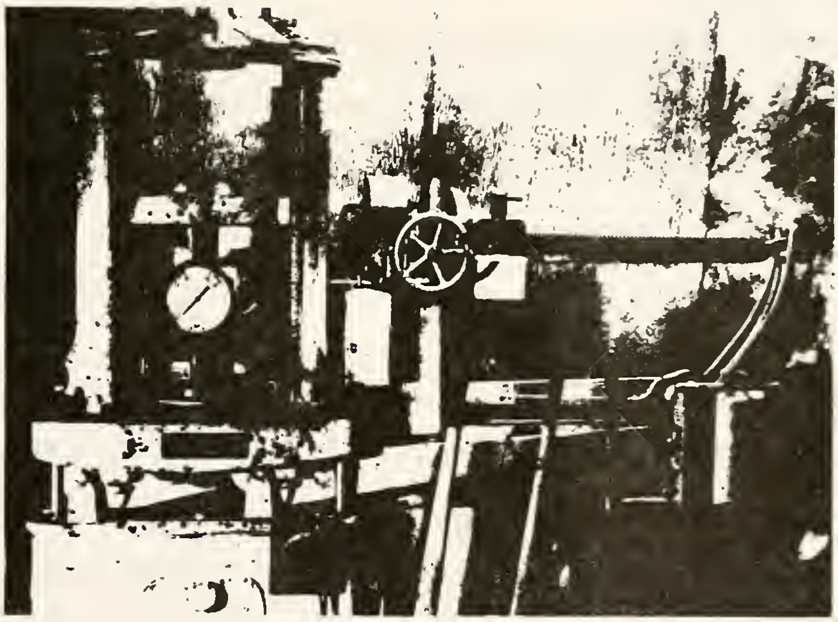


FIGURE 3.7 HVEEM STABILOMETER AND COMPRESSION MACHINE

stabilometer is a triaxial testing device which measures the horizontal pressure developed by a test specimen as a vertical pressure is applied. The compression machine was capable of applying loads at a constant head speed of 0.05 inch per minute (0.02 mm per second) as required by the ASTM standards for the Hveem test.

3.1.4 Marshall Testing Equipment

The autographic Marshall testing apparatus, shown in Figure 3.8, was used to conduct the Marshall stability tests on the recycled mixtures. The recorder provides a continuous load-deformation plot as a specimen is being loaded to failure in the Marshall test. A typical load-deformation plot by the recorder is depicted in Figure 3.9. The load deformation plot enables one to accurately determine the Marshall stability, flow and index.

3.1.5 Foamix Asphalt Dispenser

When a small amount of water is injected into a hot asphalt cement, the water will be vaporized and a large volume of foamed asphalt will be generated. A laboratory Foamix asphalt dispenser developed by CONOCO Inc. was used to produce the foamed asphalt to be added to the recycled mixtures. It is pictured in Figure 3.10. Hot asphalt is stored in the thermostatically controlled 2-gallon storage tank and is continuously circulated by a gear pump at a constant speed. The desired amount of foamed asphalt is produced by a three step automatic operation, which can be activated by a contact switch. In step one, water and compressed air flow through the nozzle in a preflush cycle controlled by a timer. In step two, asphalt flow is switched from

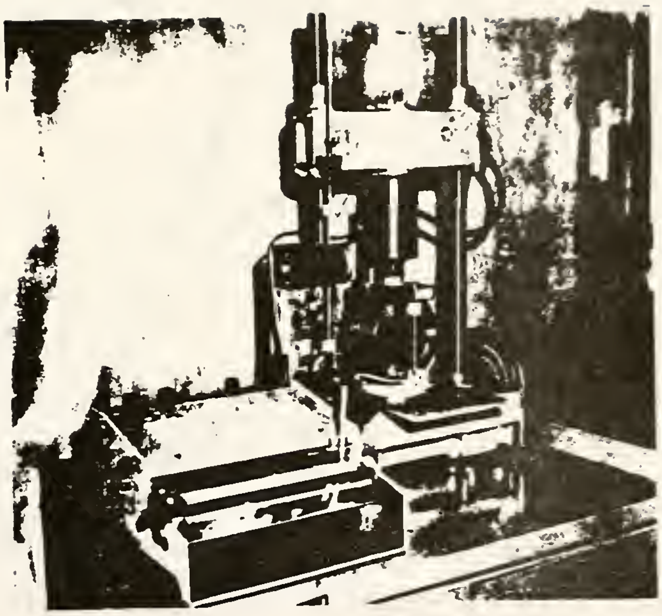


FIGURE 3.8 AUTOGRAPHIC MARSHALL TESTING APPARATUS

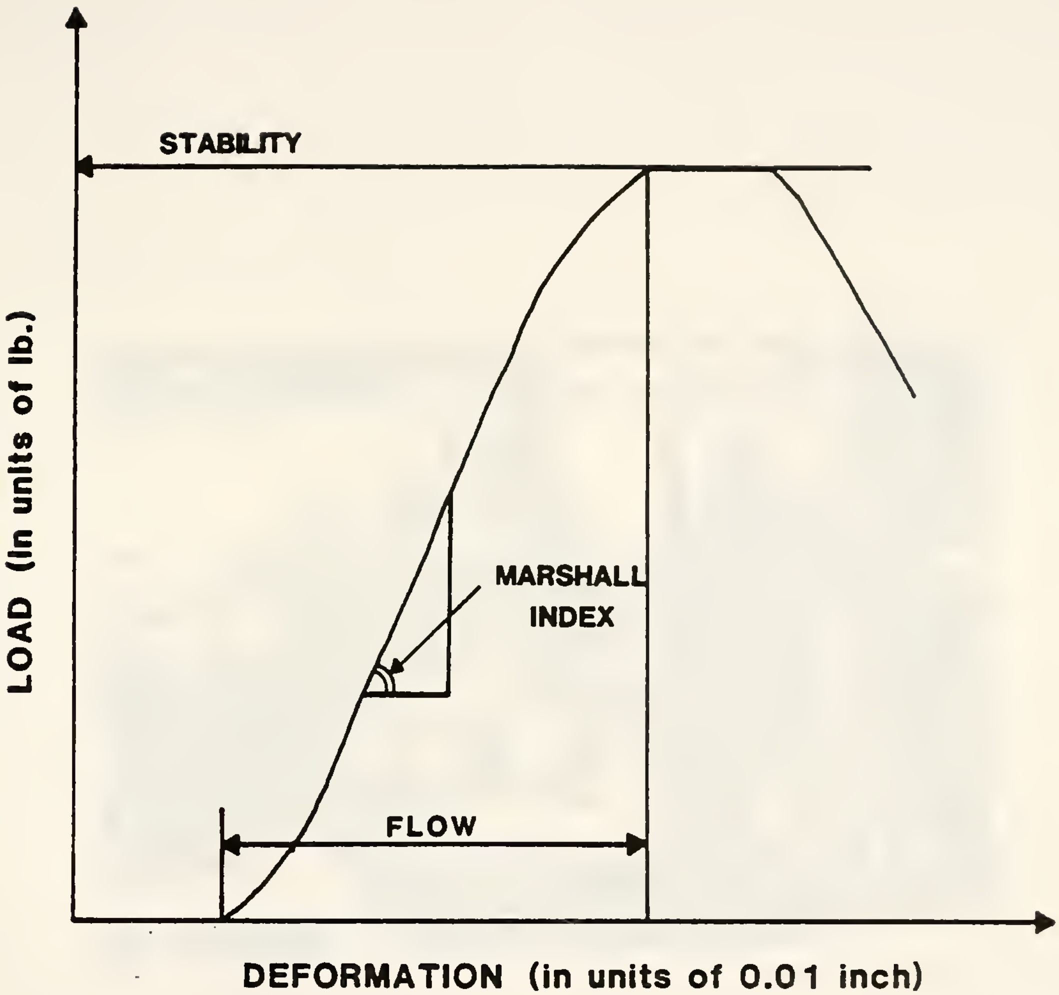


FIGURE 3.9 TYPICAL LOAD-DEFORMATION PLOT
IN MARSHALL TEST

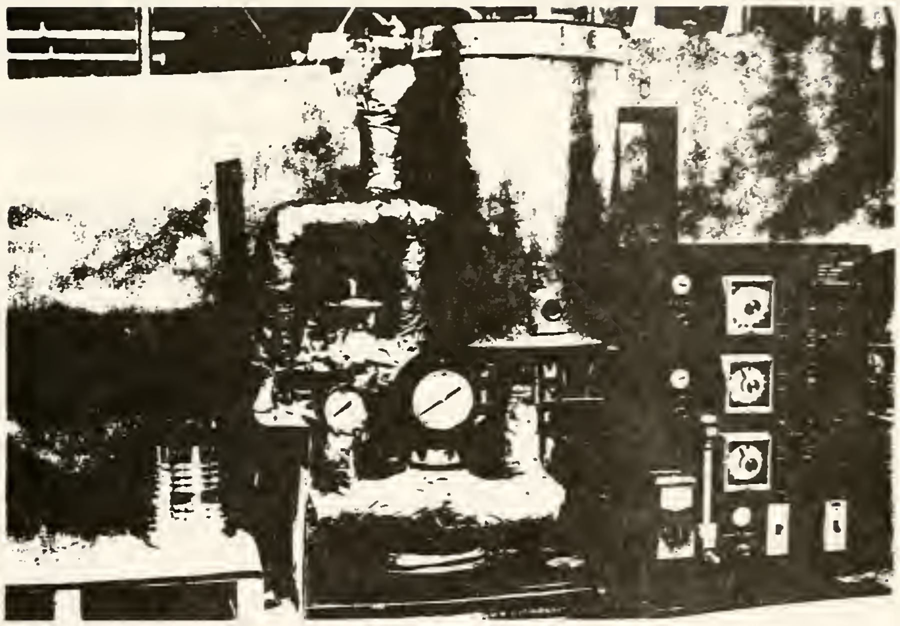


FIGURE 3.10 LABORATORY FOAMIX ASPHALT DISPENSER

the circulation operation to the nozzle for the selected time interval controlled by a second timer to deliver the desired amount of asphalt. Asphalt flow is then switched back to the circulation operation. In step three, the water and compressed air continues to flow through the nozzle for a postflush cycle controlled by a third timer. The operation is then finished and the timers are ready for the next operation.

3.2 Recycled Paving Mixtures

The paving materials used in this study include an old pavement material and an artificially aged paving mixture. They are described in the following section.

3.2.1 Old Pavement Material

An old pavement material was obtained from a state road near Wabash, Indiana, and used in this study. The material had been crushed to a maximum size of 1 inch (2.54 cm). A typical sample of the pavement material is pictured in Figure 3.11. The material was sieved into four size groups. The percentage by weight of the total for each size group is given below.

Size Group	Percent of Total
> 3/8 in. (9.5 mm)	28
3/8 in - #4 (9.5 - 4.75 mm)	36
#4 - #16 (4.75 - 1.18 mm)	33
< #16 (1.18 mm)	3

The pavement material was to be recombined in this same proportion for each batch of recycled mixture. This was done to obtain less variability in the pavement material used.

FIGURE 3.11 OLD PAVEMENT MATERIAL

3.2.1.1 Recovered Bitumen

A centrifuge extraction of bitumen (ASTM-D2172 Method A) performed on the pavement material indicated an average bitumen content of 5.0% by weight of the aggregate (from the results of five extraction tests). Recovered asphalt using the Abson Recovery Method (ASTM D1856) had the following physical properties.

Standard Test	Average Value
ASTM D5 Penetration (100 g, 5 sec., 25°C)	25 (dmm)
ASTM D2171 Absolute Viscosity (60°C)	63,800 poise

3.2.1.2 Recovered Aggregate

The recovered aggregate consisted mainly of crushed limestone. The gradation of the recovered aggregate is depicted in Figure 3.12. It is compared to the gradation range of Indiana's Type II No. 9 surface mix aggregate. It can be seen that the aggregate is slightly lacking the coarser sizes.

3.2.1.3 Other Aged Conditions

The same pavement material was artificially aged to two other conditions by heating it in a forced draft oven at 120°C (148°F) for one day and three days. The physical properties of the recovered asphalt from these two mixes are shown below:

Length of Heating	Penetration (100 g, 5 sec., 25°C)	Absolute Viscosity (at 60°C
1 day	14.0 (dmm)	> 200,000 poise
3 days	9.0 (dmm)	> 200,000 poise

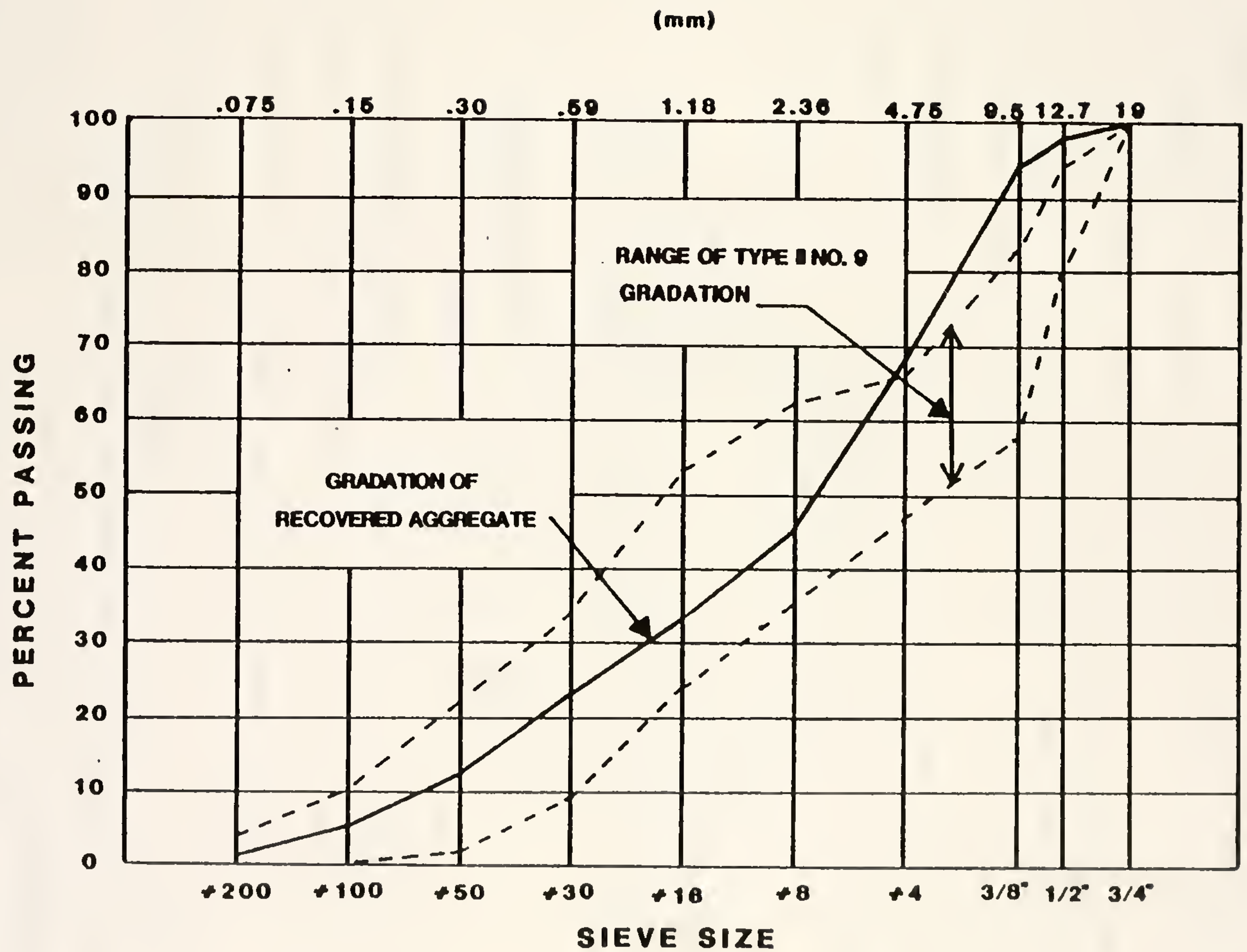


FIGURE 3.12 GRADATION OF RECOVERED PAVEMENT AGGREGATE

3.2.2 Artificially Aged Paving Mixture

Less variability and better control of the material used was desired, so a large portion of the recycled mixes under study were made from an artificially aged paving mixture. The artificially aged mixture was made to resemble the old pavement material described earlier. The material is pictured in Figure 3.13.

The aggregate used was a limestone and the gradation was the same as that of the old aggregate. The aggregate was mixed with 5.5% of AP-3 grade asphalt cement at 150°C (302°F). The mixture was then artificially aged by placing it in a forced draft oven at 120°C (248°F) for 24 hours. The recovered asphalt from the artificially aged mixture had the following physical properties:

Standard Test	Average Value
ASTM D5 Penetration (100 g, 5 sec., 25°C)	24 (dmm)
ASTM D2171 Absolute Viscosity (60°C)	32,300 poise

3.3 Virgin Aggregate

The virgin aggregate used in the study was a limestone obtained from the Erie Stone Company of Huntington, Indiana. The aggregate has been stored in the Purdue Bituminous Laboratory and has been used by many researchers. Its physical properties are shown in Table 3.1.

3.4 Virgin Asphaltic Materials

The asphalt cement used in making the artificially aged paving mixture was an AP-3 as designated in the Indiana State Highway standard specifications [61]. The asphalt cement was supplied by AMOCO, Whiting, Indiana. Its physical properties are shown in Table 3.2.

FIGURE 3.13 ARTIFICIALLY AGED PAVING MIXTURE

TABLE 3.1 PHYSICAL PROPERTIES OF LIMESTONE AGGREGATE [60]

Size Fraction	Bulk Specific Gravity (ASTM C127)	Bulk SSD Specific Gravity (ASTM C127)	Apparent Specific Gravity (ASTM (127)	% Absorption (ASTM C128)
Coarse Aggregate	2.602	2.648	2.725	1.72
Fine Aggregate	2.749	2.778	2.831	1.05
Filler	-	-	2.809	-

TABLE 3.2 PHYSICAL PROPERTIES OF AP-3

Property	Standard	Test Condition	Value
Penetration	ASTM D5	100 g, 5 sec., 25°C	90 (dmm)
Absolute Viscosity	ASTM D2171	60°C	1460 poise
Specific Gravity	ASTM D70	25°C	1.026
Ductility	ASTM D113	25°C	> 100 cm

TABLE 3.3 PHYSICAL PROPERTIES OF AC-2.5

Property	Standard	Test Condition	Value
Penetration	ASTM D5	100 g, 5 sec., 25°C	> 300 (dmm)
Absolute Viscosity	ASTM D2171	60°C	300 poise
Kinematic Viscosity	ASTM D2170	135°C	160 cSt
Specific Gravity	ASTM D70	25°C	1.024
Ductility	ASTM D113	25°C	> 100 cm

The asphalt cement used to generate foamed asphalt was a soft asphalt designated as AC-2.5. It was supplied by AMOCO, Whiting, Indiana. Its physical properties are described in Table 3.3.

A high-float anionic asphalt emulsion, designated as AE-150 in the Indiana State Highway standard specification [61], was used as a virgin binder in the study. It was formulated and manufactured by the K. E. McConnaughhay Laboratory of Lafayette, Indiana. Its physical properties are shown in Table 3.4.

3.5 Rejuvenating Agents

The three rejuvenating agents used are Reclamite, Mobilsol, and DUTREX 739. Reclamite and Mobilsol were in the forms of emulsion, while DUTREX 739 was a highly viscous oil.

The Reclamite and Mobilsol were provided by the K. E. McConnaughhay Laboratory of Lafayette, Indiana. Their physical and chemical properties are described in Table 3.5. The DUTREX 739 was provided by the Shell Development Company of Houston, Texas. Its physical and chemical properties are presented in Table 3.6.

TABLE 3.4 PHYSICAL PROPERTIES OF AE-150

Property	Standard	Test Condition	Value
Percent Residue by Distillation	ASTM D244	Standard	70.0%
Oil Portion of Distillate	ASTM D244	Standard	1.5%
Tests on Distillation Residue			
Penetration	ASTM D5	100 g, 5 sec., 25°C	215 (dmm)
Specific Gravity	ASTM D70	25°C	1.010
Float	ASTM D139	60°C	> 200 sec.

TABLE 3.5 PROPERTIES OF RECLAMITE AND MOBILSOL

Property (1)	Standard	Test Condition	Values	
			Reclamite	Mobilsol
Percent Residue	Evaporation	Heating up to 120°C with a direct flame	63%	72%
Specific Gravity of Residue	ASTM D70	25°C	.966	.974
Saybolt Furol Viscosity	ASTM D88	25°C	25 sec.	69 sec.
Molecular Analysis (2)				
Asphaltenes			0.5%	-
Polar Compounds			17.7%	17.1%
1st Acidaffins			16.4%	16.0%
2nd Acidaffins			38.6%	39.5%
Saturates			26.8%	27.5%

(1) After Iida [20]
(2) After Anderson et al [62]

TABLE 3.6 PROPERTIES OF DUTREX 739

Property[1]	Value
Saybolt Furol Viscosity (at 25°C)	9600 sec.
Specific Gravity (at 16°C)	1.0344
Distillation Test	
Initial Boiling Point	393°C (740°F)
5%	407°C (765°F)
10%	411°C (772°F)
50%	437°C (818°F)
90%	473°C (884°F)
Molecular Analysis	
Asphaltenes	0%
Polar Compounds	18.9%
Aromatics	75.1%
Saturates	6.0%
Estimated Molecular Weight	340

(1) All the information with the exception of Saybolt Fural viscosity, were supplied by Shell Development Company.

CHAPTER 4

DESIGN OF THE EXPERIMENT

4.1 Introduction

The main objective of this study is to evaluate the feasibility of using the gyratory testing machine to design recycled asphalt paving mixtures on a long-term basis. The long-term behavior of a recycled asphalt mixture is dependent on temperature, additional traffic compaction and curing time. In order to evaluate effectively the feasibility of predicting long-term performance from short-term results, the effects of these three factors on the behavior of a wide variety of recycled mixtures have to be fully understood.

Nine sets of experiments were designed to study the behavior of a wide variety of cold recycled asphalt mixtures in depth. Specimens were compacted with the gyratory machine and gyratory indices were obtained during the compaction process. These gyratory indices were to be correlated to the long-term behavior of these mixtures as measured by the resilient modulus, R-value and Marshall tests.

This chapter presents the description of the response variables and the independent variables used, and the experimental designs for this study.

4.2 Response Variables

The response variables used in the laboratory study include the gyratory indices measured by the gyratory testing machine during the compaction process and other variables measured at some specific curing times after compaction. They are described in the following sections.

4.2.1 Gyratory Indices

As a specimen is being compacted in the gyratory machine, the gyratory motion experienced by the specimen is recorded by a gyrograph and the magnitude of the gyratory angle is indicated by the width of the gyrograph. Gyratory Indices can then be obtained from the gyrograph.

4.2.1.1 Gyratory Elasto-Plastic Index (GEPI)

The gyratory elasto-plastic index is defined as:

$$\text{GEPI} = \frac{\text{Minimum Intermediate Gyrograph Width}}{\text{Initial Gyratory Angle}}$$

It gives an indication of the amount of shear strain (elastic and/or plastic) under an induced amount of fixed initial shear strain.

4.2.1.2 Gyratory Stability Index (GSI)

The gyratory stability index is defined as:

$$\text{GSI} = \frac{\text{Maximum Gyrograph Width}}{\text{Minimum Intermediate Gyrograph Width}}$$

It gives an indication of the stability of the mixture under compaction. An increase in the stability index would indicate a reduction in stability or shear resistance.

4.2.1.3 Gyratory Compactibility Index (GCI)

The gyratory compactibility index is defined as:

$$GCI_x = \frac{\text{unit weight at x revolutions}}{\text{unit weight at 60 revolutions}}$$

It gives an indication of the relative degree of compaction at a specific compactive effort.

4.2.2 Resilient Modulus (M_R)

The resilient modulus is defined as the ratio of the applied stress to the resilient strain (recoverable strain) when a dynamic load is applied. It is the dynamic elastic modulus of a viscoelastic material.

4.2.3 Poisson's Ratio (ν)

The Poisson's ratio is the ratio of the transverse elastic strain to the vertical elastic strain when a vertical stress is applied.

4.2.4 Stabilometer Resistance Value (R-Value)

The R-Value is an empirical number which indicates the stability or resistance to plastic deformation of a pavement material, and is usually used in the evaluation of base course materials. Marshall size specimens are tested in the stabilometer at room temperature to a vertical pressure of 160 psi (1.10 MPa). The R-Value is then calculated from the horizontal pressure and the displacement of the specimen according to an empirical formula (see Section 2.2.3 for details).

4.2.5 Marshall Variables

The modified Marshall test (run at room temperature instead of the standard 60°C) was used in the study. The variables obtained from this test and used in the analysis are the Marshall stability, flow and index. (See Figure 3.9 on how to read these values from the load-deformation plot).

4.2.5.1 Marshall Stability (S_M)

The Marshall stability is defined as the maximum load required to produce failure of a standard Marshall specimen in a Marshall test. It is a semi-empirical figure indicating the relative resistance of a material to plastic deformation.

4.2.5.2 Marshall Flow (F_M)

The Marshall flow is the vertical deformation of a Marshall specimen as the maximum load is reached. It is expressed in units of .01 inch (.25 mm). It is an empirical number which indicates the relative amount of plastic deformation before failure occurs.

4.2.5.3 Marshall Index (I_M)

The Marshall index is defined as the slope of the linear portion of the load-deformation plot in a Marshall test. It is usually used in conjunction with the Marshall stability and flow values to evaluate the performance of a cold-mix paving material [18].

4.2.6 Percent Water Absorbed (% W_a)

The percentage water absorbed is the amount of water absorbed by a specimen after soaking in water for 24 hours (Water Sensitivty test). It is expressed as a percent by weight of the specimen before submersion in water. It gives an indication of the amount of permeable voids in the compacted specimen.

4.3 Independent Variables

4.3.1 Pavement Material

Four different pavement materials were used to make the recycled mixtures in this study. They include an artificially aged material and three old pavement materials of different aged condition.

4.3.2 Type of Binder or Agent Added

The binders or agents added to the recycled mixtures included a high float asphalt emulsion designated as AE-150, a foamed asphalt and three rejuvenating agents, namely, Reclamite, Mobilsol and DUTREX 739.

4.3.3 Percent Binder or Agent Added

The five levels of percent binder or agent added were 0%, .5%, 1%, 2% and 3% by weight of the aggregate.

4.3.4 Percent Virgin Aggregate Added

Either 0% or 25% of virgin aggregate was used.

4.3.5 Compactive Effort

Different compactive efforts were produced by different numbers of revolutions made by the gyratory compactor. The three main compactive efforts used were 20, 40 and 60 revolutions at 200 psi (1.38 MPa) ram pressure.

4.3.6 Curing Time

Curing time is the time between the compaction and the testing of a specimen. The five curing times used were 1 day, 7 days, 14 days and 28 days at room temperature, and ultimate curing, which was accomplished by placing the specimens in a forced draft oven at 60°C for 24 hours.

4.3.7 Testing Temperature

Testing temperature is the temperature at which a specimen is tested. The three testing temperatures used were 0°, 23° and $40^\circ C$ (32°, 73° and $104^\circ F$).

4.4 Experimental Designs

4.4.1 Design No. 1

The first set of experiments dealt with the artifically aged paving mixtures with AE-150 as the added binder. The experimental design is shown in Table 4.1. The factors studied were the compactive effort (2 levels), the percent AE residue added (5 levels), the testing temperature (3 levels), and the curing time (5 levels).

4.4.2 Design No. 2

The experimental design for the second set of experiments is presented in Table 4.2. The recycled mixtures were made from an old pavement material with AE-150 as the added binder. The factors studied were the compactive effort (2 levels), the percent AE residue added (5 levels), the testing temperature (2 levels) and the curing time (5 levels).

4.4.3 Design No. 3

In the third set of experiments, old pavement materials of three different aged conditions were used with AE-150 as the added binder. The old pavement material (used in Design No. 2) was artificially aged to two other conditions by heating in a forced draft oven at $120^\circ C$ for one day and three days. The as-is condition constituted the third aged condition.

TABLE 4.1 : DESIGN FOR TESTS ON ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO. 1)

CURING TIME	TEMPERATURE (° C)	20 REVS					60 REVS				
	% AE RESIDUE ADDED	0	.5	1	2	3	0	.5	1	2	3
1 DAY	23	X	X	X	X	X	X	X	X	X	X
	40	X	X	X	X	X	X	X	X	X	X
7 DAYS	23	X	X	X	X	X	X	X	X	X	X
	40	X	X	X	X	X	X	X	X	X	X
14 DAYS	23	X	X	X	X	X	X	X	X	X	X
	40	X	X	X	X	X	X	X	X	X	X
28 DAYS	23	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
	40	X	X	X	X	X	X	X	X	X	X
ULTIMATE CURING	0	+	+	+	+	+	+	+	+	+	+
	23	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	40	+	+	+	+	+	+	+	+	+	+

NOTE : X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

TABLE 4.2 : DESIGN FOR TESTS ON OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO. 2)

COMPACTION		20 REVS					60 REVS				
CURING TIME	**TEMPERATURE (°C)** / **% AE RESIDUE ADDED**	0	.5	1	2	3	0	.5	1	2	3
1 DAY	23	X	X	X	X	X	X	X	X	X	X
7 DAYS	23	X	X	X	X	X	X	X	X	X	X
14 DAYS	23	X	X	X	X	X	X	X	X	X	X
28 DAYS	23	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
ULTIMATE CURING	23	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
ULTIMATE CURING	40	+	+	+	+	+	+	+	+	+	+

NOTE : X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

\+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

The experimental design of part 1 of Design No. 3 is displayed in Table 4.3. A compactive effort of 20 revolutions at 200 psi (1.38 MPa) was used. Two aged conditions (1 day and 3 days heating) of the pavement material were used. The other factors studied were the percent AE residue added (4 levels), the testing temperature (2 levels) and the curing time (5 levels).

Table 4.4 displays the experimental design for part 2 of Design No. 3. The two aged conditions of the pavement material used were the as-is condition and 3 days heating. The compactive effort was 40 revolutions at 200 psi (1.38 MPa). The other independent variables studied were the percent AE residue added (5 levels), the testing temperature (2 levels) and the curing time (5 levels).

4.4.4 Design No. 4

In the fourth set of experiments, a study was conducted on the artificially aged paving mixtures using foamed asphalt as the added binder. The experimental design is shown in Table 4.5. The factors included were the compactive effort (2 levels), the percent asphalt added (4 levels), the testing temperature (3 levels) and the curing time (5 levels).

4.4.5 Design No. 5

Design No. 5 utilized the old pavement material with foamed asphalt as the added binder. The experimental design is displayed in Table 4.6. The compactive effort used was 20 revolutions at 200 psi (1.38 MPa). The factors included were the percent asphalt added (4 levels), the testing temperature (2 levels), and the curing time (5 levels).

TABLE 4.3 : DESIGN FOR TESTS ON OLD PAVEMENT MATERIAL THAT HAS BEEN FURTHER AGED BY HEATING, WITH AE-150 ADDED (DESIGN NO. 3, PART 1)

CURING TIME	TEMPERATURE (°C)	1 DAY HEATING				3 DAYS HEATING			
% AE RESIDUE ADDED		0	1	2	3	0	1	2	3
1 DAY	23	X	X	X	X	X	X	X	X
7 DAYS	23	X	X	X	X	X	X	X	X
14 DAYS	23	X	X	X	X	X	X	X	X
28 DAYS	23	X	X	X	X	X	X	X	X
ULTIMATE CURING	23	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
ULTIMATE CURING	40	X	X	X	X	X	X	X	X

NOTE : X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

O R-VALUE & MARSHALL TEST, 2 SAMPLES PER CELL

COMPACTIVE EFFORT: 20 REVOLUTIONS AT 200 PSI

TABLE 4.4 : DESIGN FOR TESTS ON OLD PAVEMENT MATERIAL THAT HAS BEEN FURTHER AGED BY HEATING, WITH AE-150 ADDED (DESIGN NO.3, PART 2)

CURING TIME	TEMPERATURE (°C)	NO HEATING					3 DAYS HEATING			
% AE RESIDUE ADDED		0	.5	1	2	3	0	1	2	3
1 DAY	23	+	+	+	+	+	+	+	+	+
7 DAYS	23	+	+	+	+	+	+	+	+	+
14 DAYS	23	+	+	+	+	+	+	+	+	+
28 DAYS	23	+	+	+	+	+	+	+	+	+
ULTIMATE CURING	23	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	40	+	+	+	+	+	+	+	+	+

NOTE :

+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

COMPACTIVE EFFORT: 40 REVOLUTIONS AT 200 PSI

TABLE 4.5 : DESIGN FOR TESTS ON ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO. 4)

CURING TIME	TEMPERATURE (°C)	20 REVS, 0 % ASPHALT ADDED	20 REVS, 1	20 REVS, 2	20 REVS, 3	60 REVS, 0	60 REVS, 1	60 REVS, 2	60 REVS, 3
1 DAY	23	X	X	X	X	X	X	X	X
1 DAY	40	X	X	X	X	X	X	X	X
7 DAYS	23	X	X	X	X	X	X	X	X
7 DAYS	40	X	X	X	X	X	X	X	X
14 DAYS	23	X	X	X	X	X	X	X	X
14 DAYS	40	X	X	X	X	X	X	X	X
28 DAYS	23	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
28 DAYS	40	X	X	X	X	X	X	X	X
ULTIMATE CURING	0	+	+	+	+	+	+	+	+
ULTIMATE CURING	23	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
ULTIMATE CURING	40	+	+	+	+	+	+	+	+

NOTE :
- X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL
- \+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL
- O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

TABLE 4.6 : DESIGN FOR TESTS ON OLD PAVEMENT MATERIAL WITH FOAMED ASPHALT ADDED (DESIGN NO. 5)

CURING TIME	TEMPERATURE (°C) \ % ASPHALT ADDED	0	1	2	3
1 DAY	23	X	X	X	X
7 DAYS	23	X	X	X	X
14 DAYS	23	X	X	X	X
28 DAYS	23	⊗	⊗	⊗	⊗
ULTIMATE CURING	23	⊕	⊕	⊕	⊕
	40	+	+	+	+

NOTE: X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

\+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

COMPACTIVE EFFORT: 20 REVOLUTIONS

4.4.6 Design No. 6

In the sixth set of experiments, rejuvenating agents were added to the artificially aged paving mixtures. The three rejuvenating agents used were Reclamite, Mobilsol and DUTREX 739. Table 4.7 shows the experimental design for one rejuvenating agent. The experimental designs for all three rejuvenating agents were identical. The other factors included were the compactive effort (2 levels), the percent agent added (3 levels), the testing temperature (3 levels), and the curing time (5 levels).

4.4.7 Design No. 7

In Design No. 7, the rejuvenating agent, Reclamite, was added to the old pavement material. The experimental design is presented in Table 4.8. The compactive effort used was 20 revolutions at 200 psi (1.38 MPa) and testing was run at 23°C. The independent variables studied were the percent agent added (3 levels) and the curing time (5 levels).

4.4.8 Design No. 8

In the eighth set of experiments, 25% of virgin aggregate was added to the artificially aged paving mixtures and AE-150 was used as the added binder. The experimental design is shown in Table 4.9. The independent variables were the compactive effort (2 levels), the percent total binder (2 levels), the testing temperature (3 levels), and the curing time (5 levels).

4.4.9 Design No. 9

In the ninth set of experiments, water sensitivity tests were run on some recycled mixtures made with the old pavement material, to study

TABLE 4.7 : DESIGN FOR TESTS ON ARTIFICIALLY AGED PAVING MIXTURES WITH REJUVENATING AGENTS ADDED (DESIGN NO. 6)

CURING TIME	TEMPERATURE (°C)	20 REVS			60 REVS		
	% AGENT ADDED →	0	.5	1	0	.5	1
1 DAY	23	X	X	X	X	X	X
1 DAY	40	X	X	X	X	X	X
7 DAYS	23	X	X	X	X	X	X
7 DAYS	40	X	X	X	X	X	X
14 DAYS	23	X	X	X	X	X	X
14 DAYS	40	X	X	X	X	X	X
28 DAYS	23	⊗	⊗	⊗	⊗	⊗	⊗
28 DAYS	40	X	X	X	X	X	X
ULTIMATE CURING	0	+	+	+	+	+	+
ULTIMATE CURING	23	⊗	⊗	⊗	⊗	⊗	⊗
ULTIMATE CURING	40	+	+	+	+	+	+

(COMPACTION: 20 REVS / 60 REVS)

NOTE : REJUVENATING AGENTS USED: RECLAMITE, MOBILSOL, & DUTREX 739

FOR EACH REJUVENATING AGENT USED:

X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

O RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

TABLE 4.8 : DESIGN FOR TESTS ON OLD PAVEMENT MATERIAL WITH RECLAMITE ADDED (DESIGN NO. 7)

CURING TIME \ % AGENT ADDED	0	.5	1
1 DAY	X	X	X
7 DAYS	X	X	X
14 DAYS	X	X	X
28 DAYS	X	X	X
ULTIMATE CURING	O	O	O

NOTE : TESTING TEMPERATURE: 23 °C
COMPACTIVE EFFORT: 20 REVOLUTIONS

X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

O R-VALUE & MARSHALL TEST, 2 SAMPLES PER CELL

TABLE 4.9 : DESIGN FOR TESTS ON ARTIFICIALLY AGED PAVING MIXTURES WITH VIRGIN AGGREGATE AND AE-150 ADDED (DESIGN NO. 8)

CURING TIME	TEMPERATURE (°C)	20 REVS, 5.0 % TOTAL BINDER	20 REVS, 6.0 % TOTAL BINDER	60 REVS, 5.0 % TOTAL BINDER	60 REVS, 6.0 % TOTAL BINDER
1 DAY	23	X	X	X	X
	40	X	X	X	X
7 DAYS	23	X	X	X	X
	40	X	X	X	X
14 DAYS	23	X	X	X	X
	40	X	X	X	X
28 DAYS	23	⊗	⊗	⊗	⊗
	40	X	X	X	X
ULTIMATE CURING	0	+	+	+	+
	23	⊗	⊗	⊗	⊗
	40	+	+	+	+

NOTE :

X RESILIENT MODULUS TEST, 2 SAMPLES PER CELL

+ RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

the resistance of these mixtures to the effect of water. The experimental design is displayed in Table 4.10. The compactive effort used was 20 revolutions at 200 psi (1.38 MPa). Two types of virgin binder (AE-150 and foamed asphalt), two curing times (1 day and ultimate curing) and three levels of binder added (0%, 1% and 2%) were used.

The nine experimental designs presented above constitute an extensive study of the long-term behavior of cold-mix recycled asphalt mixtures.

TABLE 4.10 : DESIGN FOR WATER SENSITIVITY TESTS ON OLD PAVEMENT MATERIAL WITH VIRGIN BINDER ADDED (DESIGN NO. 9)

TYPE OF BINDER	CURING TIME	% BINDER ADDED: 0	1	2
AE-150	1 DAY	⊕	⊕	⊕
AE-150	ULTIMATE CURING	⊕	⊕	⊕
FOAMED ASPHALT	1 DAY	⊕	⊕	⊕
FOAMED ASPHALT	ULTIMATE CURING	⊕	⊕	⊕

NOTE : + RESILIENT MODULUS TEST, 1 SAMPLE PER CELL

O R-VALUE & MARSHALL TEST, 1 SAMPLE PER CELL

COMPACTIVE EFFORT: 20 REVOLUTIONS AT 200 PSI

CHAPTER 5

EXPERIMENTAL PROCEDURE

5.1 Introduction

This chapter presents the experimental procedure developed and used in this laboratory study. It includes the descriptions of (1) the overall testing sequence, (2) the specimen preparation procedure, (3) the compaction procedure, (4) the resilient modulus test, and (5) the water sensitivity test.

5.2 Overall Testing Sequence

The testing sequence on the specimens was designed such that as much information as possible could be extracted from a fabricated sample. The general testing sequence for the specimens in Designs 1 to 8 is shown in Figure 5.1. Due to the non-destructive nature of the resilient modulus test, the same specimens were used repeatedly in the resilient modulus test at the various temperatures and curing times. After the resilient modulus test had been performed on the specimens, they were evaluated in the R-Value test and then in the Marshall test.

The testing sequence for the specimens in Design 9 is illustrated in Figure 5.2. Specimens at the specified curing conditions were subjected to the water sensitivity test, and then evaluated in the resilient modulus test, the R-Value test and the Marshall test.

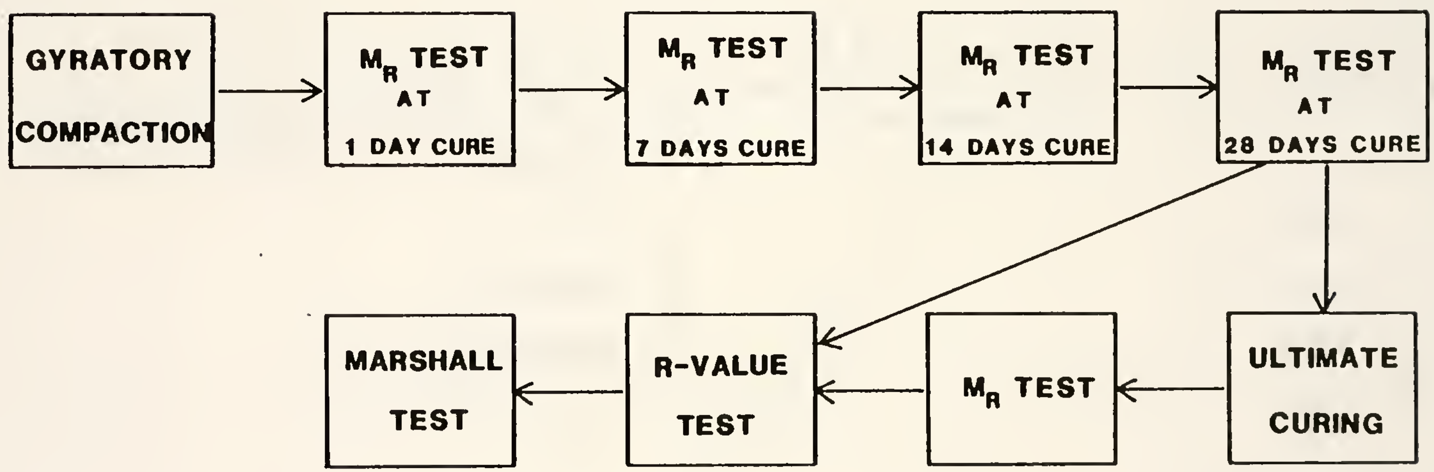


FIGURE 5.1: GENERAL TESTING SEQUENCE FOR A SPECIMEN CURED TO 28 DAYS OR ULTIMATE CONDITION

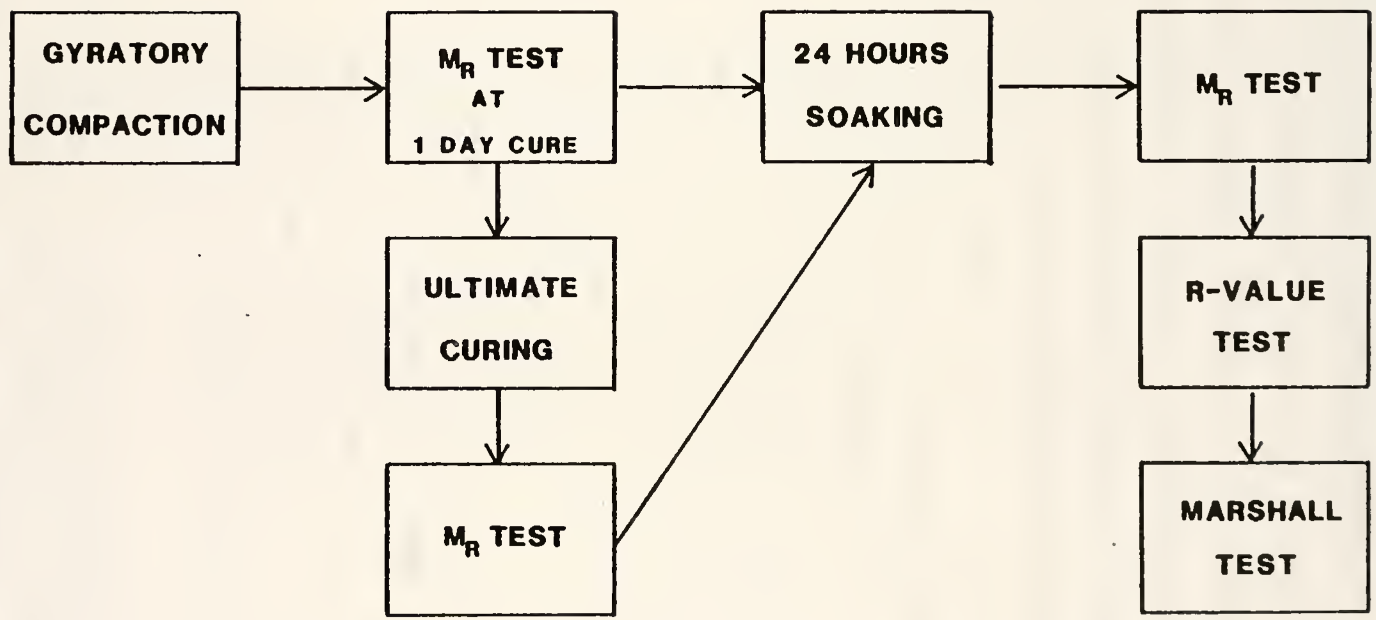


FIGURE 5.2: GENERAL TESTING SEQUENCE FOR A SPECIMEN IN THE WATER SENSITIVITY TEST (DESIGN NO. 9)

5.3 Specimen Preparation Procedure

The cold recycled asphalt mixtures used for this study were prepared in the laboratory. The mixing and curing procedure adopted by the author in previous studies on cold recycled mixes was used [2]. This procedure was originally developed by Gadallah in his study on asphalt emulsion treated mixes [18] and has been used by other researchers [20, 21]. The specimen preparation procedure consisted of the following general steps:

1. The proper amount of the pavement material to be recycled was batched for one specimen.
2. The required amount of water (if any) was added to the material and mixed thoroughly with a mechanical mixer and then with a spoon by hand. The material was then left for 10-15 minutes. This step would be omitted if no added water was required.
3. The proper amount of virgin binder or rejuvenating agent kept at room temperature was added to the material and mixed with a mechanical mixer for 1½ minutes and with a spoon by hand for 30 seconds.
4. The mix was cured for one hour in a forced-draft oven at 60°C (140°F).
5. The mix was remixed for 30 seconds with a mechanical mixer and was compacted immediately in the gyratory machine.

The purpose of adding water to the mix was to facilitate the mixing process. When asphalt emulsion, Reclamite and Mobilsol were used as the added binder, one percent water was added. When foamed asphalt was used, three percent water was added. No water was added when DUTREX was used as the added binder. The optimum amount of water to be added was determined from trial mixes.

5.4 Compaction Method

The gyratory machine was used to compact the recycled mixes. The standard procedure as specified in ASTM D3387 was generally followed. The initial gyratory angle was set at 1 degree, and a fixed roller was used. The ram pressure was set at 200 psi (1.38 MPa). The compaction procedure consisted of the following main steps:

1. Immediately after oven curing for one hour and remixing for 30 seconds, the recycled mix was placed in the gyratory mold to be compacted by the gyratory machine. The temperature of the mix was around 38°C (100°F) at the start of the compaction process.
2. The gyrograph recorder was turned on, and the gyratory compaction was started. The compaction was performed at room temperature with the heater for the gyratory mold turned off.
3. The height of the specimen was read at various points during the compaction process and at the end of the compaction process.
4. The compacted specimen was extruded from the mold within 30 minutes, and left to cure at room temperature.

It has been claimed that the gyratory machine produces more consistent efforts and compaction conditions resemble the actual field conditions [59, 63]. The gyratory machine has also been used to evaluate bituminous mixtures [64]. The gyrograph recorded during the compaction process was used to obtain the gyratory indices.

5.5 Resilient Modulus Test

The diametral resilient modulus test used in this study was modified from the one proposed by Schmidt [26], in that the vertical deformation rather than the horizontal deformation was used to calculate the resilient modulus of the test specimen. This section presents the theoretical basis and the experimental procedure for this test.

5.5.1 Theoretical Basis of the Resilient Modulus Test

In the diametral resilient modulus test, dynamic pulse loads are applied diametrally to the Marshall size specimens, and the induced vertical and horizontal deformations are recorded and used to calculate the resilient moduli. The test is based on the assumption that the specimen behaves as a linear elastic material under dynamic loads. Timochenko [27] and Frocht [65] had analyzed the stresses in an elastic circular disk subjected to a diametral loading condition. Based on their works, Schmidt [26] derived the relationship between the resilient modulus and the induced horizontal deformation of the specimen in the diametral resilient modulus test (see equation in Section 2.2.6). In the following section, the relationship between the resilient modulus and the vertical deformation of the specimen in the diametral resilient modulus test is derived.

The vertical pulse loads in the resilient modulus test were applied through a loading strip of ½ inch width (see Figure 3.4 and 3.5). Hondros [66] has analyzed the stresses in a circular disk under a short strip loading condition. Hondros' equations for the stresses along the principal diameters are presented below:

(1) Stresses along the vertical diameter (OY)

$$\sigma_{\theta y} = \frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1 - 2r^2/R^2\cos 2\alpha + r^4/R^4)} - \tan^{-1}\left(\frac{(1 + r^2/R^2}{(1 - r^2/R^2}\tan\alpha\right)\right] \quad (5.1)$$

$$\sigma_{ry} = -\frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1 - 2r^2/R^2\cos 2\alpha + r^4/R^4)} + \tan^{-1}\left(\frac{(1 + r^2/R^2)}{(1 - r^2/R^2)}\tan\alpha\right)\right] \quad (5.2)$$

$$\tau_{r\theta} = 0$$

(2) Stresses along the horizontal diameter (OX)

$$\sigma_{\theta x} = -\frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1 + 2r^2/R^2\cos 2\alpha + r^4/R^4)} + \tan^{-1}\left(\frac{(1 - r^2/R^2)}{(1 + r^2/R^2)}\tan\alpha\right)\right] \quad (5.3)$$

$$\sigma_{rx} = +\frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1 + 2r^2/R^2\cos 2\alpha + r^4/R^4)} - \tan^{-1}\left(\frac{(1 - r^2/R^2)}{(1 + r^2/R^2)}\tan\alpha\right)\right] \quad (5.4)$$

$$\tau_{r\theta} = 0$$

(See Figure 5.3 for the notation of the polar stresses.)

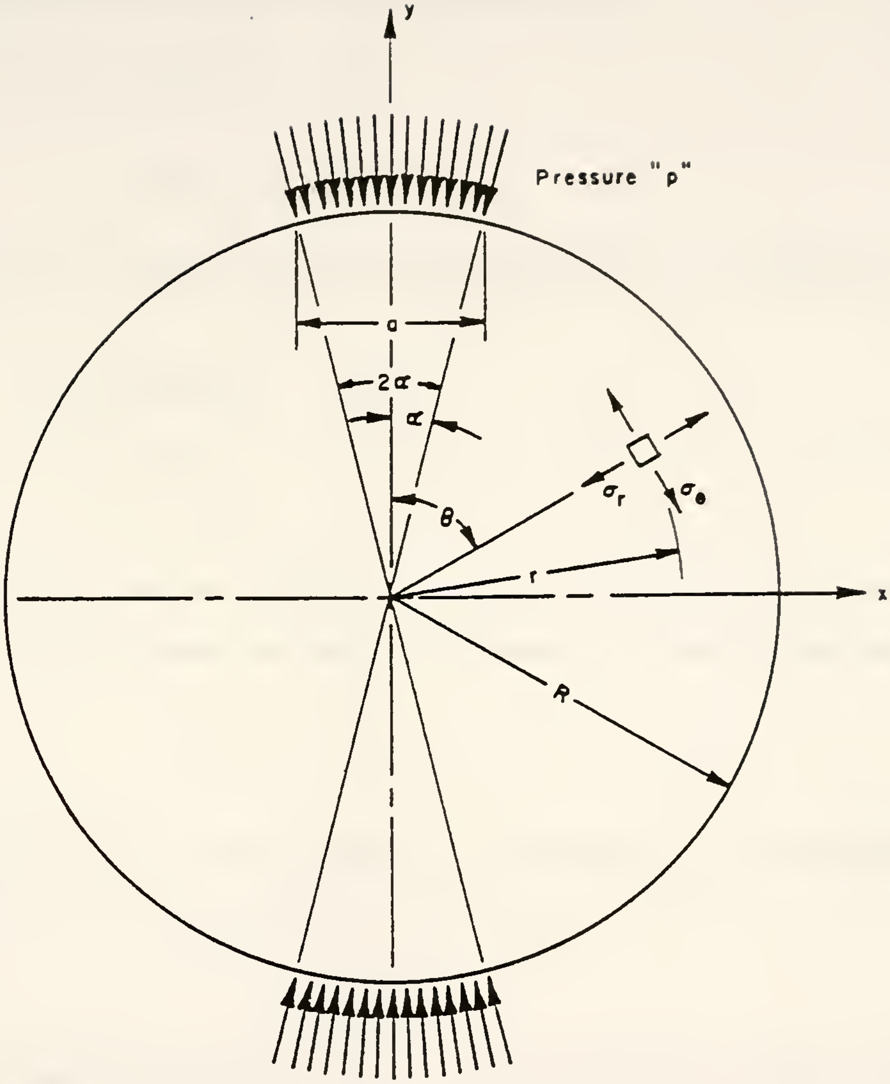


FIGURE 5.3 STRESS COMPONENTS IN A CIRCULAR DISK UNDER A SHORT STRIP LOADING CONDITION

According to the elastic stress-strain relationship, the strains along the vertical diameter can be expressed as:

$$\varepsilon_{\theta y} = \frac{1}{E} (\sigma_{\theta y} - \nu \sigma_{ry}) \tag{5.5}$$

$$\varepsilon_{ry} = \frac{1}{E} (\sigma_{ry} - \nu \sigma_{\theta y}) \tag{5.6}$$

The strains along the horizontal diameter can be expressed as:

$$\varepsilon_{\theta x} = \frac{1}{E} (\sigma_{\theta x} - \nu \sigma_{rx}) \tag{5.7}$$

$$\varepsilon_{rx} = \frac{1}{E} (\sigma_{rx} - \nu \sigma_{\theta x}) \tag{5.8}$$

The total vertical deformation, d_v, is the integration of the vertical strains along the vertical diameter, and can be expressed as:

$$d_v = 2 \int_o^R \varepsilon_{ry} \, dr \tag{5.9}$$

Similarly, the total horizontal displacement d_h can be expressed as:

$$d_h = 2 \int_o^R \varepsilon_{rx} \, dr \tag{5.10}$$

The complete expression for d_v can be obtained by substituting equations 5.1 and 5.2 into equation 5.6, which is, in turn, substituted into equation 5.9. Similarly, the complete expression for d_h can be obtained by substituting equations 5.3 and 5.4 into equation 5.8, which is then substituted into equation 5.10. Due to the complexity of the expressions for d_v and d_h, it was decided to solve for d_v and d_h using a numerical method, in which the integration was approximated by incremental summations.

For the case when the width of the loading strip is ½ inch (1.27 cm), the diameter of the specimen is 4 inches (10.16 cm), the thickness of the specimen is t, and the load is P, the following relationships can be obtained.

$$\alpha = .124 \text{ radian } (7.125 \text{ degrees}) \tag{5.11}$$

$$p = \frac{2P}{(1 \text{ inch})\ t} \tag{5.12}$$

Using these values for α and p, the expressions for d_v and d_h (in integration forms) were solved using the numerical method of incremental summations. The expressions for the deformations became:

$$d_v = \frac{P}{\pi t E}(11.257 - .193\ \nu) \tag{5.13}$$

$$d_h = \frac{P}{\pi t E}(.841 + 3.141\ \nu) \tag{5.14}$$

From equation 5.13, it can be noted that the Poisson's ratio, ν, has only a very small effect (less than 1%) on the vertical deformation, d_v. Thus, d_v can be approximated as:

$$d_v = -\frac{11.257\ P}{\pi t E}$$

$$= -\frac{3.583\ P}{tE} \tag{5.15}$$

The elastic modulus can then be expressed as:

$$E = \frac{-3.583\ P}{t\ d_v} \tag{5.16}$$

This equation was used for the calculation of the resilient modulus in this study.

If equation 5.14 is used to solve for E, the expression for E will be as follows:

$$E = \frac{P\,(0.27 + \nu)}{t\, d_h} \tag{5.17}$$

This is the same as the equation used by Schmidt [26]. It can be noted that the expression for E in equation 5.17 can be greatly affected by the choice of ν. A change of the value of ν from 0.3 to 0.5 will cause the value of E to increase by 35%. However, when E is calculated from the vertical deformation using equation 5.16, the variation of ν from 0 to 0.5 will cause an error of less than 1% in the calculated value of E.

The expression for the Poisson's ratio in terms of d_v and d_h can be obtained by substituting equation 5.16 into equation 5.14. It is as follows:

$$\nu = 3.59\,\frac{d_h}{d_v} - 0.27 \tag{5.18}$$

This equation was used for the calculation of the Poisson's ratio in this study. It is noted that this is also an approximated expression for ν.

5.5.2 Experimental Procedure for the Resilient Modulus Test

The procedure for the resilient modulus test consisted of the following steps:

1. The test specimen was left in a temperature-controlled room for 2-4 hours to reach the required temperature. A dummy specimen with a thermometer inserted inside was placed in

the same condition as that of test specimen and used to measure the temperature of the test specimen before and during the test.

2. The specimen was removed from the temperature control room and placed in the resilient modulus test equipment, which was at room temperature. The dummy specimen was used to ascertain that the temperature of the test specimen was within 2 Centigrade degrees from the required test temperature. Care was taken to ascertain that the specimen was well centered in testing apparatus.
3. The pulsating load was then applied to the specimen. 10 to 20 pulse loads were applied to the specimen to precondition the specimen before the actual vertical and horizontal deformation readings were taken. The vertical and horizontal deformations were measured by the three LVDTs and plotted on the chart recorder.
4. After the deformations for at least three pulse loads were taken, the pulsating load was stopped. The specimen was rotated 120^{o} and tested again in the same procedure as described in step 3. The specimen was then rotated another 120^{o} and tested for the third time.

The typical deformation plots from the resilient modulus test are illustrated in Figure 5.4. The average resilient (or recoverable) deformations were used for the calculation of the resilient modulus and the Poisson's ratio.

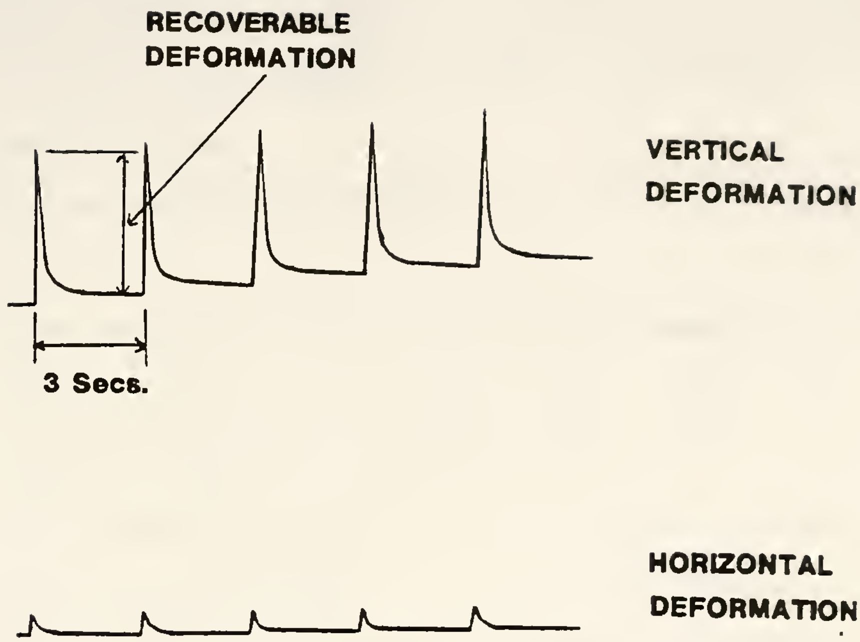


FIGURE 5.4 TYPICAL DEFORMATION PLOTS FROM THE RESILIENT MODULUS TEST

5.6 Water Sensitivity Test

A water sensitivity test was used to measure the resistance of the recycled mixes to the action of water. The method used was a modification of a procedure recommended by the Asphalt Institute [67]. It is briefly summarized below:

1. The test specimen was subjected to a vacuum of 30 mm Hg. for one hour.
2. After the one hour period, water at room temperature (23°C or 73°F) was drawn into the vacuum chamber, submerging the specimen and vacuum saturating them.
3. The vacuum was then released and the specimen was then left in the water bath for 24 hours before testing.
4. Prior to testing, the saturated surface-dry weight of the specimen was determined to calculate the percentage of water absorption.

CHAPTER 6

RECYCLED MIXTURES WITH ASPHALT EMULSION ADDED

6.1 Introduction

This chapter presents the results of the first three sets of experiments (Designs 1, 2 & 3), which dealt with the long-term behavior of the recycled mixtures with AE-150 added. In design no. 1 (shown in Table 4.1), the recycled mixtures tested were made from an artificially aged paving mixture. In design no. 2 (shown in Table 4.2), the mixes were made from an old pavement material. In design no. 3 (shown in Tables 4.3 & 4.4), old pavement materials of three different aging conditions were used to make the recycled mixtures.

The general laboratory procedure described in Chapter 5 was used to prepare and to test the recycled mixes. One percent water (by weight of the aggregate) was added to all the mixtures before the mixing process. The independent variables included the Percent AE Residue Added, the Compactive Effort, the Curing Time and the Testing Temperature. Gyratory indices were obtained during the compaction process. The properties of the mixes measured at various curing times and temperatures were the resilient modulus, the Poisson's ratio, the Hveem R-Value and the Marshall variables.

Due to the great number of data obtained, only the results of the resilient modulus, R-value, Marshall variables and gyratory indices are presented in the main text. For interested readers, the values of the Poisson's ratio, bulk specific gravity and percent air voids can be found in Appendix D.

6.2 Method of Analysis

The response variables were analyzed with the aid of the Analysis of Variance (ANOVA) statistical method. The ANOVA determined whether the effects of certain factors and/or interactions of factors were statistically significant.

One major assumption in ANOVA is the homogeneity of variance. The assumption of homogeneity of variance was checked using the Foster-Burr Q test [68]. If the Q-test value was less than the Q-critical value at $\alpha = 0.001$, the assumption of homogeneity of variance would be accepted. If it was rejected, an appropriate transformation would be applied to the variable, and the transformed variable would be used in the ANOVA. The results of all the Foster-Burr Q-tests can be found in Appendix A.

The statistical package programs available at Purdue University Computing Center were used to perform the Foster-Burr Q-test and the ANOVA [69-72].

The complete statistical model for the resilient modulus in design no. 1 is shown below as an example:

$$Y_{ijk\ell m} = \mu + P_i + R_j + PR_{ij} + S(P\text{-}R)_{(ij)k} + \delta_{(ijk)} + C_\ell + PC_{i\ell} + RC_{j\ell} + PRC_{ij\ell} + S(P\text{-}R)C_{(ij)k\ell} + \omega_{(ijk\ell)} + T_m$$

$$+ PT_{im} + RT_{im} + PRT_{ijm} + S(P-R)T_{(ij)km} + CT_{\ell m} + PCT_{i\ell m}$$

$$+ RCT_{j\ell m} + PRCT_{ij\ell m} + \varepsilon_{(ijk\ell m)}$$

where $Y_{ijk\ell m}$ = Response variable

μ = Overall mean of response variable

P_i = Effect of percent AE residue added

R_j = Effect of compactive effort

C_ℓ = Effect of curing time

T_m = Effect of testing temperature

$S(P-R)_{(ij)k}$ = Within error of P-R combination

δ,ω = Restriction errors

ε = Experimental error

PR_{ij}, $PC_{i\ell}$....., $PRCT_{ij\ell m}$ = Effects of interactions of factors

$i,\ell = 1,2,3,4,5$ $m = 1,2,3$ $j,k = 1,2$

The model followed the split plot experimental design [68]. The first restriction error, δ, was due to the fact that readings at the various curing times were taken from the same specimen. The second error, ω, was due to the fact that readings at the various testing temperatures were taken from the same specimen at the same curing. (This was done to minimize the number of specimens.)

This general model included all the factors, interaction terms and error terms, and was a complete representation of the response variables in design no. 1. However, ANOVA results for the first three experimental designs indicated that the effects of the interactions of three or more factors were assumed to be zero, and these terms were "pooled" together with the error term in the ANOVA. (See Appendix B.)

6.3 Results of Experimental Design No. 1

This section presents the results of experimental design no. 1, which dealt with the artifically aged paving mixtures with AE-150 as the added binder.

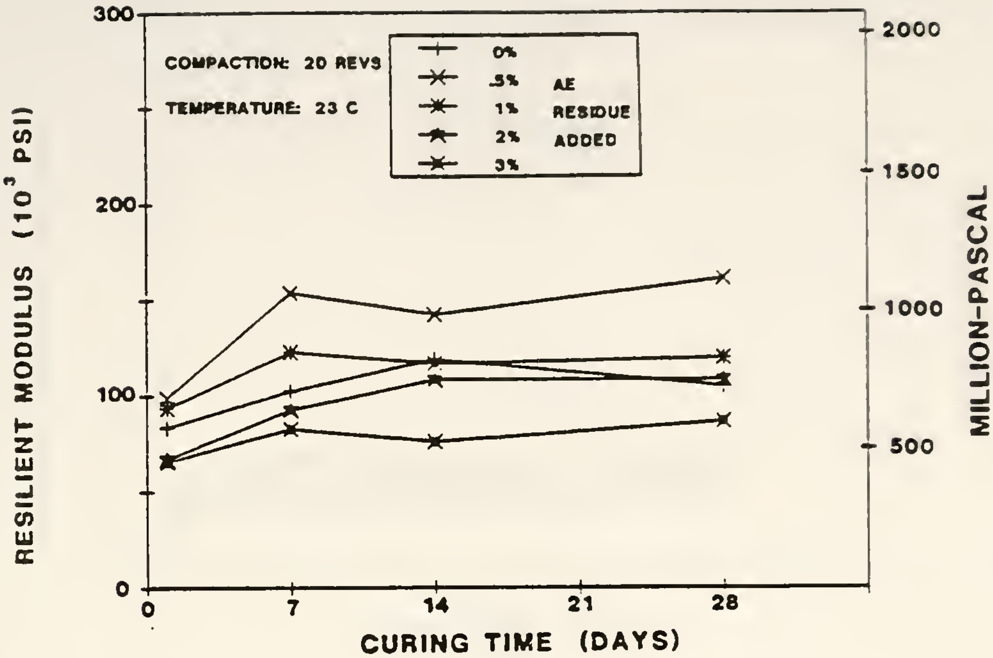
6.3.1 Resilient Modulus

The resilient moduli of the recycled mixes in design no. 1 are presented in Figure 6.1 as functions of curing time, from 1 day to 28 days. It can be observed that the resilient moduli increased significantly from 1 day to 7 days, and leveled off after 7 days. The increase in resilient modulus with time can be explained by the increase in stiffness of the binder as the asphalt emulsion continued to cure (through evaporation of its water).

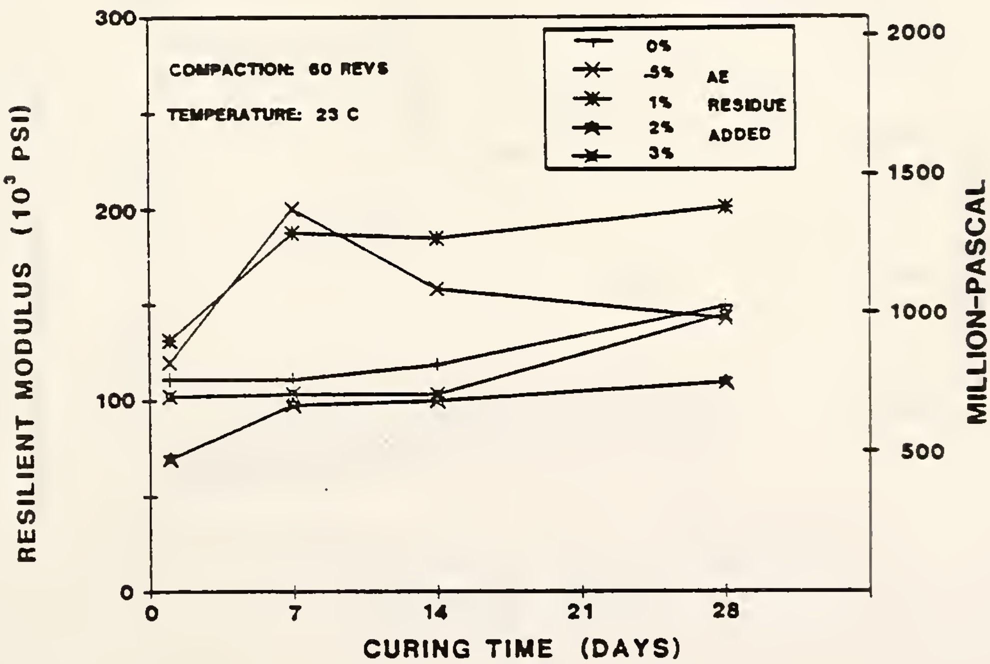
ANOVAs were performed on the resilient modulus data using the following mathematical model:

$$Y_{ijk\ell m} = \mu + P_i + R_j + PR_{ij} + S(P\text{-}R)_{(ij)k} + \delta_{(ijk)} + C_\ell + T_m$$
$$+ PC_{i\ell} + RC_{j\ell} + PT_{im} + RT_{jm} + C_{\ell m} + \varepsilon_{(ijk\ell)m}$$

This model is similar to the general model described in the previous section, with the exception that the interaction terms of three or more factors were "pooled" together with the error term into one single term, ε. The variable M_R did not pass the Foster-Burr Q-test for homogeneity of variance. Thus, the transformed variable $\sqrt{M_R}$, which passed the Q-test, was used in the analysis. ANOVA was performed on

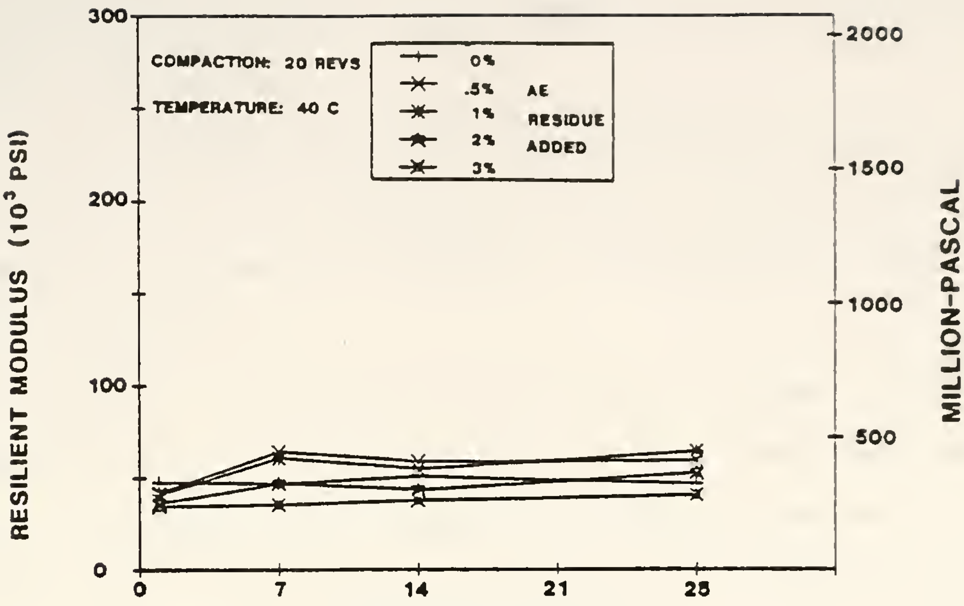


(A)

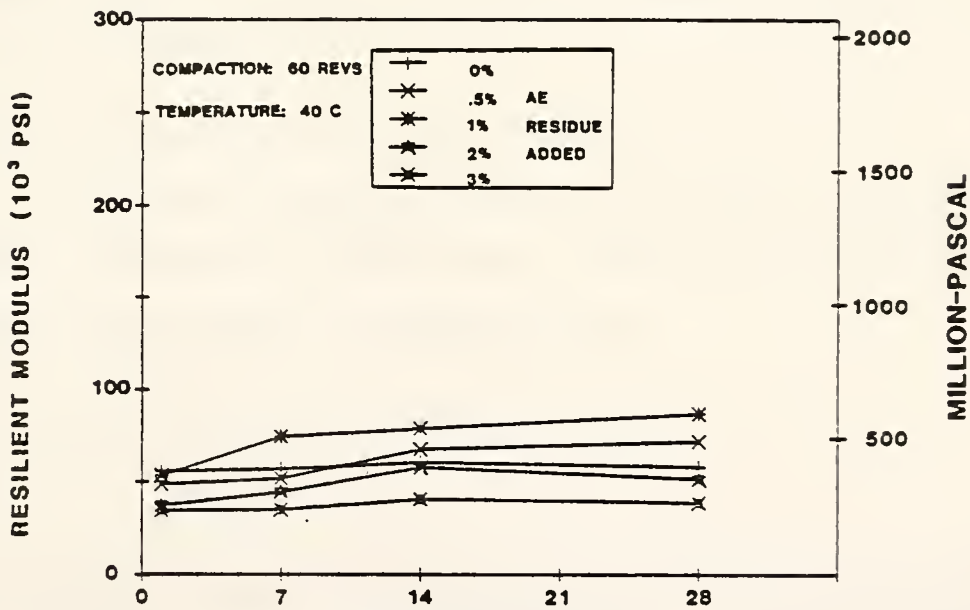


(B)

FIGURE 6.1 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO. 1)



(C)



(D)

FIGURE 6.1 (Continued)

the data for curing times of 1 day to 28 days. The results are presented in Table 6.1.

From the ANOVA results, it can be noted that the effects of percent AE residue added (P), compactive effort (R), curing time (C) and testing temperature (T) were all significant. The significant interaction terms were TP, TR and TC.

Figure 6.2 presents the resilient moduli at ultimate curing as functions of percent AE residue added. It can be noted that the optimum percent AE residue added increased as the testing temperature decreased. For the compactive effort of 20 revolutions, the optimum AE residue added was .5% at 40°C, 1% at 23°C, and 2% at 0°C. For the compactive effort of 60 revolutions, the optimum AE residue added was .5% at 40°C, .5% at 23°C and 3% at 0°C.

6.3.2 Hveem R-Value and Marshall Variables

Hveem R-Value and Marshall tests were performed on the recycled mixes at 28 days and ultimate curing. ANOVAs were performed on the obtained data using the following model:

$$Y_{ijk} = \mu + C_i + R_j + P_k + CR_{ij} + CP_{ik} + RP_{kj} + \varepsilon_{(ijk)}$$

This is a completely randomized factorial design. The terms in the model are as defined earlier. The ANOVA results are presented in Table 6.2.

Figure 6.3 depicts the Hveem R-values as functions of percent AE residue added. It can be observed that the optimum AE residue added was around .5% for the two compactive efforts and the two curing times.

TABLE 6.1 ANOVA Results for the Resilient Modulus in Design No. 1

Factor	d.f.	S.S.	M.S.	F
P	4	108.52	27.13	12.6*
R	1	27.31	27.31	12.7*
PR	4	13.81	3.45	1.6
S(P-R)	10	21.52	2.15	-
C	3	42.84	14.28	28.8*
T	1	524.73	524.73	1058.8*
CP	12	10.95	.91	1.84
CR	3	.52	.17	.34
TP	4	12.17	3.04	6.13*
TR	1	5.45	5.45	11.0*
TC	3	4.49	1.50	3.03*
ε	113	56.0	.50	

* Significant at $\alpha = 0.05$

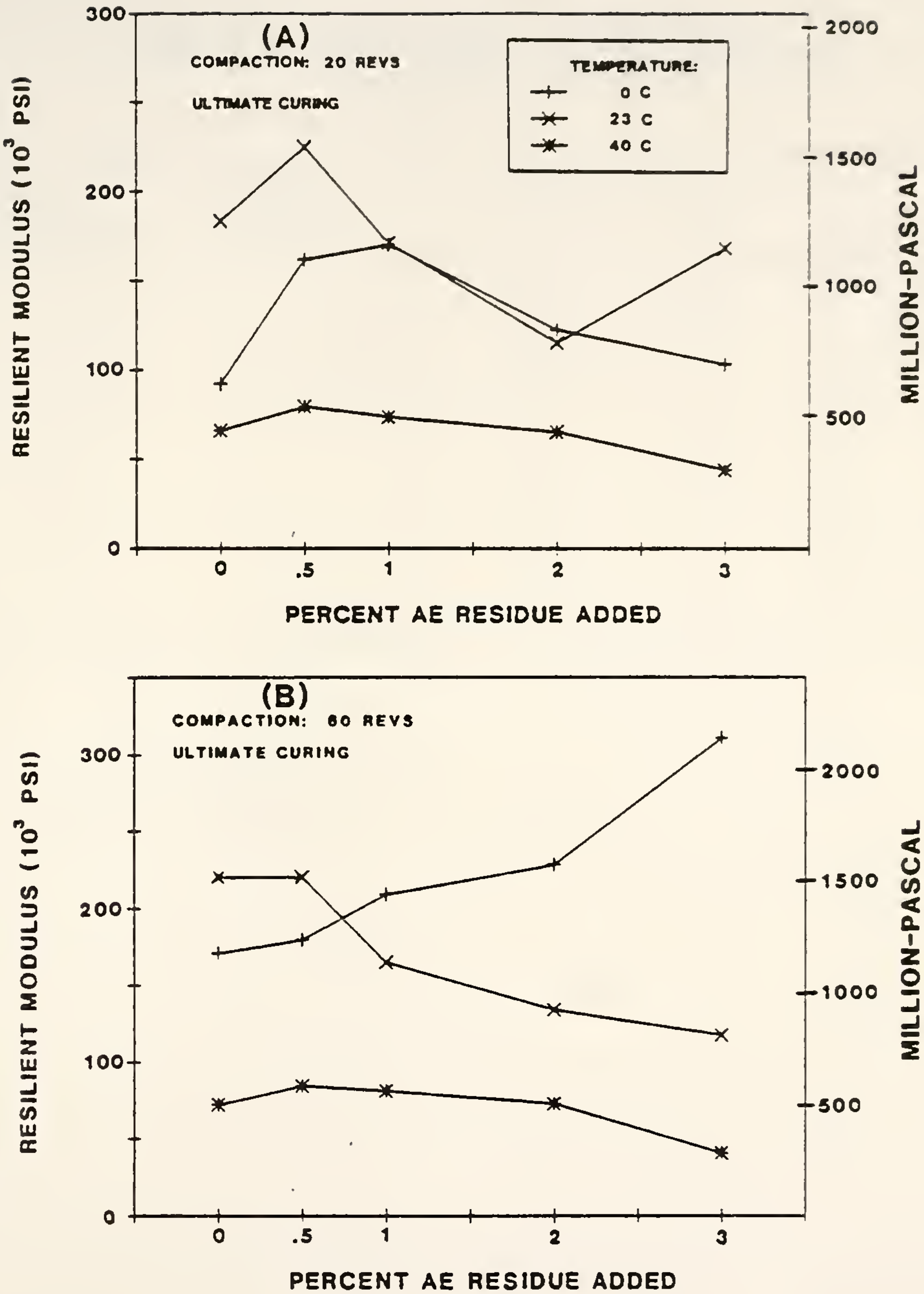


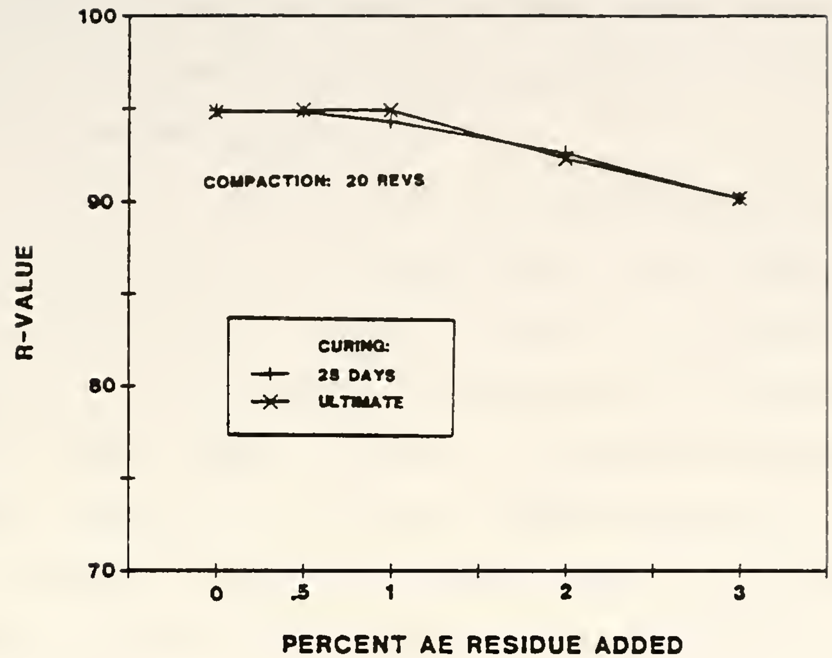
FIGURE 6.2 RESILIENT MODULI AT ULTIMATE CURING FOR ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO.1)

TABLE 6.2: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 1

Source of Variation	Response Variables:	R-Value	S_M	I_M	F_M
C		N.S.	N.S.	S.	S.
R		N.S.	S.	S.	N.S.
P		S.	S.	S.	S.
CR		N.S.	N.S.	N.S.	N.S.
CP		N.S.	S.	N.S.	N.S.
RP		N.S.	S.	N.S.	N.S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$



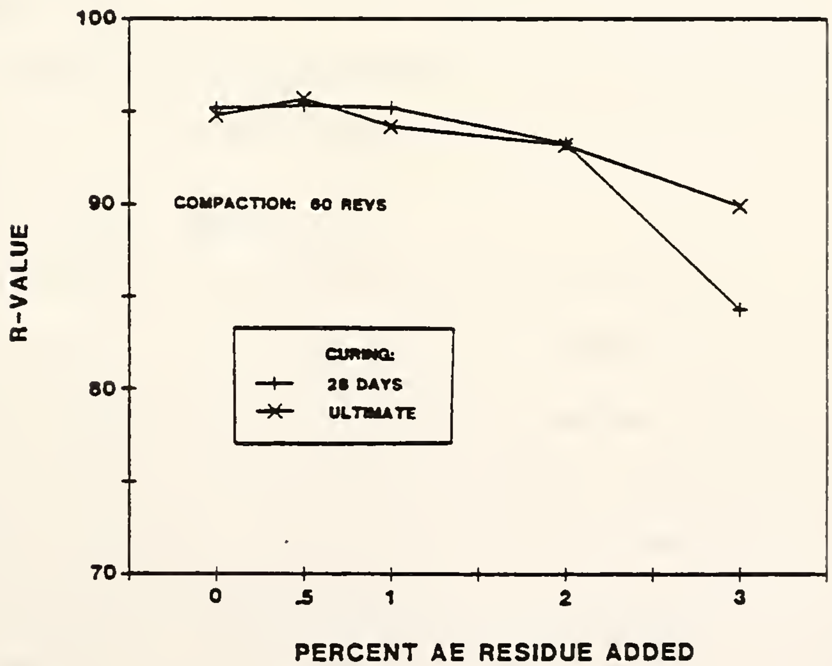


FIGURE 6.3 HVEEM R-VALUES OF ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO.1)

The effect of compactive effort and the difference between 28 days curing and ultimate curing were not significant, as indicated by the plot and the ANOVA result.

Figures 6.4 and 6.5 present the Marshall stabilities and indices as functions of percent AE residue added. Like the Hveem R-value plot, they both indicated the optimum AE residue to be around .5%. Unlike the R-value, both the Marshall stability and index increased significantly with higher compactive effort. For the Marshall stability, the difference between 28 days curing and ultimate curing was not significant. For the Marshall index, the difference between 28 days curing and ultimate curing was significant, as indicated by the plot and the ANOVA result.

Values for the Marshall flow will not be presented in the main text, but can be found in Appendix D.

6.3.3 Gyratory Indices

The gyratory indices for the mixes in design no. 1 are presented in Figure 6.6 as functions of percent AE residue added. It can be noted that the gyratory compactibility indices (GCIs) were insensitive to the changes in percent AE residue added. The stability index (SI) remained relatively constant for AE residue added of less than 2% and increased drastically thereafter. The elasto-plastic index (EPI) increased as AE residue added increased from 0% to 1%, leveled off as AE residue increased from 1% to 2%, and went up again thereafter.

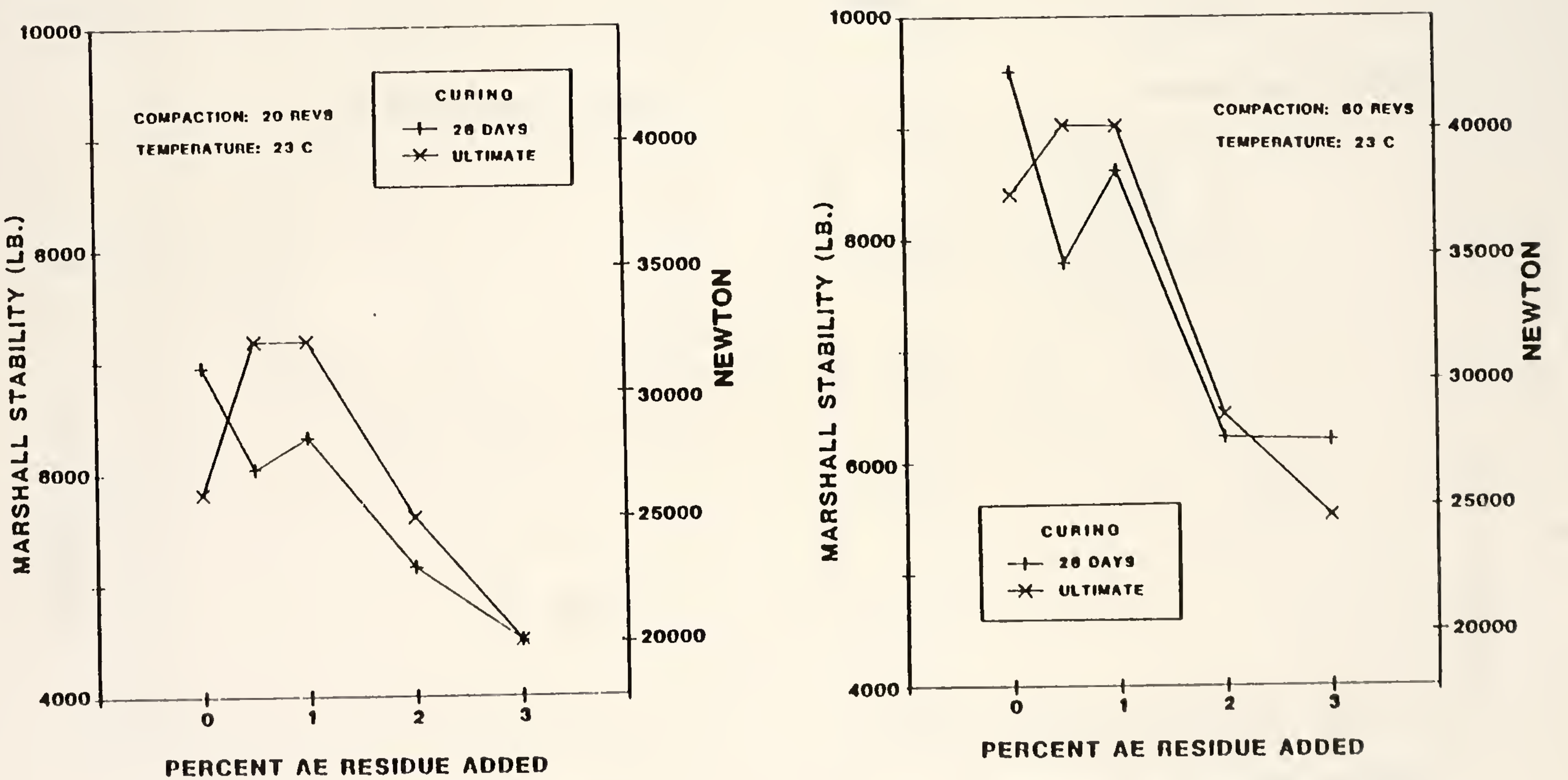


FIGURE 6.4 MARSHALL STABILITIES OF ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO.1)

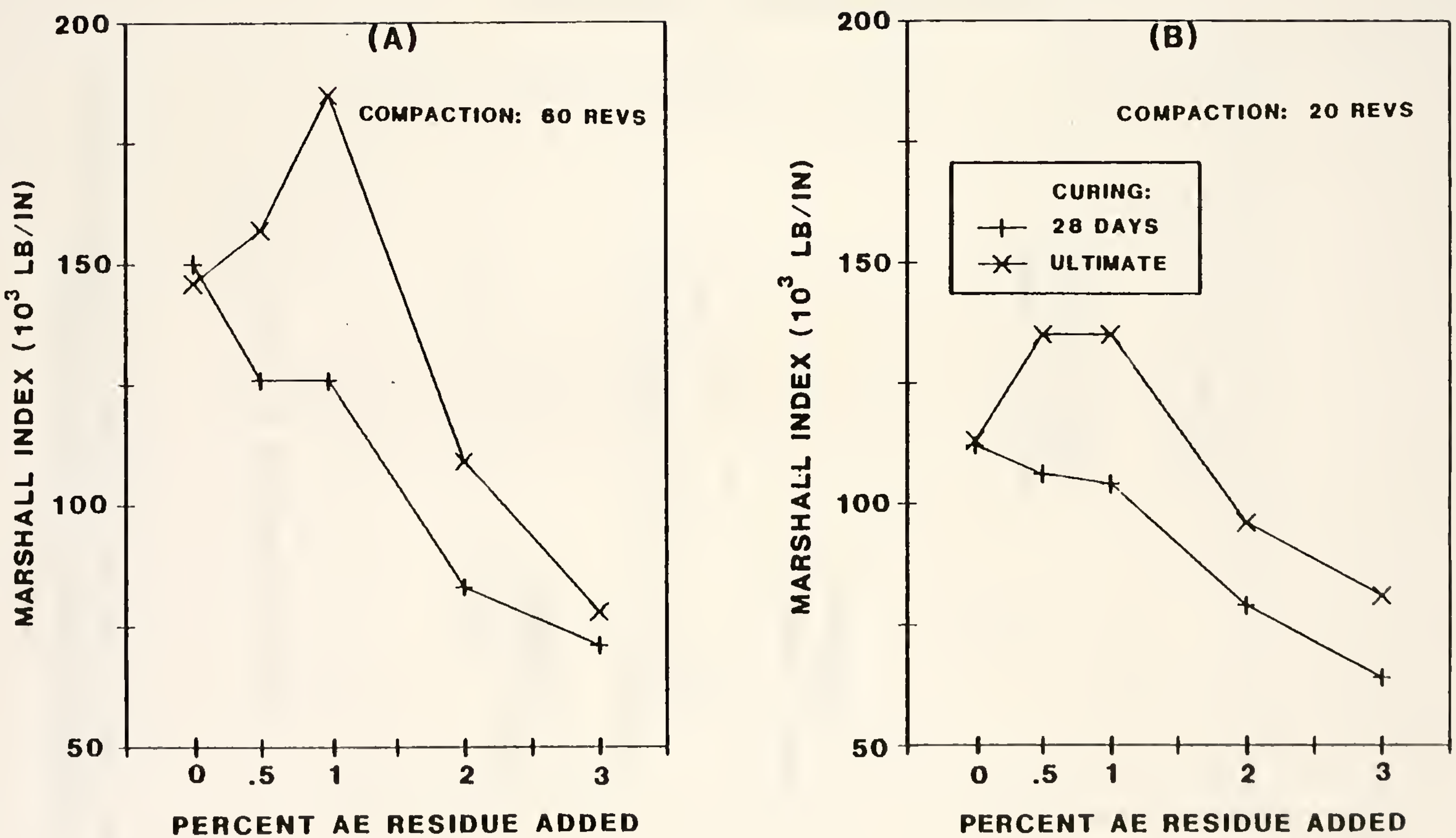


FIGURE 6.5 MARSHALL INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO.1)

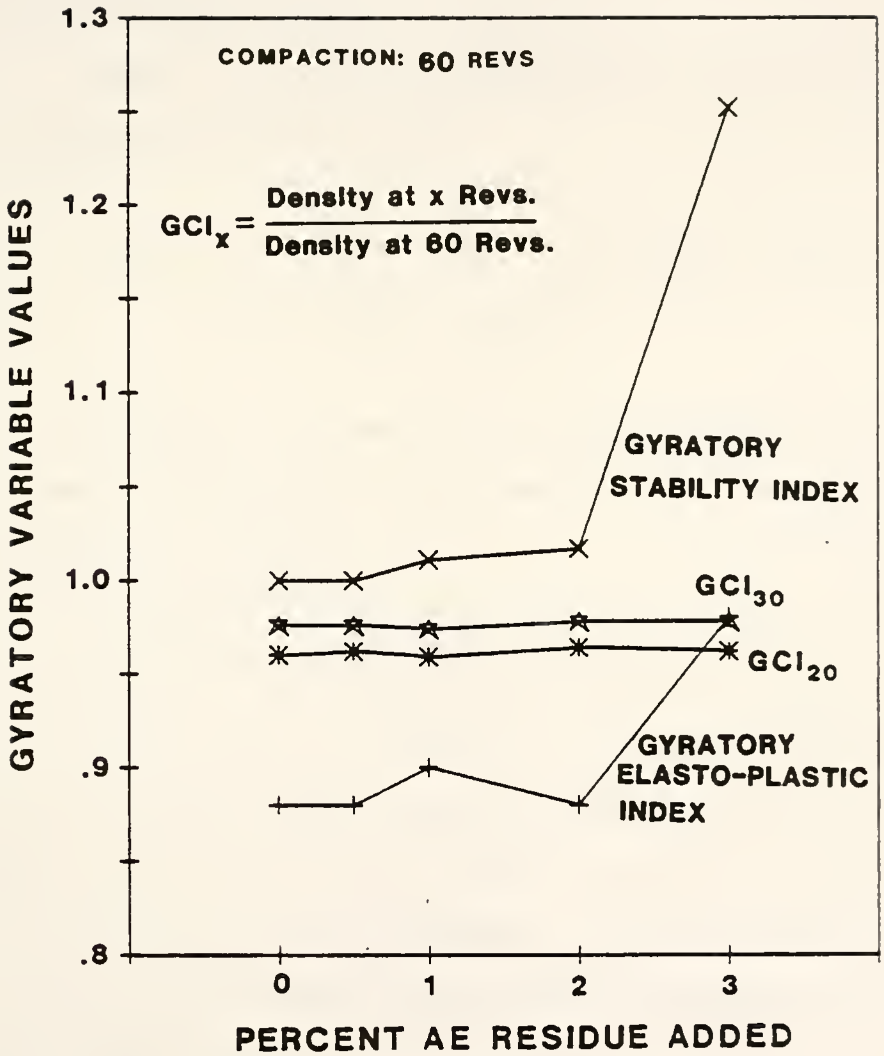


FIGURE 6.6 GYRATORY INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH AE-150 ADDED (DESIGN NO.1)

6.4 Results of Experimental Design No. 2

This section presents the results of experimental design no. 2, which dealt with the old pavement material with AE-150 as the added binder.

6.4.1 Resilient Modulus

ANOVAs were performed on the resilient modulus data using the following mathematical model:

$$Y_{ijk\ell} = \mu + P_i + R_j + PR_{ij} + S(P\text{-}R)_{(ij)k} + \delta_{(ijk)} + C_\ell + PC_{i\ell} + RC_{j\ell} + \varepsilon_{(ijk\ell)}$$

The terms in the model are as defined earlier. The ANOVA was performed on the data for curing times of 1 day to 28 days. The results are given in Table 6.3.

The resilient moduli of the mixes in design no. 2 are presented in Figure 6.7 as functions of curing time from 1 day to 28 days. It can be observed that for the compactive effort of 20 revolutions, the resilient moduli increased significantly from 1 day to 7 days, and leveled off after 7 days. For the compactive effort of 60 revolutions the effect of curing time was not significant. This was caused by the effect of the interaction between curing time and compactive effort, as indicated by the ANOVA result.

Figure 6.8 depicts the resilient moduli at ultimate curing as functions of percent AE residue added. It can be noted that the optimum percent AE residue added increased as the testing temperature decreased. The optimum AE residue added was .5% at 40°C and 1% at 23°C.

TABLE 6.3 ANOVA Results for the Resilient Modulus in Design No. 2

Factor	d.f.	S.S.	M.S.	F
P	4	37434	9358	7.09*
R	1	2338	2338	1.77
PR	4	6241	1560	1.18
S(P-R)	10	13204	1320.4	
C	3	1163	388	1.16
CP	12	5026	419	1.25
CR	3	4352	1451	4.34*
ε	42	14027	334.0	

* Significant at $\alpha = .05$

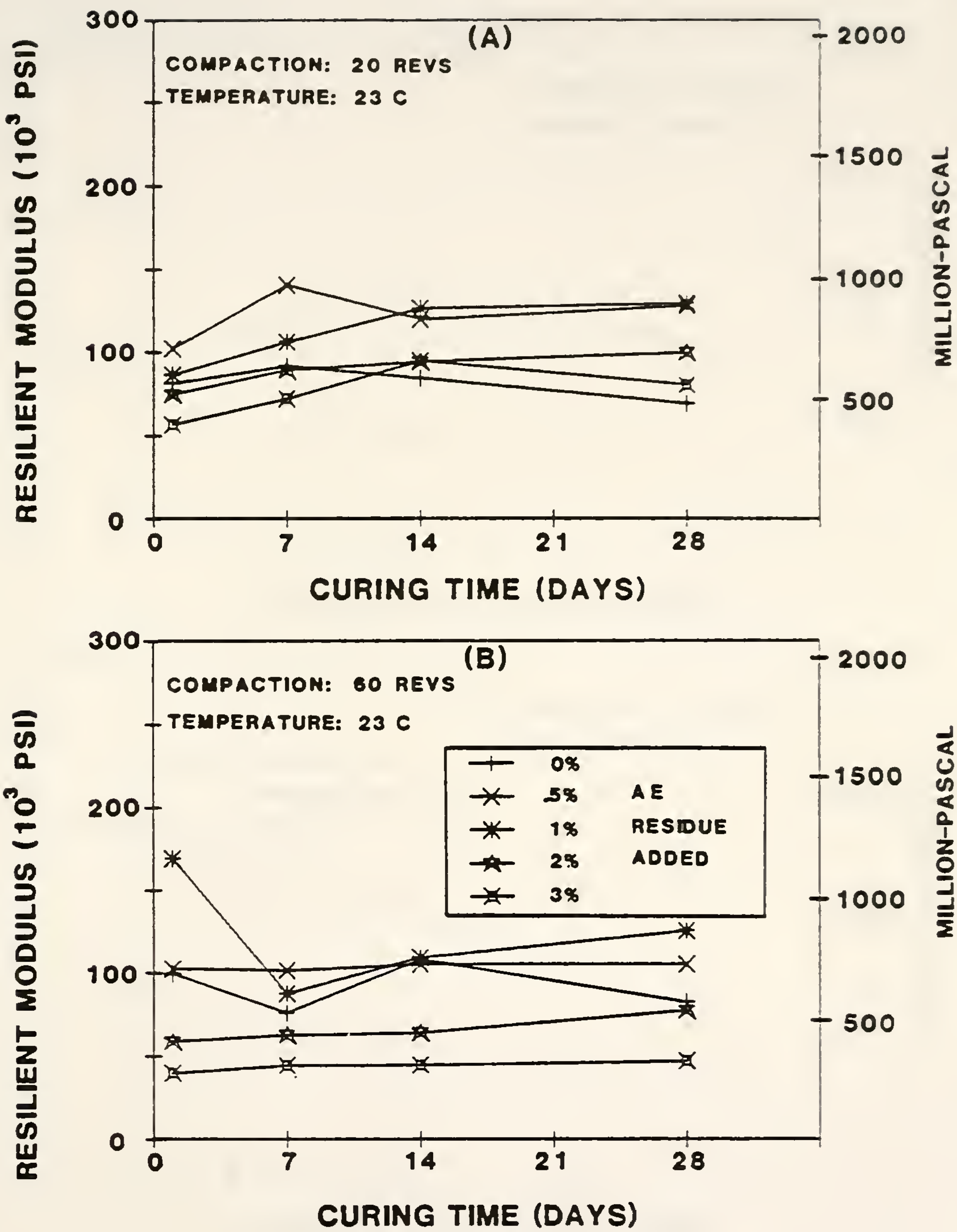


FIGURE 6.7 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO.2)

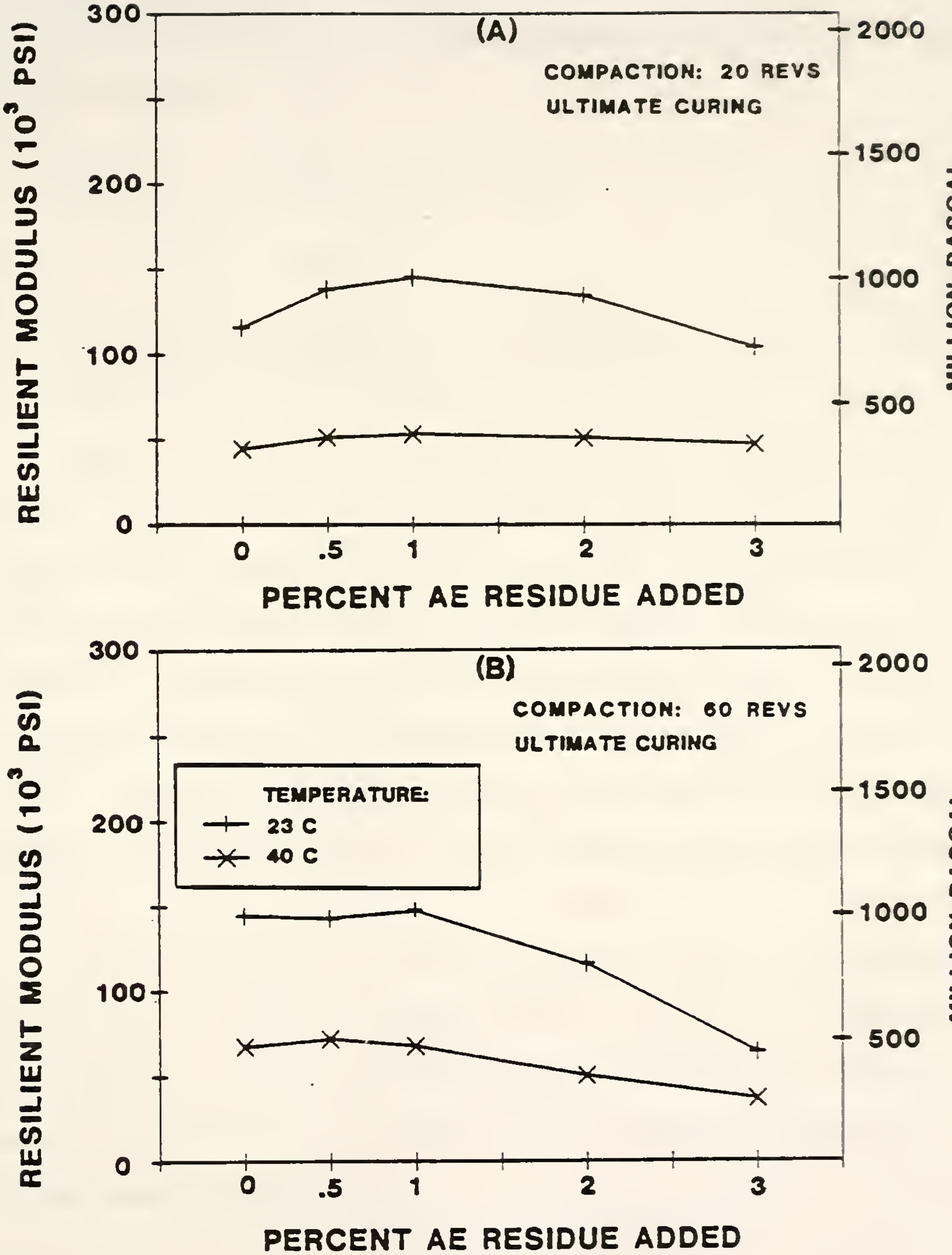


FIGURE 6.8 RESILIENT MODULI AT ULTIMATE CURING FOR OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO.2)

6.4.2 Hveem R-Value and Marshall Variables

ANOVAs were performed on the Hveem R-values and Marshall variables using the following model:

$$Y_{ijk} = \mu + C_i + R_j + P_k + CR_{ij} + CP_{ik} + RP_{jk} + \epsilon_{(ijk)}$$

The terms in the model are as defined earlier. This is a completely randomized design. The ANOVA results are displayed in Table 6.4.

Figure 6.9 presents the R-values as functions of percent AE residue added. It can be noted that the optimum AE residue added was around .5% for the two compactive efforts and the two curing times considered. The difference between 28 days curing and ultimate curing was not significant, as indicated by the plots and the ANOVA result. The effect of compactive effort was not significant at lower binder content of the mixes. However, at the higher binder content when the mixes became unstable, the higher compactive effort produced significantly lower R-values.

Figures 6.10 and 6.11 present the Marshall stabilities and indices as functions of percent AE residue added. It can be noted that both the Marshall stability and index increased significantly with higher compactive effort. The two variables both indicated an optimum AE residue added of around 0.5%.

6.4.3 Gyratory Indices

The gyratory indices for the mixes in design no. 2 are presented in Figure 6.12. It can be observed that the gyratory compactibility

TABLE 6.4: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 2

Source of Variation	Response Variable:	R-Value	S_M	L_M	F_M
C		N.S.	S.	N.S.	N.S.
R		S.	S.	N.S.	S.
P		S.	S.	S.	S.
CR		N.S.	N.S.	N.S.	N.S.
CP		N.S.	N.S.	N.S.	N.S.
RP		S.	S.	N.S.	S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$

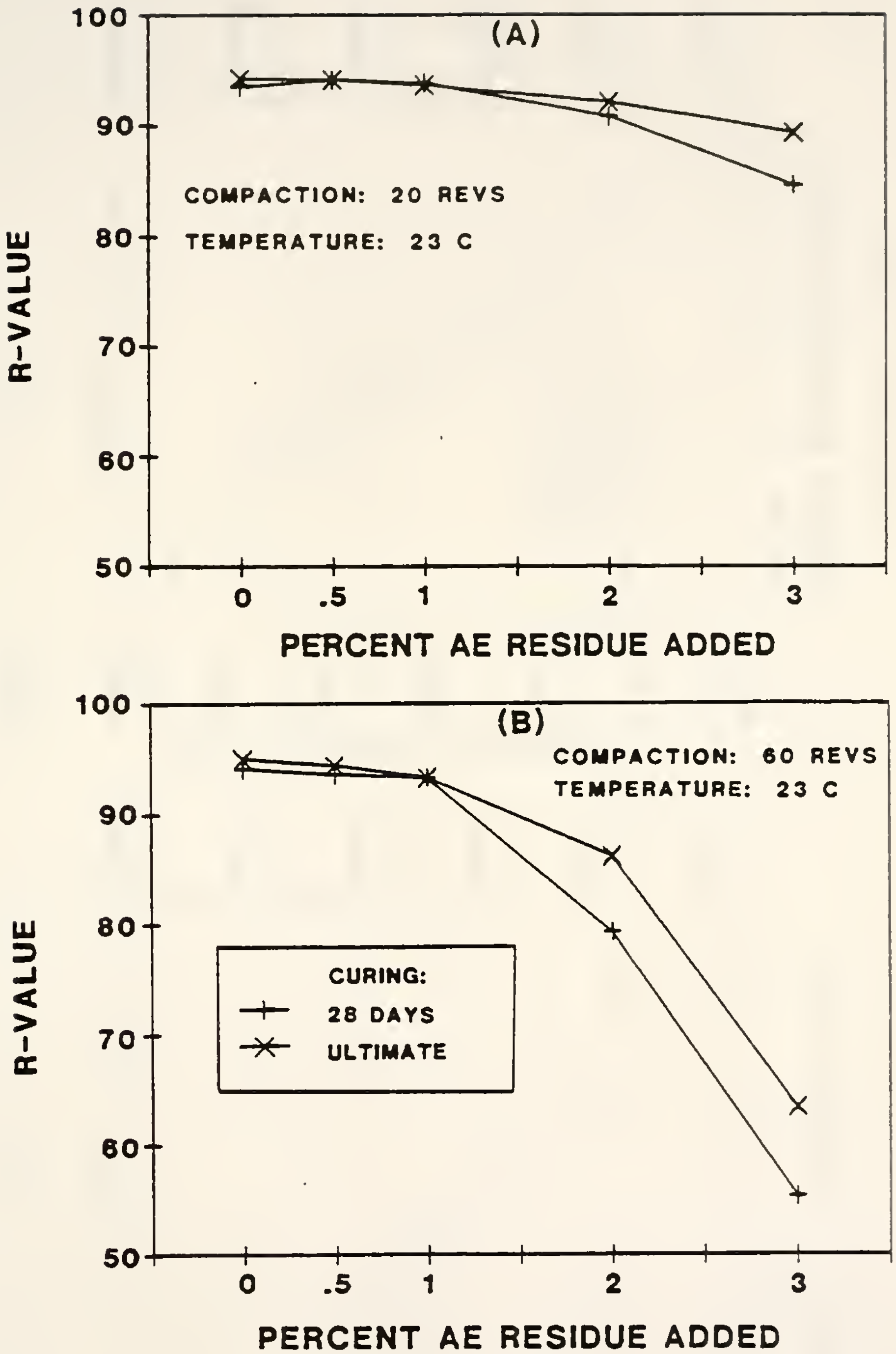


FIGURE 6.9 HVEEM R-VALUES OF OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO.2)

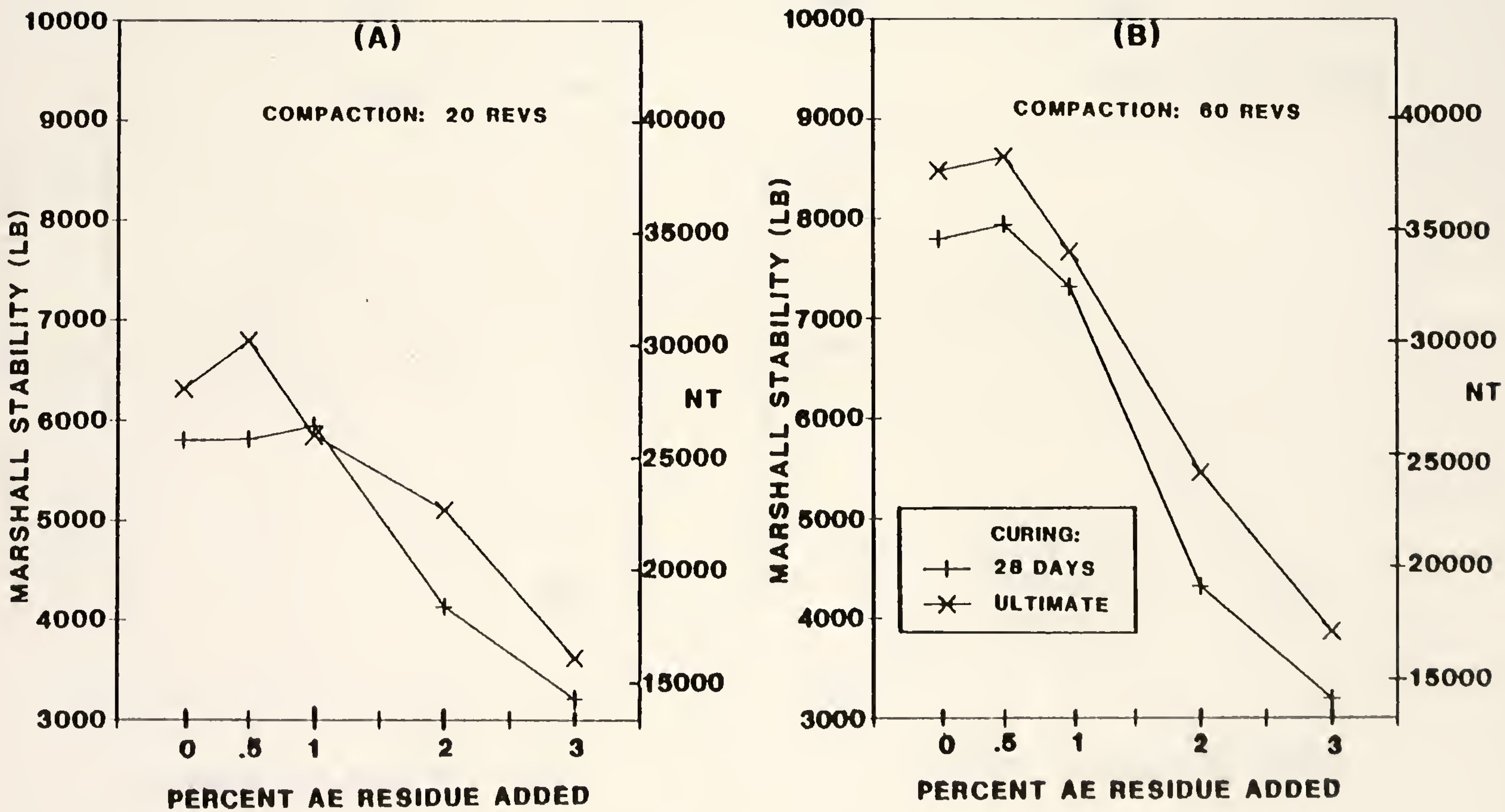


FIGURE 6.10 MARSHALL STABILITIES OF OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO.2)

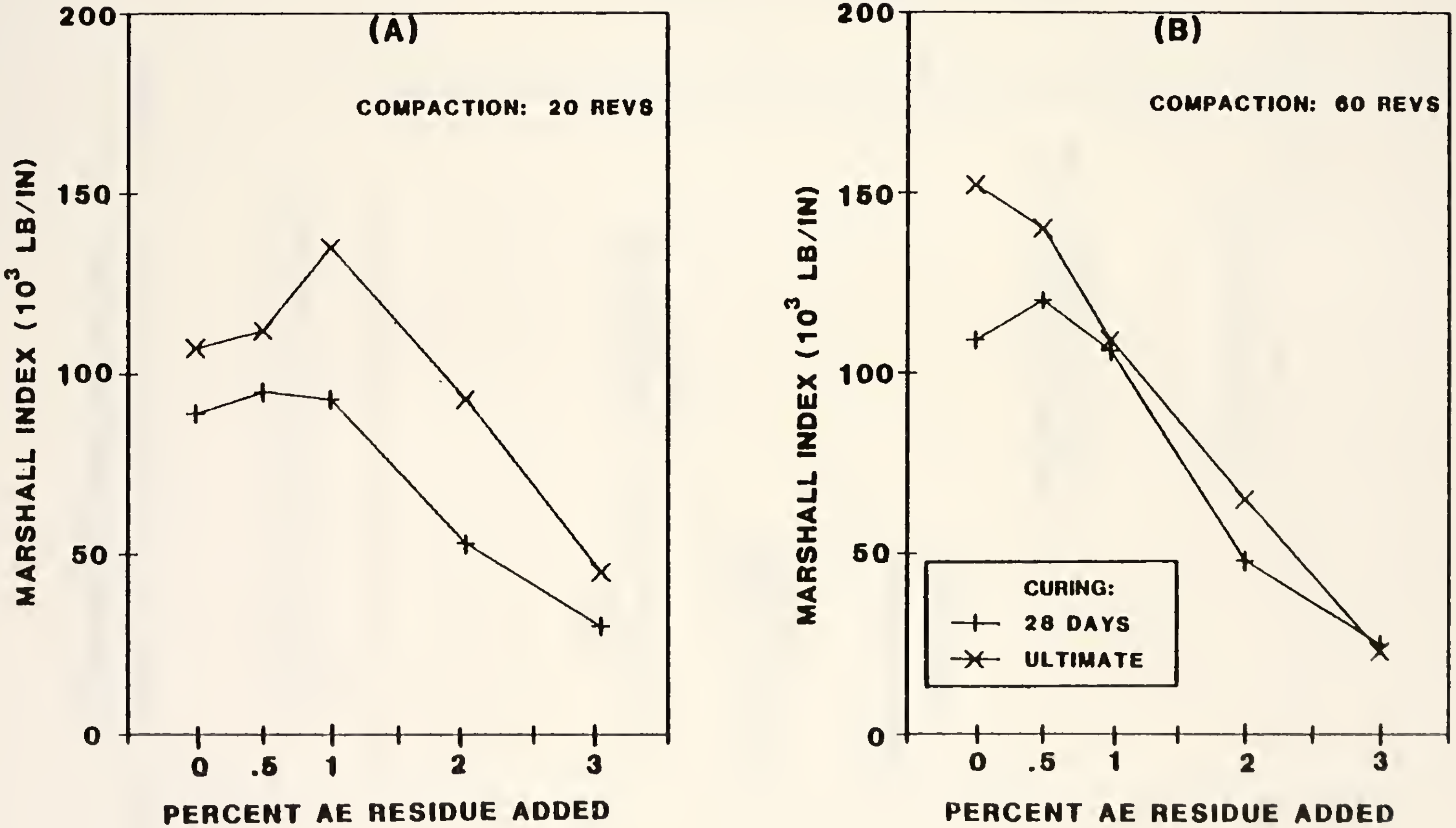


FIGURE 6.11 MARSHALL INDICES OF OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO.2)

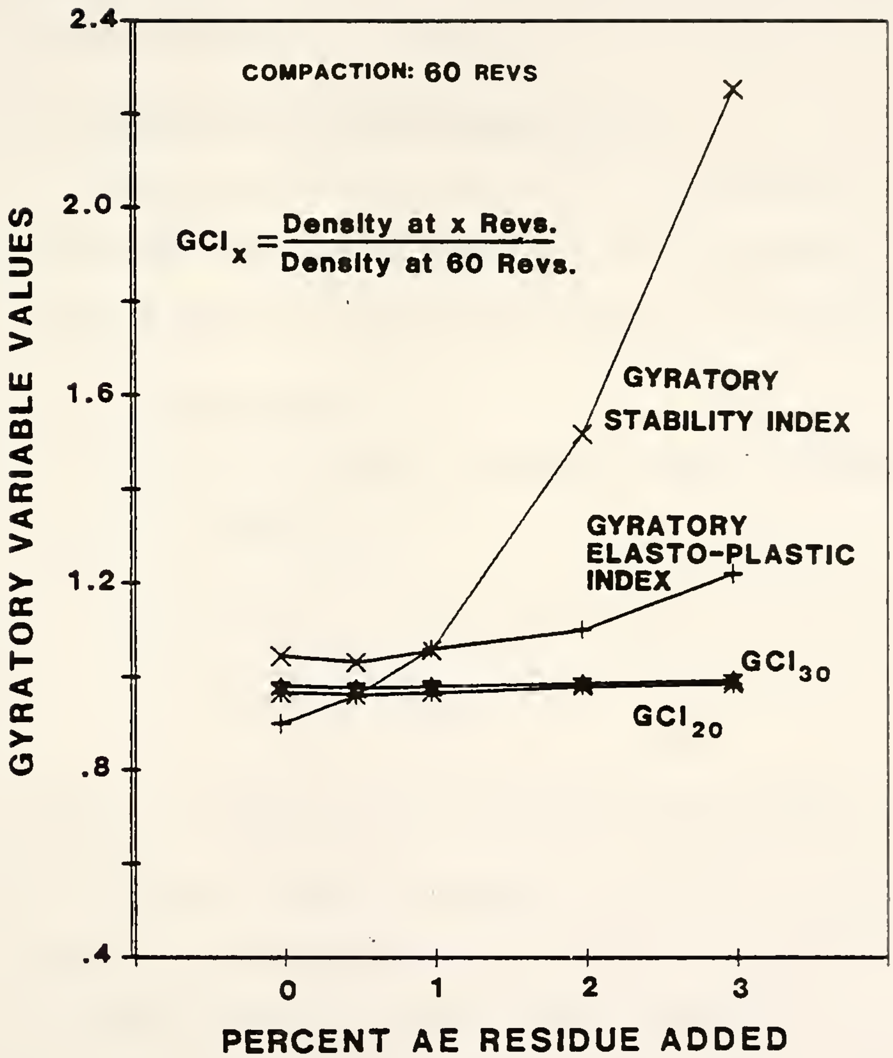


FIGURE 6.12 GYRATORY INDICES OF OLD PAVEMENT MATERIAL WITH AE-150 ADDED (DESIGN NO.2)

indices (GCIs) were insensitive to the changes in percent AE residue added. The stability index (SI) remained relatively constant for AE residue added of less than 1% and increased greatly thereafter. The elasto-plastic index (EPI) increased as AE residue added increased from 0% to 1%, leveled off as AE residue added, went from 1% to 2%, and increased again thereafter.

6.5 Results of Experimental Design No. 3

This section presents the results of experimental design no. 3, which dealt with recycled mixes made from old pavement materials of different aged conditions with AE-150 as the added binder.

6.5.1 Resilient Modulus

ANOVAs were performed on the resilient modulus data in design no. 3 using the following model:

$$Y_{ijk\ell} = \mu + P_i + A_j + PA_{ij} + S(P\text{-}A)_{(ij)k} + \delta_{(ijk)} + C_k + PC_{ik} + AC_{j\ell} + \varepsilon_{(ijk\ell)}$$

where A = Effect of aged condition of the pavement material

The other terms in the model are as defined earlier. Separate ANOVAs were performed on the data for parts 1 and 2 of design no. 3. The ANOVA results are shown in Tables 6.5 and 6.6.

The resilient moduli of the mixes in part 1 of design no. 3 are presented in Figure 6.13. Due to the scattering of the obtained data, the ANOVA result indicated that the curing time was the only significant factor to affect the resilient modulus of the mixes in part 1.

TABLE 6.5 ANOVA Results for the Resilient Modulus in Design 3 Part 1

Factor	d.f.	S.S.	M.S.	F
P	3	15043	5014	1.75
A	1	995	995	.35
PA	3	6176	2059	.72
S(P-A)	8	22883	2860	
C	3	4225.8	1409	5.17*
CP	9	3305.7	367.3	1.35
CA	3	65.6	21.9	.08
ε	33	8994	272.5	

* Significant at $\alpha = 0.05$

TABLE 6.6 ANOVA Results for the Resilient Modulus in Design 3 Part 2

Factor	d.f.	S.S.	M.S.	F
P	4	3317.5	829.4	.64
A	1	7688.0	7688	5.96*
PA	4	9037.2	1291	
C	3	4184.8	1394.9	6.16*
CP	12	3043.1	253.6	1.12
CA	3	512.2	170.7	.75
ϵ	8	1811.8	226.5	

* Significant at $\alpha = 0.05$

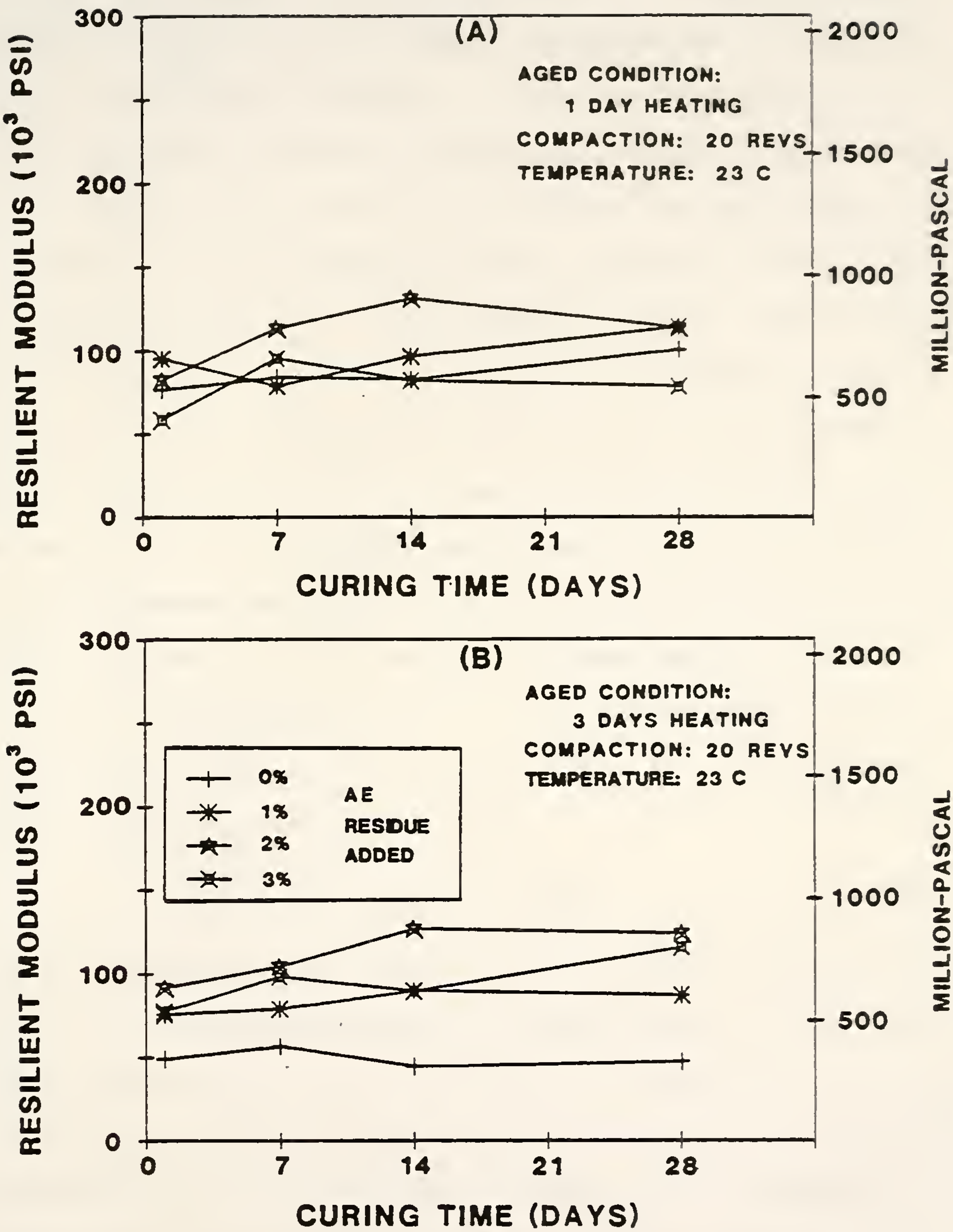


FIGURE 6.13 RESILIENT MODULI AS FUNCTIONS OF CURING TIME FOR RECYCLED MIXES IN DESIGN 3 PART 1

The resilient moduli of the mixes in part 2 of design no. 3 are presented in Figure 6.14. It can be noted that the resilient moduli increased significantly from 1 day to 7 days, and leveled off after 7 days. The ANOVA result also indicated that the aged condition of the pavement material was an important factor to the resilient modulus.

Figures 6.15 and 6.16 show the resilient moduli at ultimate curing as functions of percent AE residue added for the mixes in part 1 and part 2 of design no. 3. It can be observed that the harder (or more aged) the old binder material was, the more virgin binder would be required to restore the mix to its optimum condition. For the old pavement material in as-is condition, the optimum AE residue added was .5%. For the old pavement material of 1-day-heating condition, the optimum AE residue added was 1%. For the material of 3-days-heating condition, the optimum AE residue added was 2%. For the same pavement material (3-days-heating condition), it can be noted that higher compactive efforts produced higher resilient moduli.

6.5.2 Hveem R-Value and Marshall Variables

The Hveem R-Values of the mixes in design no. 3 were presented in Figure 6.17 as functions of percent AE residue added. It can be seen that the optimum levels of AE residue added as indicated by the R-value results were the same as those indicated by the resilient modulus results. It can also be noted that the greater compactive effort produced a greater drop in R-value when the mix was unstable (for example, when 3% of AE residue was added).

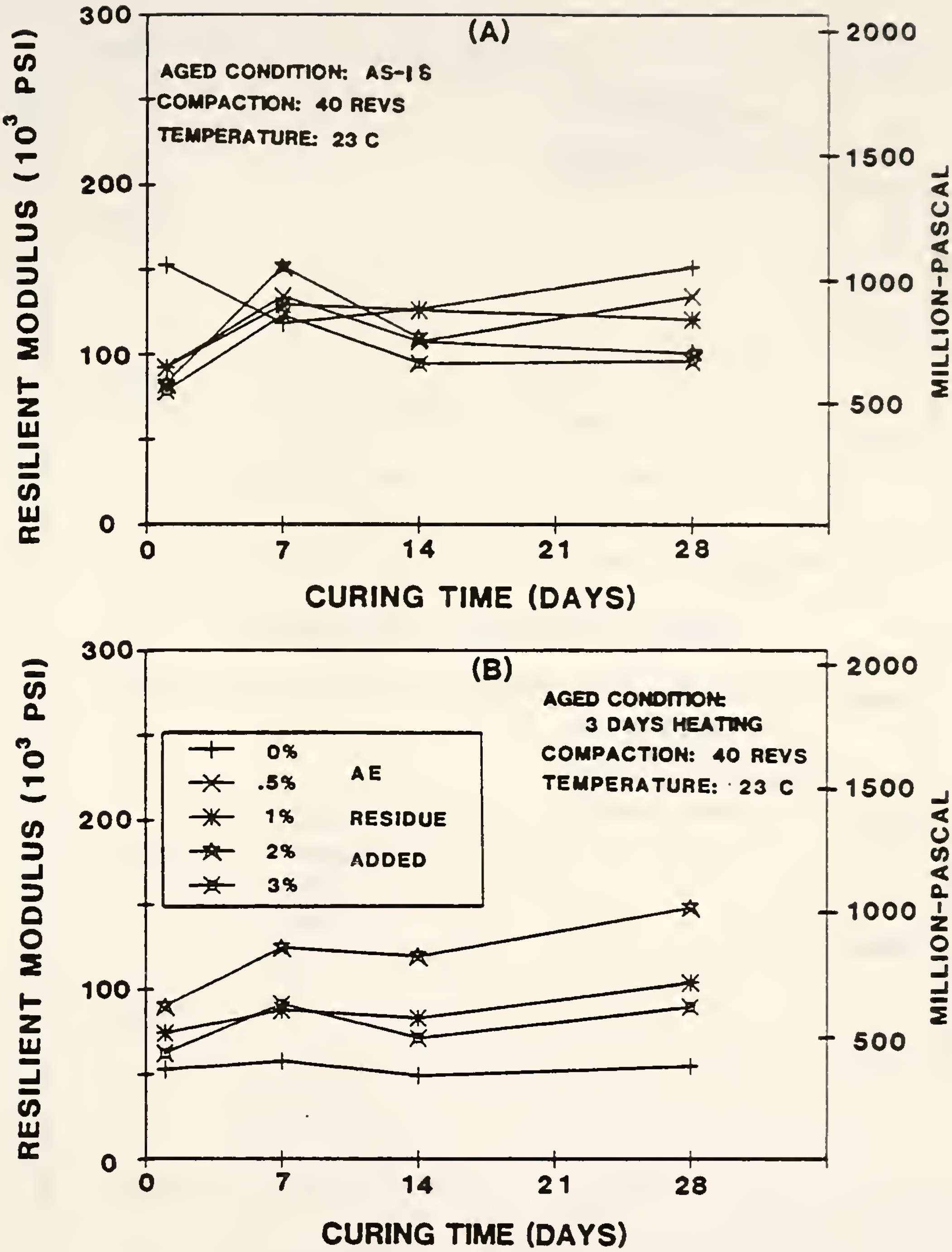


FIGURE 6.14 RESILIENT MODULI AS FUNCTIONS OF CURING TIME FOR RECYCLED MIXES IN DESIGN 3 PART 2

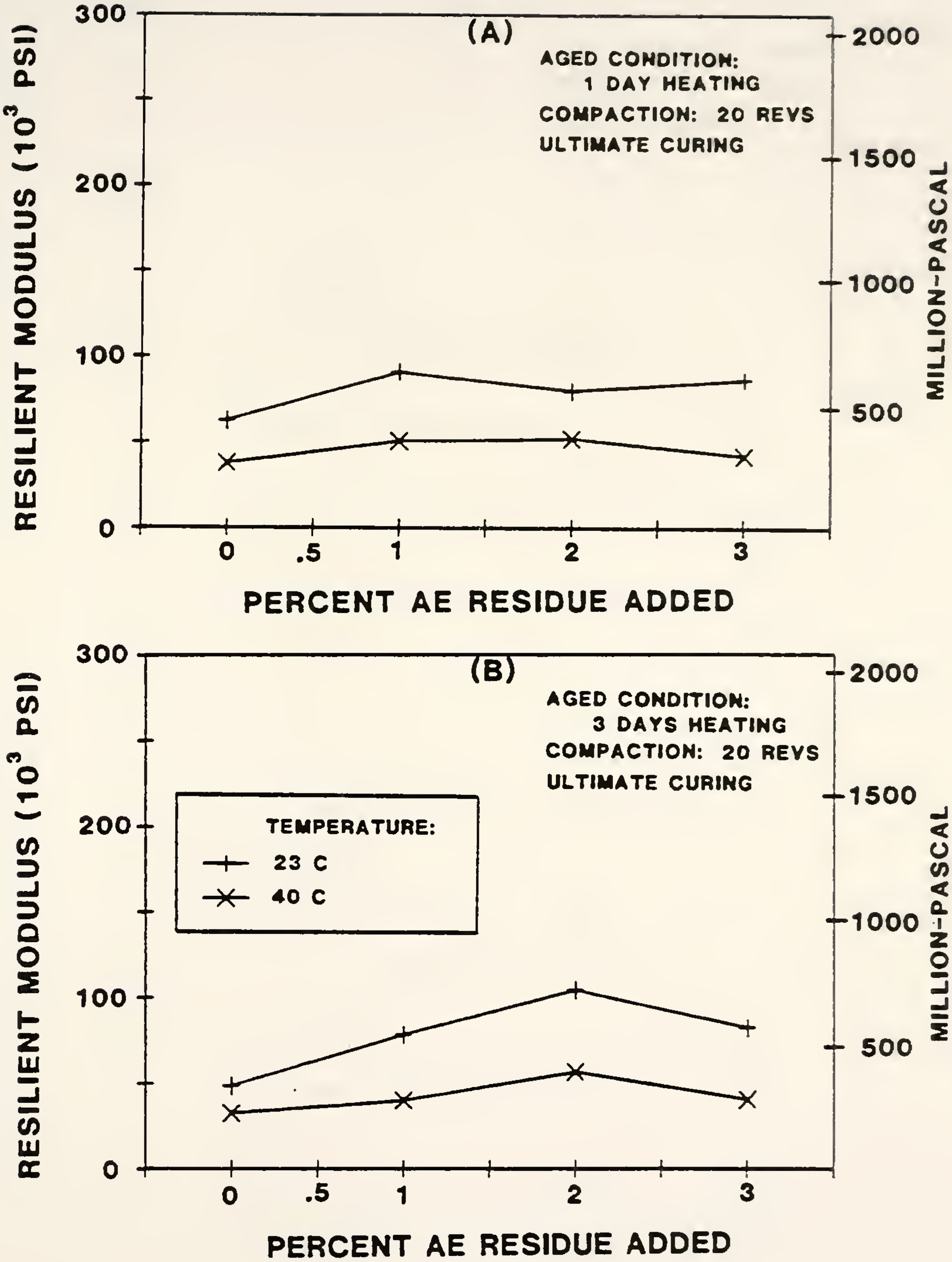


FIGURE 6.15 RESILIENT MODULI AT ULTIMATE CURING FOR RECYCLED MIXES IN DESIGN 3 PART 1

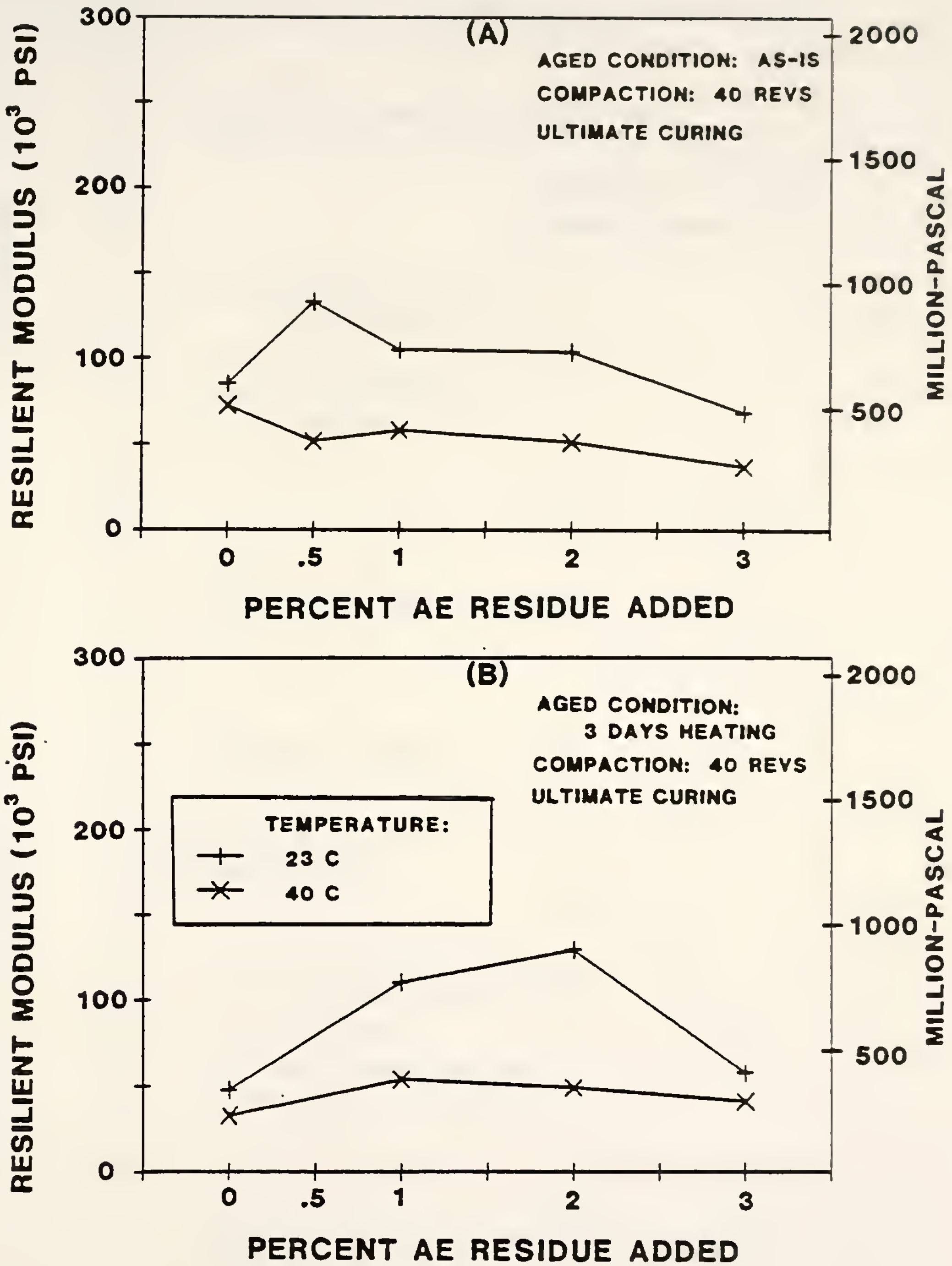


FIGURE 6.16 RESILIENT MODULI AT ULTIMATE CURING FOR RECYCLED MIXES IN DESIGN 3 PART 2

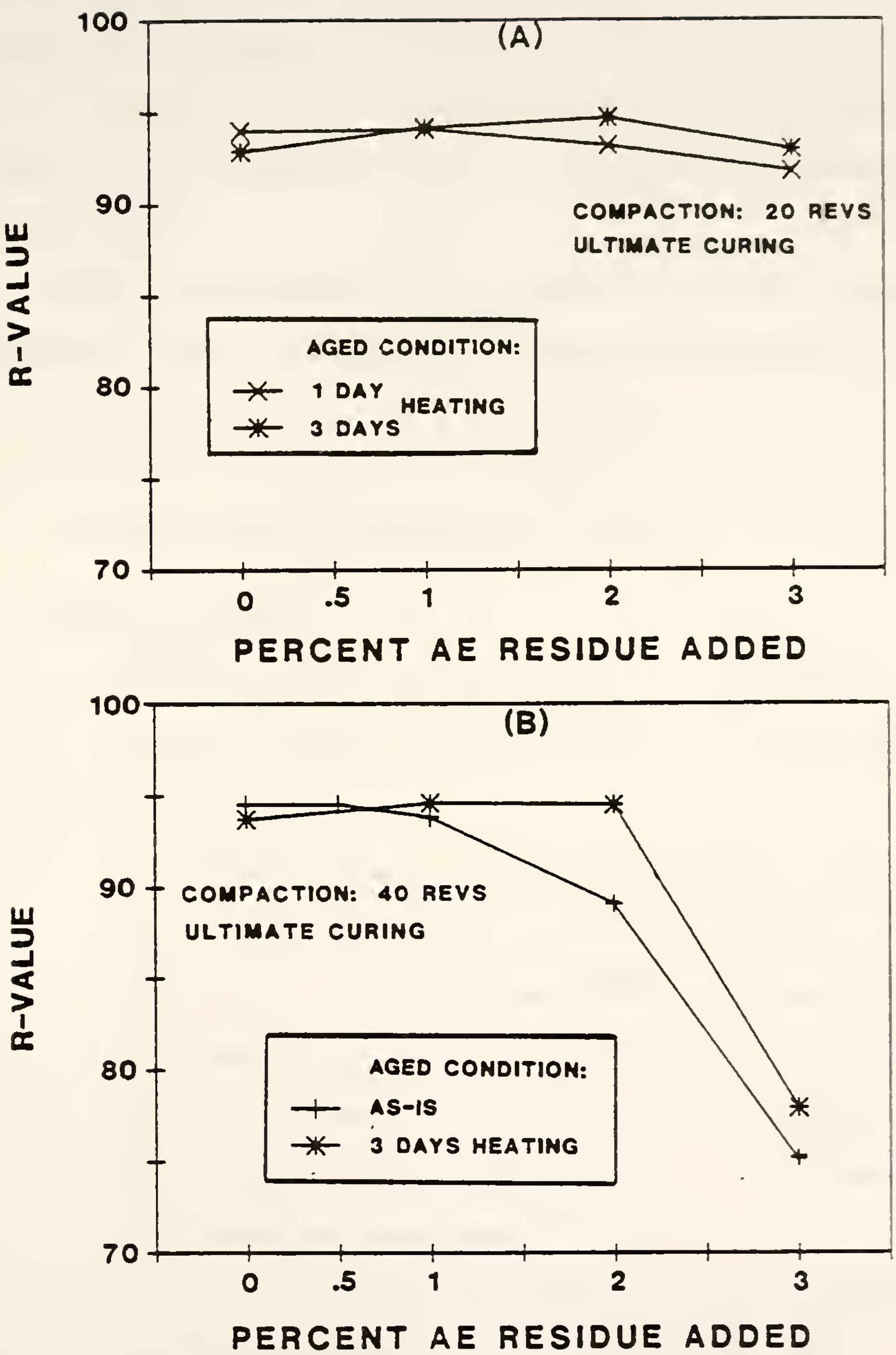


FIGURE 6.17 HVEEM R-VALUES OF RECYCLED MIXES IN DESIGN 3

Figures 6.18 and 6.19 present the Marshall stabilities and indices for the mixes in design no. 3. It can be noted that the optimum levels of AE residue added as indicated by these two variables were similar to those indicated by the resilient modulus and Hveem R-value results.

ANOVAs were performed on the R-values and Marshall variables of the mixes in part 1 of design 3, using the following model:

$$Y_{ijk} = \mu + P_i + A_j + PA_{ij} + \varepsilon_{(ij)k}$$

The ANOVA results are displayed in Table 6.7.

6.6 Summary of Results

The findings presented in this chapter, on the behavior of the recycled mixes with AE-150 as the added binder, are summarized into the following points.

1. The resilient modulus increased significantly with curing time in the first 7 days, and leveled off after 7 days. The increase in resilient modulus with time was caused by the increase in stiffness of the binder as the asphalt emulsion continued to cure. The curing of the asphalt emulsion became less significant after 7 days, when most of its water had evaporated.
2. The level of AE residue added had a significant effect on the resilient modulus, Hveem R-value and Marshall variables.

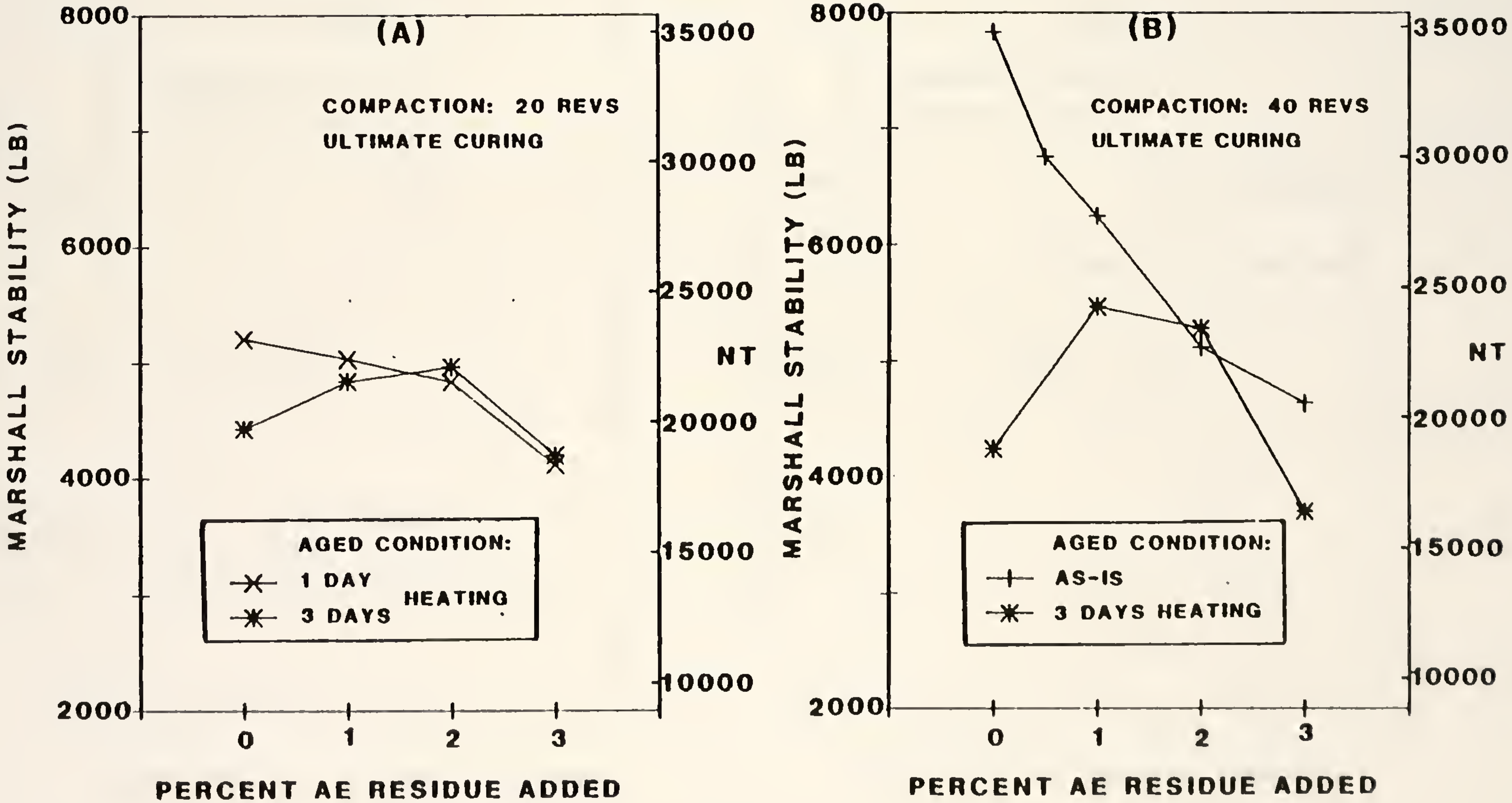


FIGURE 6.18 MARSHALL STABILITIES OF RECYCLED MIXES IN DESIGN 3

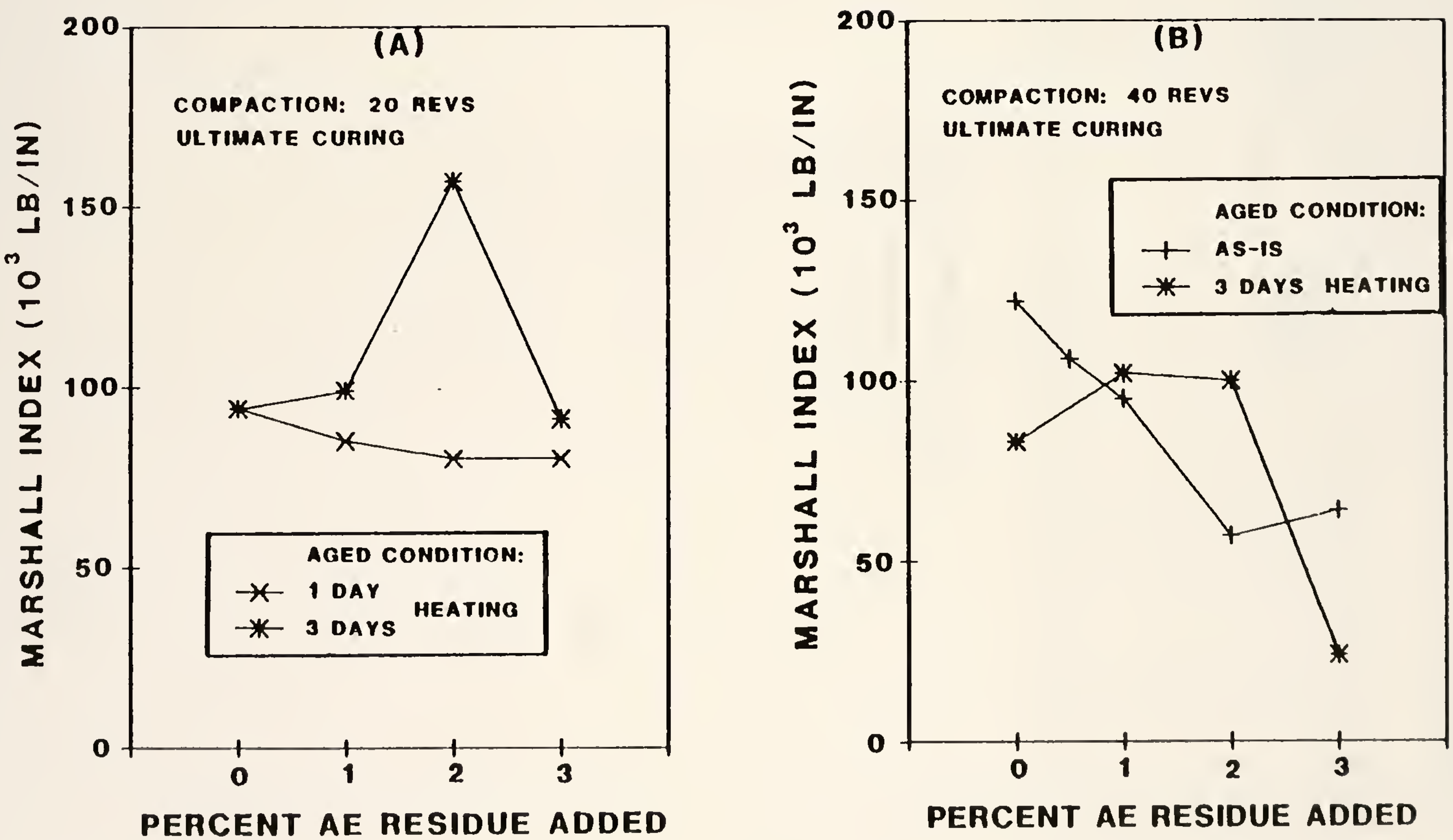


FIGURE 6.19 MARSHALL INDICES OF RECYCLED MIXES IN DESIGN 3

TABLE 6.7: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 3 PART 1

Source of Variation	Response Variable:	R-Value	S_M	I_M	F_M
P		S.	S.	N.S.	N.S.
A		N.S.	N.S.	N.S.	S.
PA		N.S.	N.S.	N.S.	N.S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$

3. The optimum level of AE residue added increased as the testing temperature decreased.
4. Higher compactive effort generally produced a higher resilient modulus, Marshall stability and index. When the binder content was too high and the mix was unstable, higher compactive effort produced lower R-values.
5. The gyratory stability index was relatively constant for binder content near or below the optimum level, and increased significantly as the binder content was above the optimum level.
6. The gyratory elasto-plastic index increased with increasing binder content, leveled off when the binder content was around the optimum level, and increased again when the binder content was above the optimum level.
7. The gyratory compactibility index was insensitive to the changes in binder content of the mixes.
8. The difference between 28 days curing and ultimate curing was generally not significant. (The comparisons of the resilient moduli at these two curing conditions are presented in Appendix C.)

CHAPTER 7

RECYCLED MIXTURES USING FOAMED ASPHALT

7.1 Introduction

This chapter presents the results of Designs 4 and 5, which dealt with the behavior of the recycled mixtures with foamed asphalt added. In design no. 4 (shown in Table 4.5), the recycled mixtures tested were made from an artificially aged paving mixture. In design no. 5 (shown in Table 4.6), the mixes were made from an old pavement material.

The general laboratory procedure described in Chapter 5 was used to prepare and to test the recycled mixes. The foamed asphalt added was made from a soft asphalt graded as AC-2.5 and 2% added water. Three percent water (by weight of the aggregate) was added to the recycled mixtures before the addition of the foamed asphalt. The method of analysis on the data was similar to that presented in Chapter 6.

7.2 Results of Experimental Design No. 4

7.2.1 Resilient Modulus

The resilient moduli of the recycled mixes in design no. 4 are presented in Figure 7.1 as functions of curing time, from 1 day to 28 days. It can be observed that the resilient modulus increased significantly with curing time from 1 day to 14 days, and leveled off after 14 days. The increase in resilient modulus with time was due to the drying of the mixture through evaporation of its water. When most of

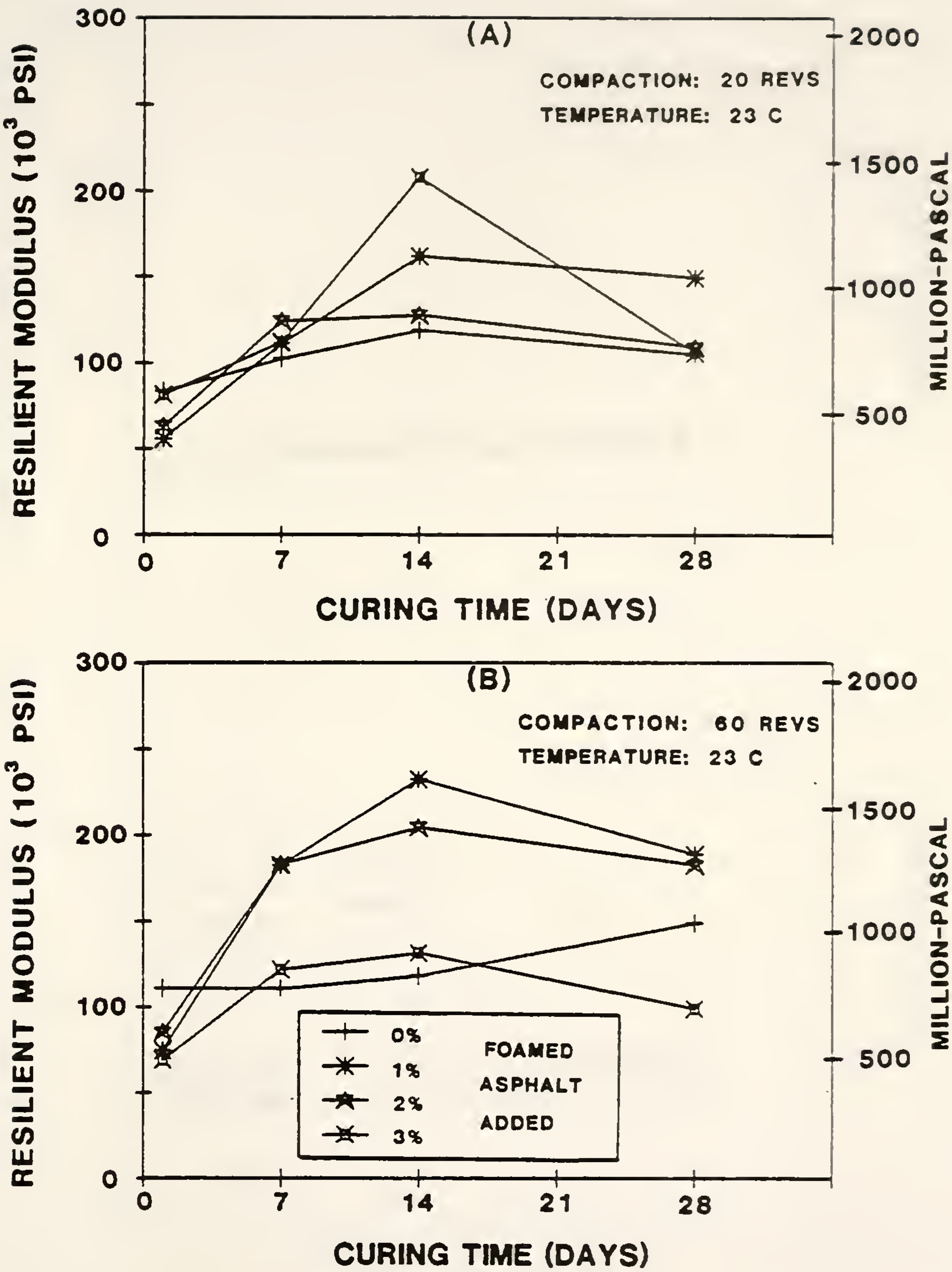


FIGURE 7.1 EFFECTS OF CURING ON THE RESILIENT MODULI OF ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.4)

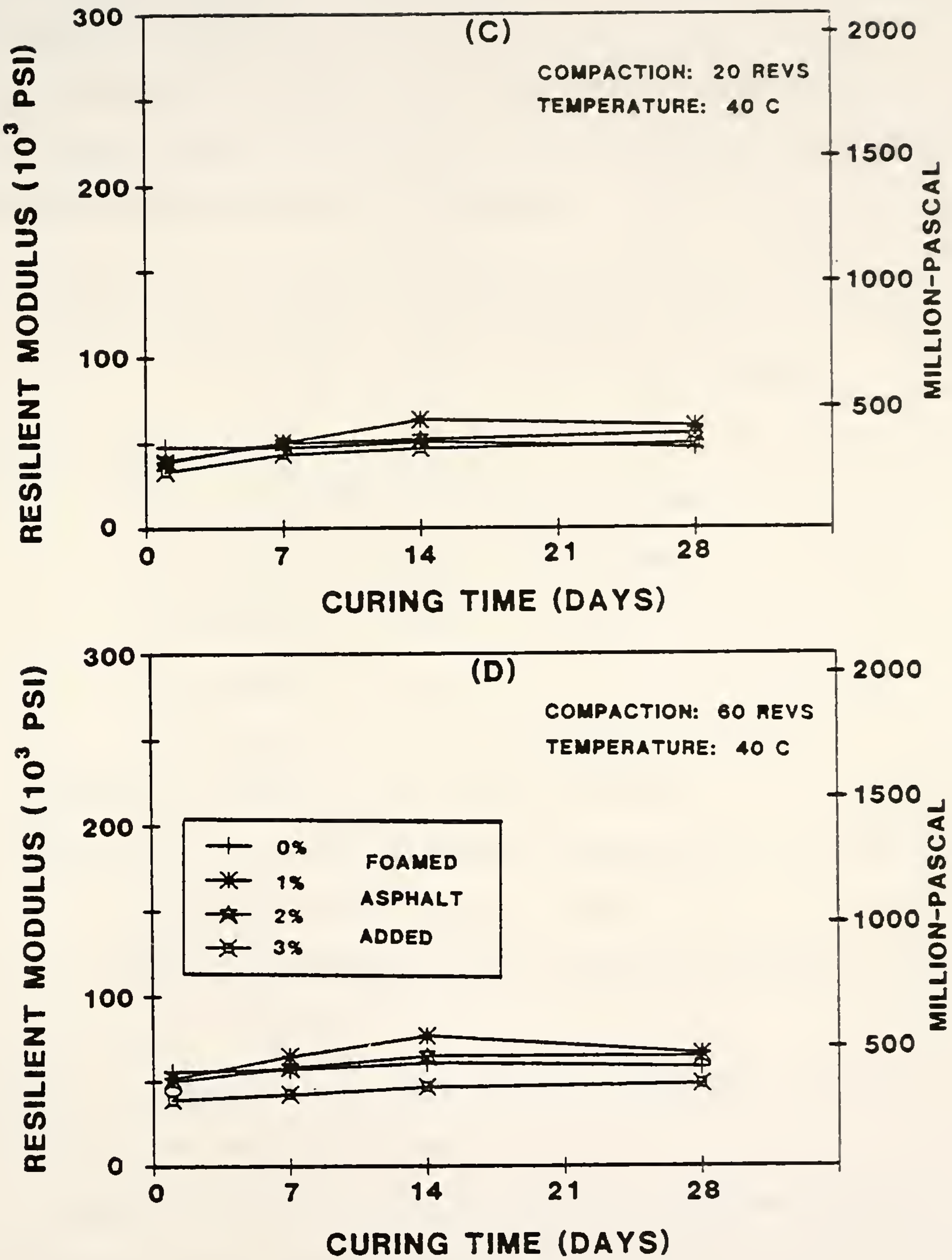


FIGURE 7.1 (Continued)

the moisture in the mixture had evaporated, the effect of curing time became less significant.

ANOVAs were performed on the transformed resilient modulus ($\sqrt{M_R}$), which passed the Foster-Burr Q-test for homogeneity of variance. The statistical model used is as follows:

$$Y_{ijk\ell m} = \mu + P_i + R_j + PR_{ij} + S(P\text{-}R)_{(ij)k} + \delta_{(ijk)} + C_\ell + T_m$$
$$+ PC_{i\ell} + RC_{j\ell} + PT_{im} + RT_{jm} + CT_{\ell m} + \varepsilon_{(ijk\ell m)}$$

where $Y_{ijk\ell m}$ = Response variable

μ = Overall mean of response variable

P_i = Effect of percent asphalt added

R_j = Effect of compactive effort

C_ℓ = Effect of curing time

T_m = Effect of testing temperature

$S(P\text{-}R)_{(ij)k}$ = Within error of PR combinations

PR_{ij}, $PC_{i\ell}$ ....., $CT_{\ell m}$ = Effects of interactions of two factors

$\delta_{(ijk)}$ = Restriction error

$\varepsilon_{(ijk\ell)m}$ = Experimental error + interaction of three or more factors.

ANOVA was performed on the data for curing times of 1 day to 28 days. The results are presented in Table 7.1.

Figure 7.2 depicts the resilient moduli at ultimate curing as functions of percent asphalt added. It can be observed that the optimum asphalt added increased as the testing temperature decreased. For the compactive effort of 20 revolutions, the optimum asphalt added was 0% at 40°C, 3% at 23°C and 3% at 0°C. For the compactive effort of 60

TABLE 7.1: ANOVA Results for the Resilient Modulus in Design No. 4

Factor	d.f.	S.S.	M.S.	F
P	2	20.25	10.12	10.4*
R	1	17.25	17.25	17.7*
PR	2	18.68	9.34	9.6*
S(P-R)	6	5.86	.977	
C	3	114.7	38.23	43.2*
T	1	395.5	395.5	446*
CP	6	9.28	1.55	1.75
CR	3	1.16	.39	.44
TP	2	.066	.033	.04
TR	1	2.95	2.95	3.33
TC	3	42.28	14.09	15.9*
ϵ	65	57.58	.886	

* Significant at $\alpha = 0.05$

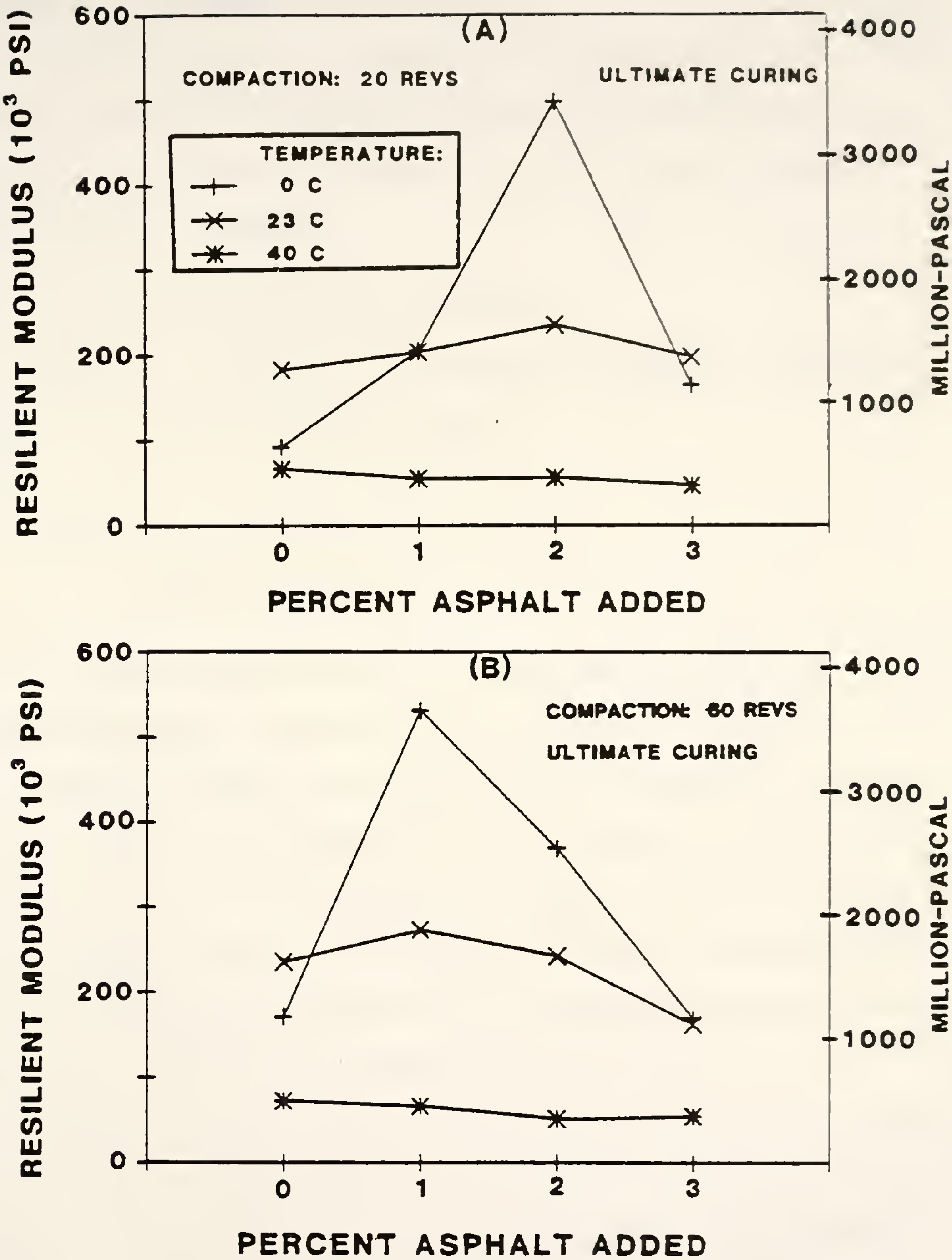


FIGURE 7.2 RESILIENT MODULI AT ULTIMATE CURING FOR ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.4)

revolutions, the optimum asphalt added was 0% at 40°C, 2% at 23°C and 2% at 0°C. It can also be noted that the resilient modulus at ultimate curing was significantly higher than that at 28 days curing. The comparisons of the resilient moduli at these two curing conditions are presented in Appendix C.

7.2.2 Hveem R-Value and Marshall Variables

ANOVAs were performed on the R-Values and Marshall variables in design no. 4 using the following model:

$$Y_{ijk} = \mu + C_i + R_j + P_k + CR_{ij} + CP_{ik} + RP_{jk} + \varepsilon_{(ijk)}$$

The terms in the model are as defined earlier. This is a completely randomized design. The ANOVA results are displayed in Table 7.2.

Figure 7.3 depicts the Hveem R-values as functions of percent asphalt added. It can be noted that for the compactive effort of 20 revolutions, the R-value was relatively insensitive to the changes in percent asphalt added. For the compactive effort of 60 revolutions, the effect of percent asphalt added was more significant, and the optimum asphalt added could be noted to be around 1%.

Figures 7.4 and 7.5 present the Marshall stabilities and indices as functions of percent asphalt added. It can be noted that, for low compactive effort (20 revs.), the Marshall stability was relatively insensitive to the changes in percent asphalt added. For high compactive effort (60 revs.), the effect of percent asphalt added was more significant, and the optimum asphalt added could be observed to be around 1%. For low compactive effort (20 revs.), the Marshall index

TABLE 7.2: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 4

Source of Variation	Response Variable:	R-Value	S_M	I_M	F_M
C		S.	S.	N.S.	N.S.
R		N.S.	S.	N.S.	N.S.
P		S.	N.S.	N.S.	N.S.
CR		S.	N.S.	N.S.	N.S.
CP		N.S.	N.S.	N.S.	N.S.
RP		S.	N.S.	N.S.	N.S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$

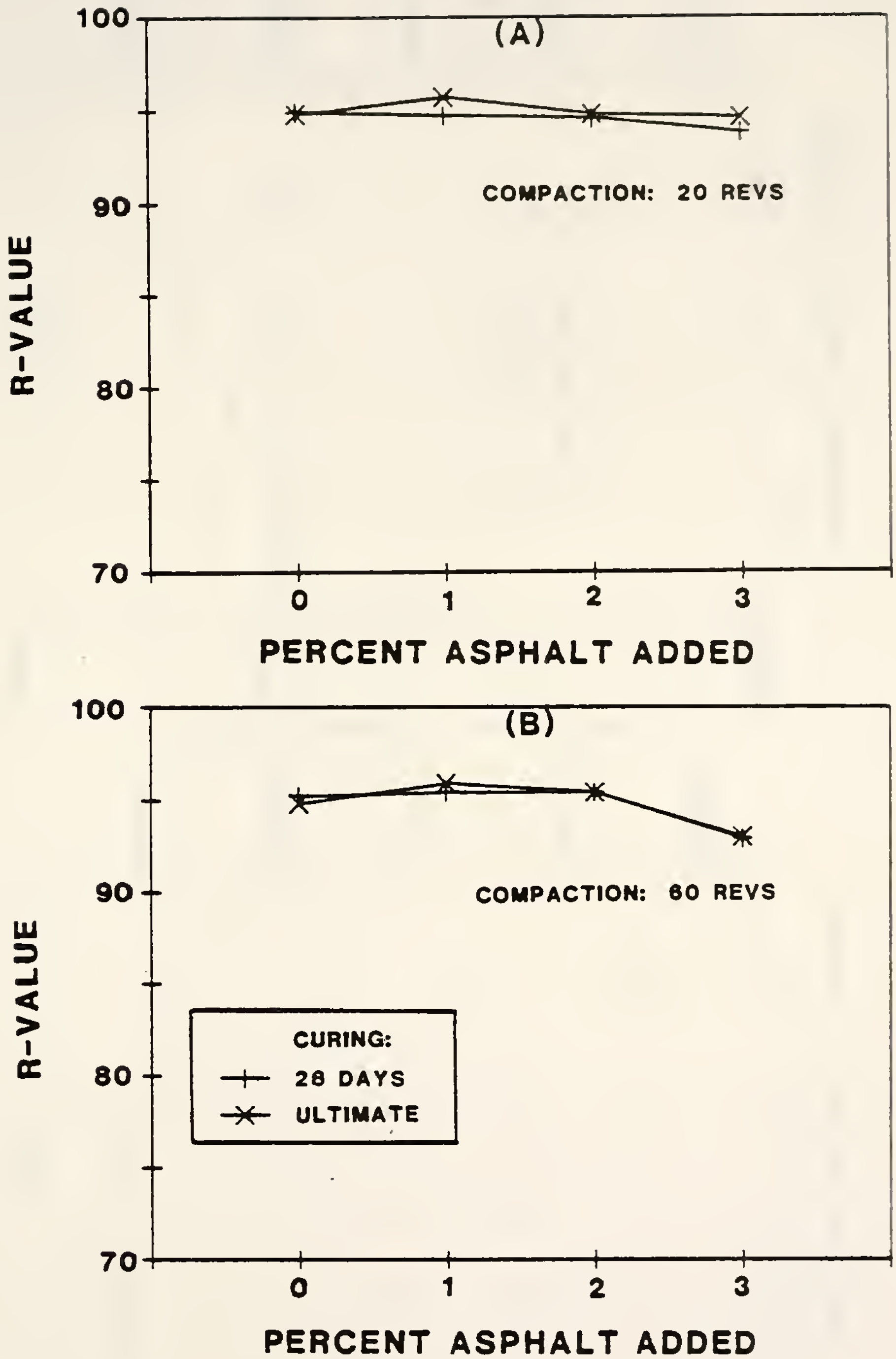


FIGURE 7.3 HVEEM R-VALUES OF ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.4)

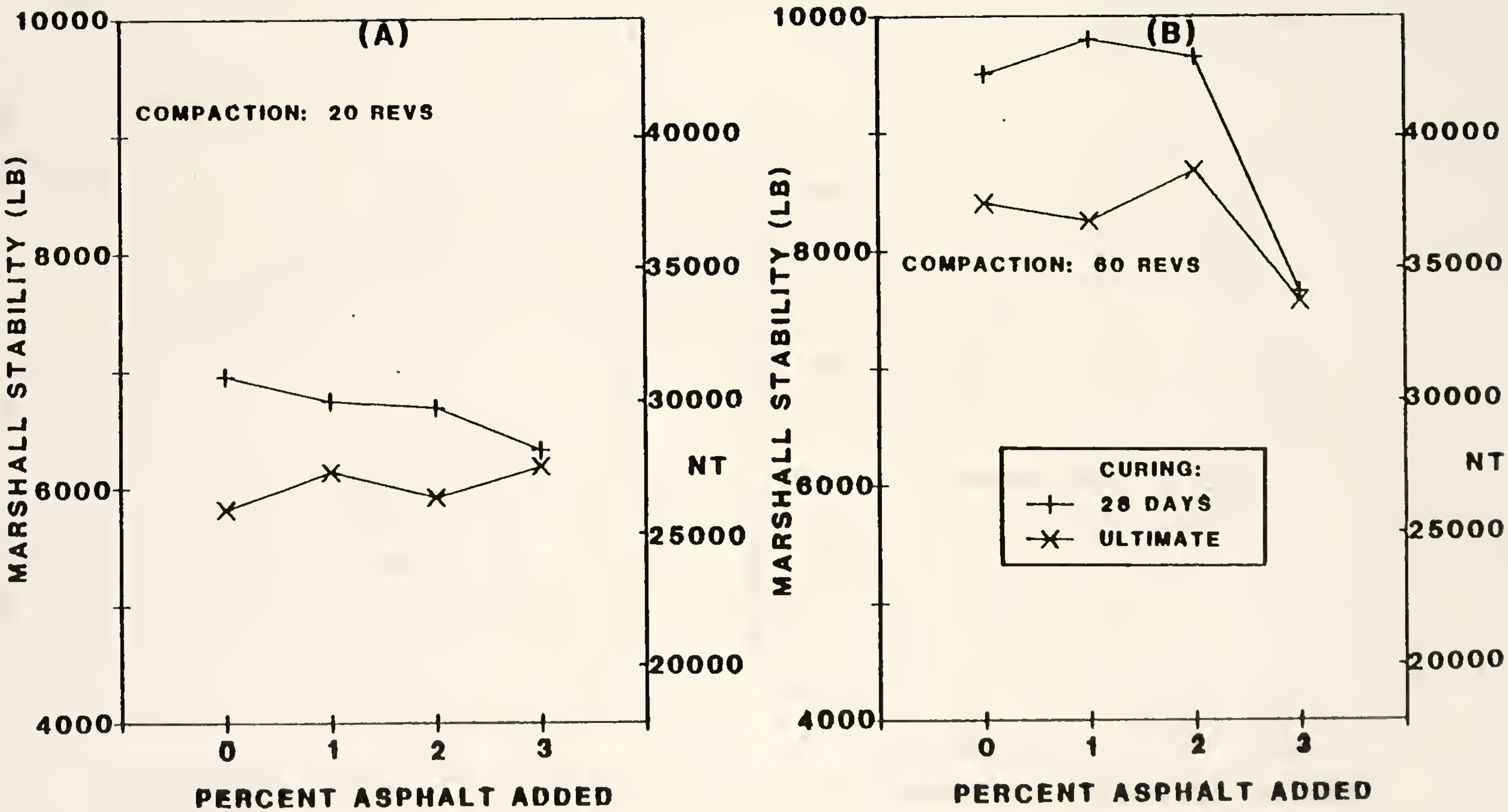


FIGURE 7.4 MARSHALL STABILITIES OF ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.4)

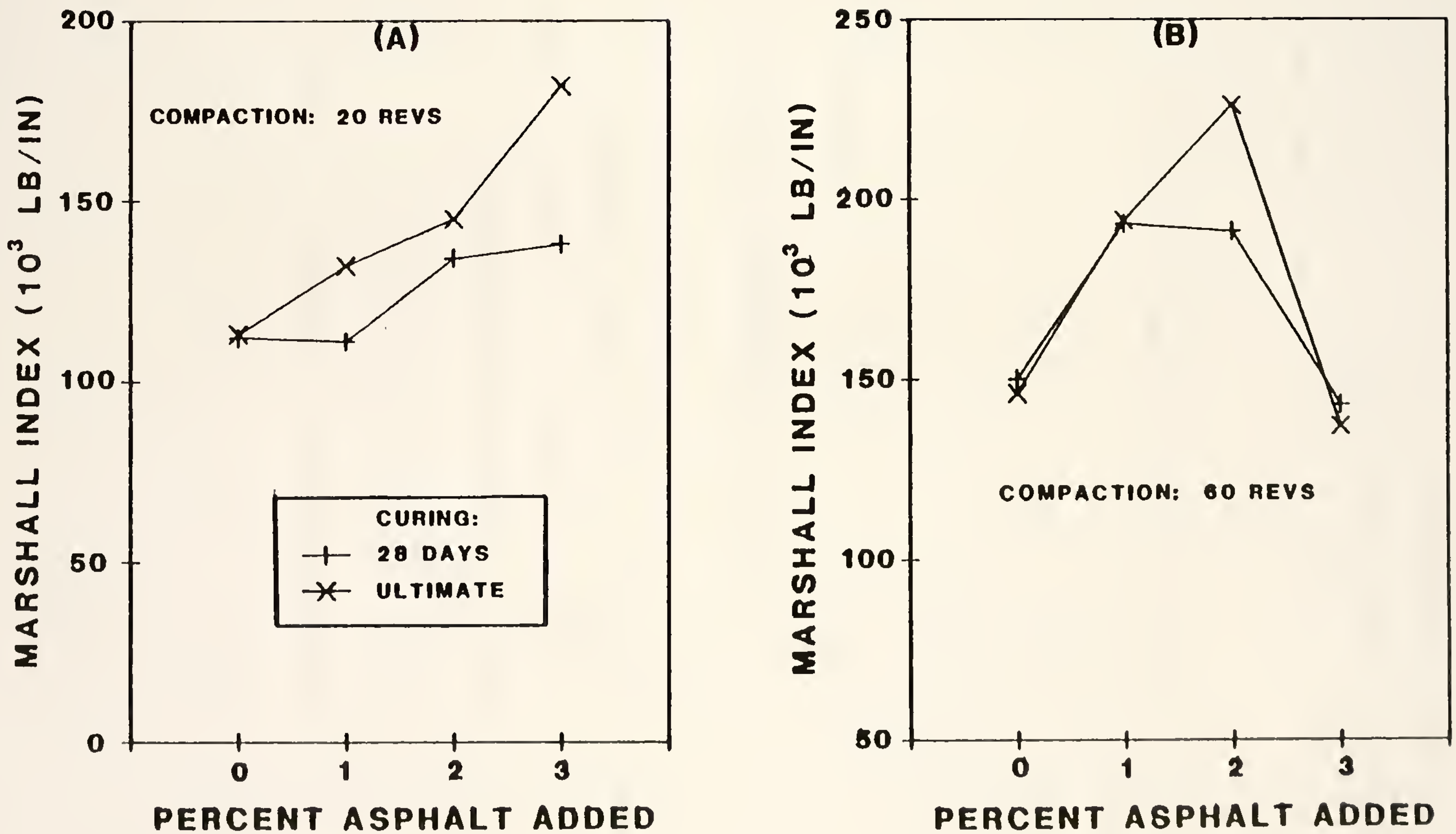


FIGURE 7.5 MARSHALL INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.4)

increased with percent asphalt added for the entire range considered. For high compactive effort (60 revs.), the maximum Marshall index was obtained when 1% to 2% of foamed asphalt was added. It can also be observed that higher compactive effort produced higher Marshall stability and index values.

7.2.3 Gyratory Indices

The gyratory indices for the mixes in design no. 4 are presented in Figure 7.6. It can be noted that the gyratory compactibility indices (GCIs) were insensitive to the changes in percent asphalt added. The stability index increased sharply with increasing binder content when asphalt added was above 2%. The elasto-plastic index increased with increasing percent asphalt added for the entire range.

7.3 Results of Experimental Design No. 5

7.3.1 Resilient Modulus

The resilient moduli of the recycled mixes in design no. 5 are depicted in Figure 7.7 as functions of curing time, from 1 day to 28 days. It can be seen that the resilient modulus increased significantly with curing time from 1 day to 14 days and leveled off thereafter. This trend is similar to that observed in design no. 4.

ANOVAs were performed on the data using the following model:

$$Y_{ijk} = \mu + P_i + S(P)_{(i)j} + \delta_{(ij)} + C_k + PC_{ik} + \varepsilon_{(ijk)}$$

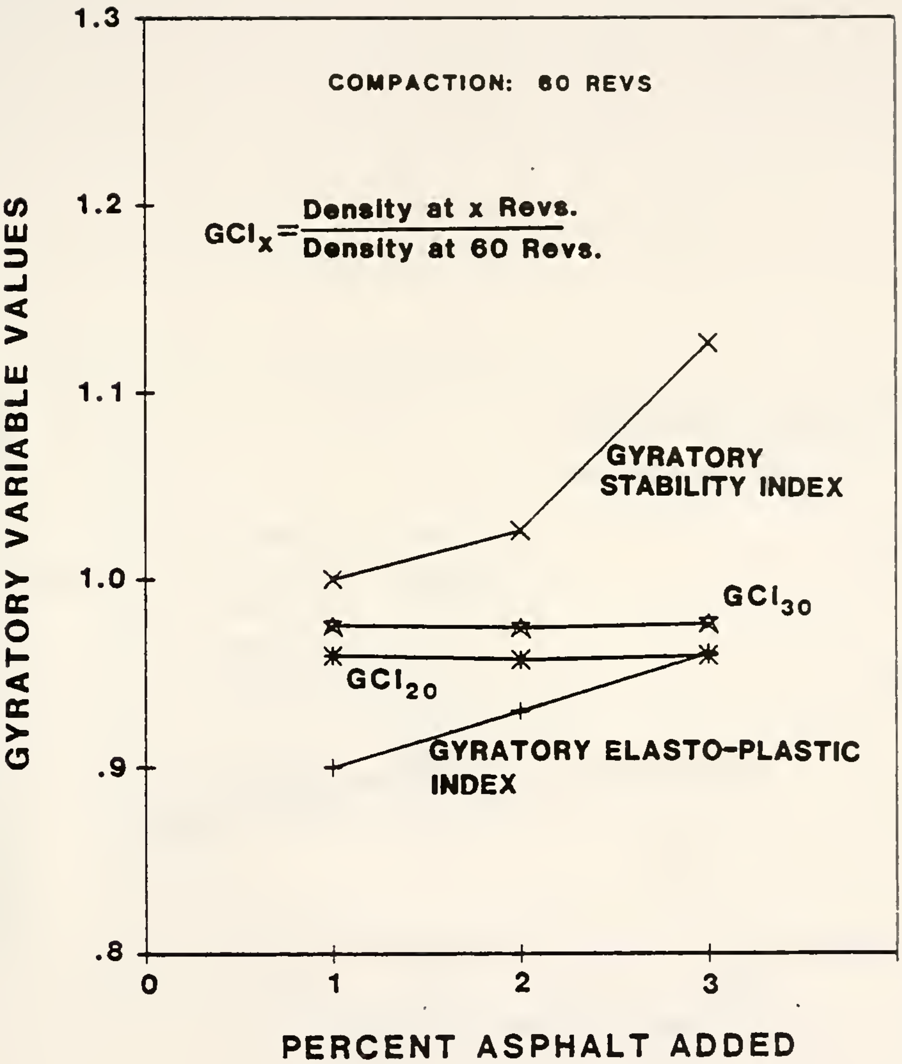


FIGURE 7.6 GYRATORY INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.4)

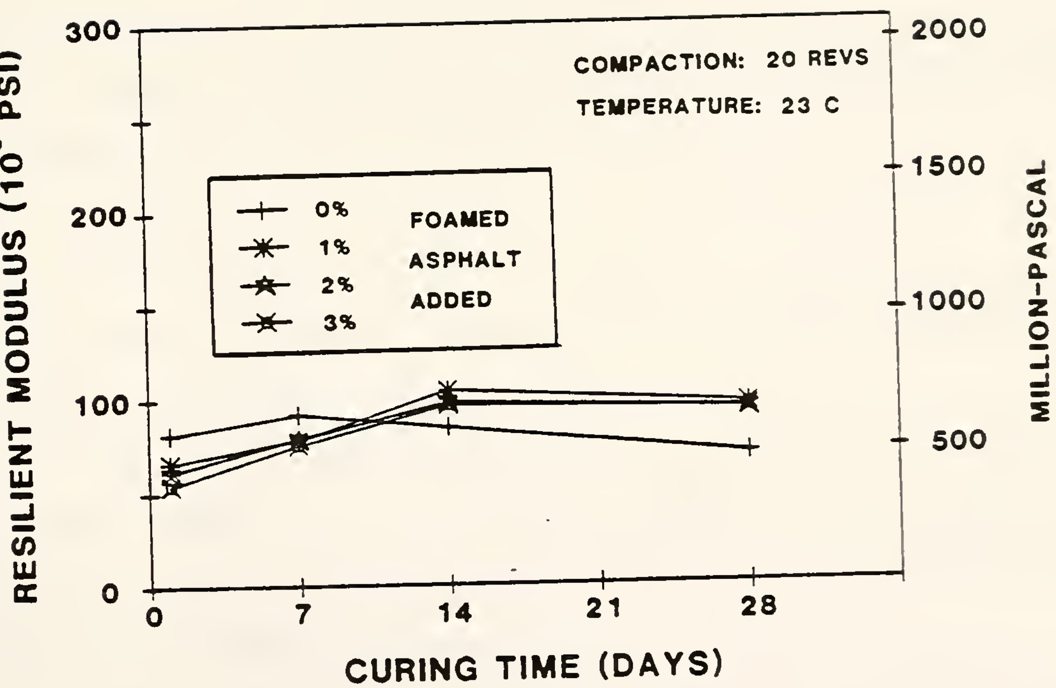


FIGURE 7.7 EFFECTS OF CURING ON THE RESILIENT MODULI OF OLD PAVEMENT MATERIAL WITH FOAMED ASPHALT ADDED (DESIGN NO.5)

ANOVA was performed on the data for curing times of 1 day to 28 days. The results are displayed in Table 7.3. The ANOVA results indicated that the curing time was a significant factor.

Figure 7.8 presents the resilient moduli at ultimate curing as functions of percent asphalt added. The resilient modulus did not vary much with the changes in percent asphalt added. However, it can be observed that the maximum resilient modulus occurred at around 1% asphalt added.

7.3.2 Hveem R-Value and Marshall Variables

ANOVAs were performed on the Hveem R-Values and Marshall variables in design no. 5 using the following model:

$$Y_{ijk} = \mu + C_i + P_j + CP_{ij} + \varepsilon_{(ij)k}$$

This is a completely randomized design. The ANOVA results are presented in Table 7.4.

Figure 7.9 presents the Hveem R-values as functions of percent asphalt added. It can be observed that the R-value was relatively constant for levels of asphalt added from 0% to 2%, and decreased significantly when asphalt added was 3%.

Figure 7.10 presents the Marshall stabilities and indices as functions of percent asphalt added. It can be observed that the ultimately cured mixes had maximum Marshall stability and index at 1% asphalt added, and the 28 days cured mixes had maximum values at 2% asphalt added.

TABLE 7.3: ANOVA Results for the Resilient Modulus in Design No. 5

Factor	d.f.	S.S.	M.S.	F
P	2	155.1	77.6	.33
S(P)	3	705.9	235.3	
C	3	5625.6	1875.2	24.3*
CP	6	84.5	14.08	.18
ε	9	694.6	77.2	

* Significant at $\alpha = 0.05$

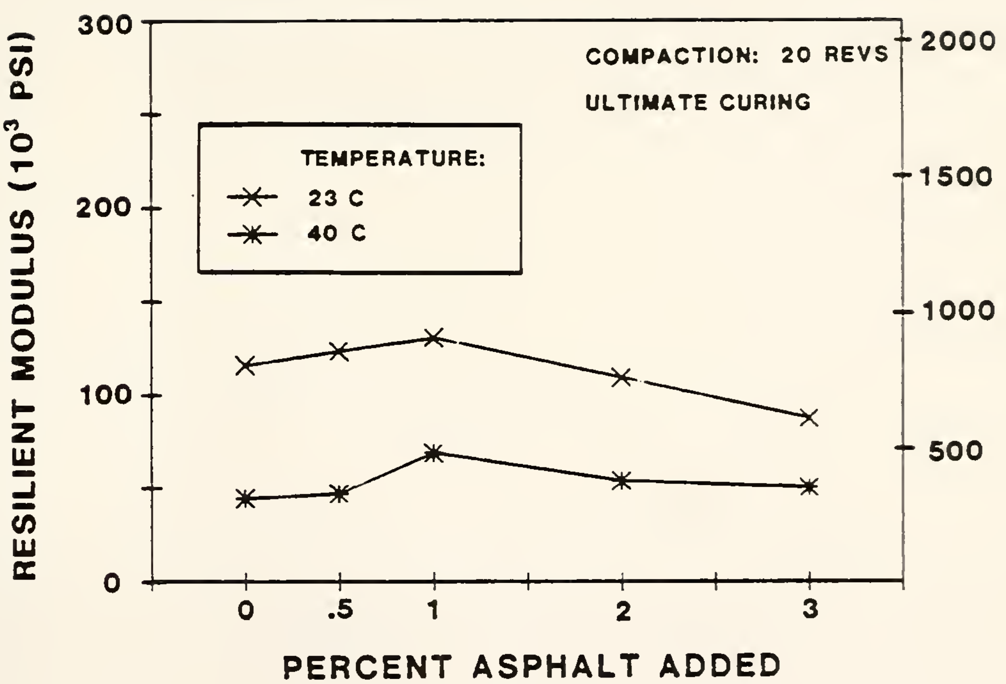


FIGURE 7.8 RESILIENT MODULI AT ULTIMATE CURING FOR OLD PAVEMENT MATERIAL WITH FOAMED ASPHALT ADDED (DESIGN NO.5)

TABLE 7.4: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 5

Source of Variation	Response Variable:	R-Value	S_M	I_M	F_M
C		S.	S.	S.	S.
P		S.	S.	S.	S.
CP		N.S.	S.	S.	N.S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$

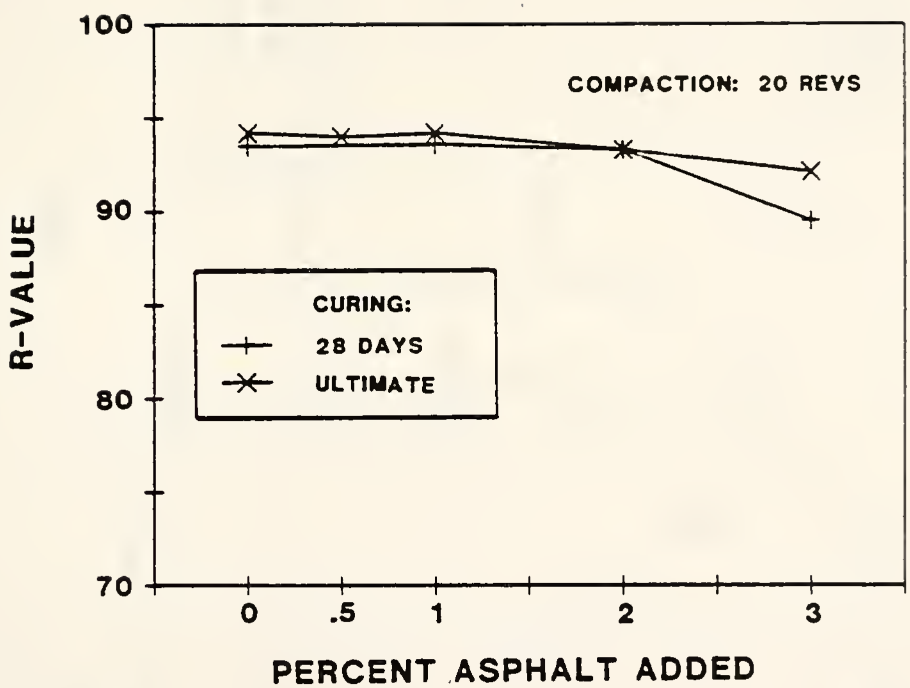


FIGURE 7.9 HVEEM R-VALUES OF OLD PAVEMENT MATERIAL WITH FOAMED ASPHALT ADDED (DESIGN NO.5)

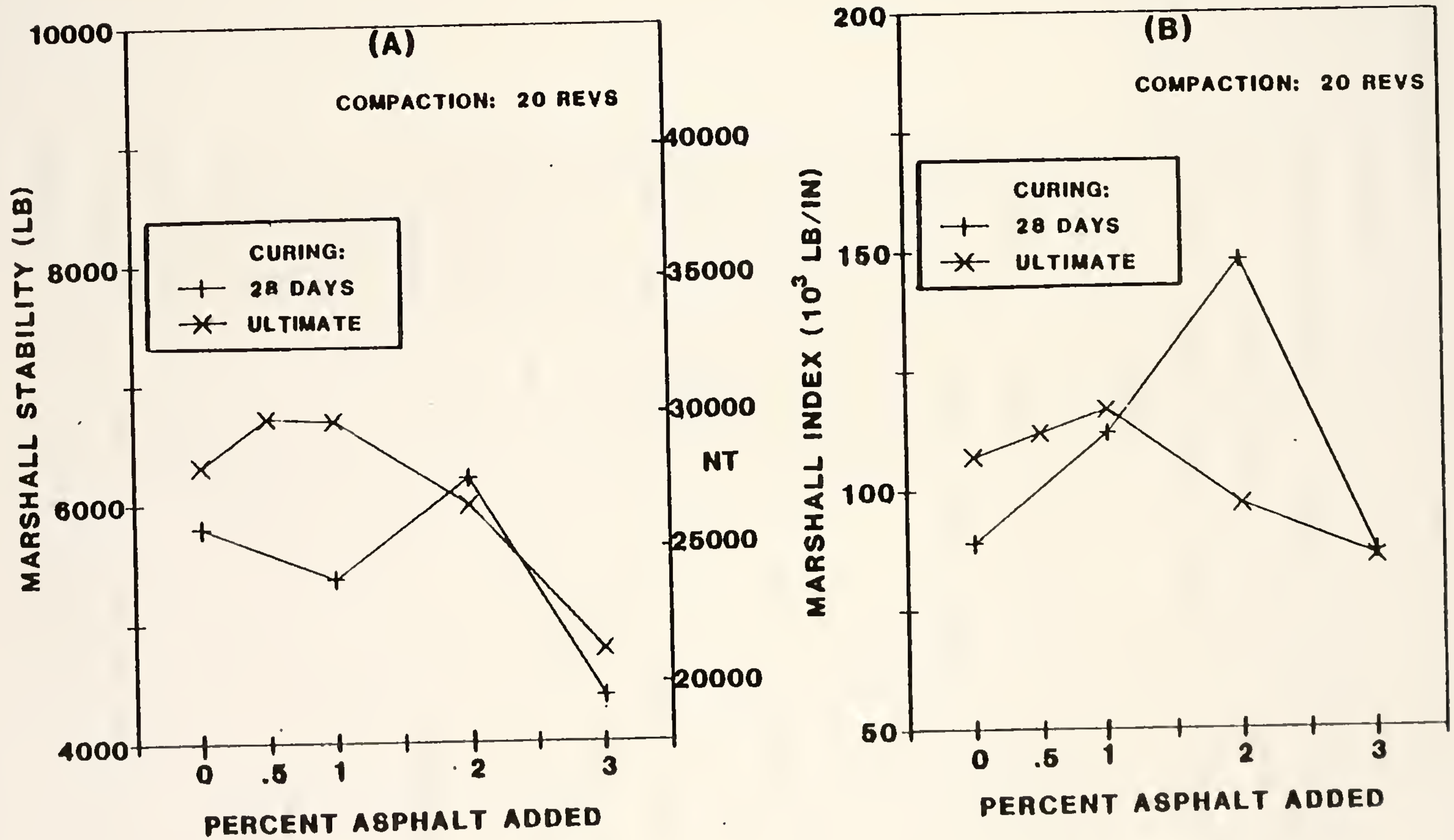


FIGURE 7.10 MARSHALL STABILITIES AND INDICES OF OLD PAVEMENT MATERIAL WITH FOAMED ASPHALT ADDED (DESIGN NO.5)

7.4 Summary of Results

The findings presented in this chapter, on the behavior of the recycled mixes with foamed asphalt as the added binder are summarized into the following points:

1. The resilient modulus increased significantly with curing time in the first 14 days, and leveled off after 14 days.
2. The level of foamed asphalt added had significant effect on the resilient modulus.
3. At low compactive effort, the Hveem R-values and Marshall variables were relatively insensitive to the changes in percent asphalt added. A high compactive effort was needed for these variables to be responsive to the changes in percent asphalt added.
4. The optimum level of asphalt added increased as the testing temperature decreased.
5. Higher compactive effort generally produced higher resilient modulus, Marshall stability and index. When the binder content was too high, higher compactive effort produced lower R-values.
6. The gyratory stability index increased significantly as the binder content was above the optimum level.
7. For the range of binder content considered, the gyratory elasto-plastic index increased with increasing level of asphalt added.
8. The gyratory compactibility index was insensitive to the changes in binder content of the mixes.

9. The difference between 28 days curing and ultimate curing was significant for these mixes.

CHAPTER 8

RECYCLED MIXTURES WITH REJUVENATING AGENT ADDED

8.1 Introduction

This chapter presents the results of Designs 6 and 7, which dealt with the behavior of the recycled mixtures with the addition of rejuvenating agents. In Design 6 (shown in Table 4.7), three rejuvenating agents (namely, Reclamite, Mobilsol and DUTREX 739) were used as the added binders to an artificially aged paving mixture. In Design 7 (shown in Table 4.8), one rejuvenating agent (Reclamite) was used as the added binder to an old pavement material.

The general laboratory procedure described in Chapter 5 was used to prepare and to test the recycled mixes. When Reclamite and Mobilsol (which were in emulsion form) were used, one percent water (by weight of the aggregate) was added to the mixture before the addition of the rejuvenating agent. When DUTREX 739 (which was in the form of a heavy oil) was used, no water was added to the mix. The method of analysis on the obtained data was similar to that presented in Chapter 6.

8.2 Results of Experimental Design No. 6

8.2.1 Resilient Modulus

The resilient moduli of the recycled mixes in design no. 6 were analyzed with the aid of the ANOVA statistical method. The statistical model used was as follows:

$$Y_{ijk\ell mn} = \mu + B_i + P_j + R_k + BP_{ij} + BR_{ik} + PR_{jk}$$

$$+ BPR_{ijk} + S(B\text{-}P\text{-}R)_{(ijk)\ell} + \delta_{(ijk\ell)} + C_m + T_n$$

$$+ BC_{im} + PC_{jm} + RC_{km} + BT_{in} + PT_{jn} + RT_{kT}$$

$$+ CT_{mn} + \varepsilon_{(ijk\ell mn)}$$

where $Y_{ijk\ell mn}$ = Response variable

μ = Overall mean of response variable

B_i = Effect of type of binder/agent

P_j = Effect of percent agent added

R_k = Effect of compactive effort

c_m = Effect of curing time

T_n = Effect of testing temperature

$S(B\text{-}P\text{-}R)$ = Within error of B-P-R combinations

δ = restriction error

BP_{ij}, BR_{ik}, ... CT_{mn} = Effects of interaction terms

$\varepsilon_{(ijk\ell mn)}$ = Experimental error + interaction of three or more factors.

ANOVA was performed on the data for curing times of 1 day to 28 days. The results are presented in Table 8.1.

Figure 8.1 presents the resilient moduli of the recycled mixes with Reclamite added as functions of curing time, from 1 day to 28 days. It can be observed that the resilient modulus generally increased with curing time. This was due to the increase in stiffness of the binder as the water in the Reclamite emulsion continued to evaporate.

TABLE 8.1: ANOVA RESULTS FOR THE RESILIENT MODULUS IN DESIGN NO. 6

Factor	d.f.	S.S.	M.S.	F
B	2	1.4	.70	.59
P	1	57.96	57.96	49.1*
R	1	36.92	36.92	31.3*
BP	2	4.74	2.37	2.0
BR	2	3.32	1.66	1.4
PR	1	1.57	1.57	1.3
BPR	2	4.00	2.00	1.7
S(B-P-R)	12	14.16	1.18	
C	3	51.23	17.08	30.3*
T	1	464.10	464.10	822.*
CB	6	10.71	1.78	3.2*
CP	3	2.81	.94	1.7
CR	3	1.99	.66	1.2
TB	2	1.66	.83	1.5
TP	1	10.01	10.01	17.7*
TR	1	9.66	9.66	17.1*
CT	3	21.31	7.10	12.6*
ε	145	81.82	.56	

* Significant at $\alpha = 0.05$

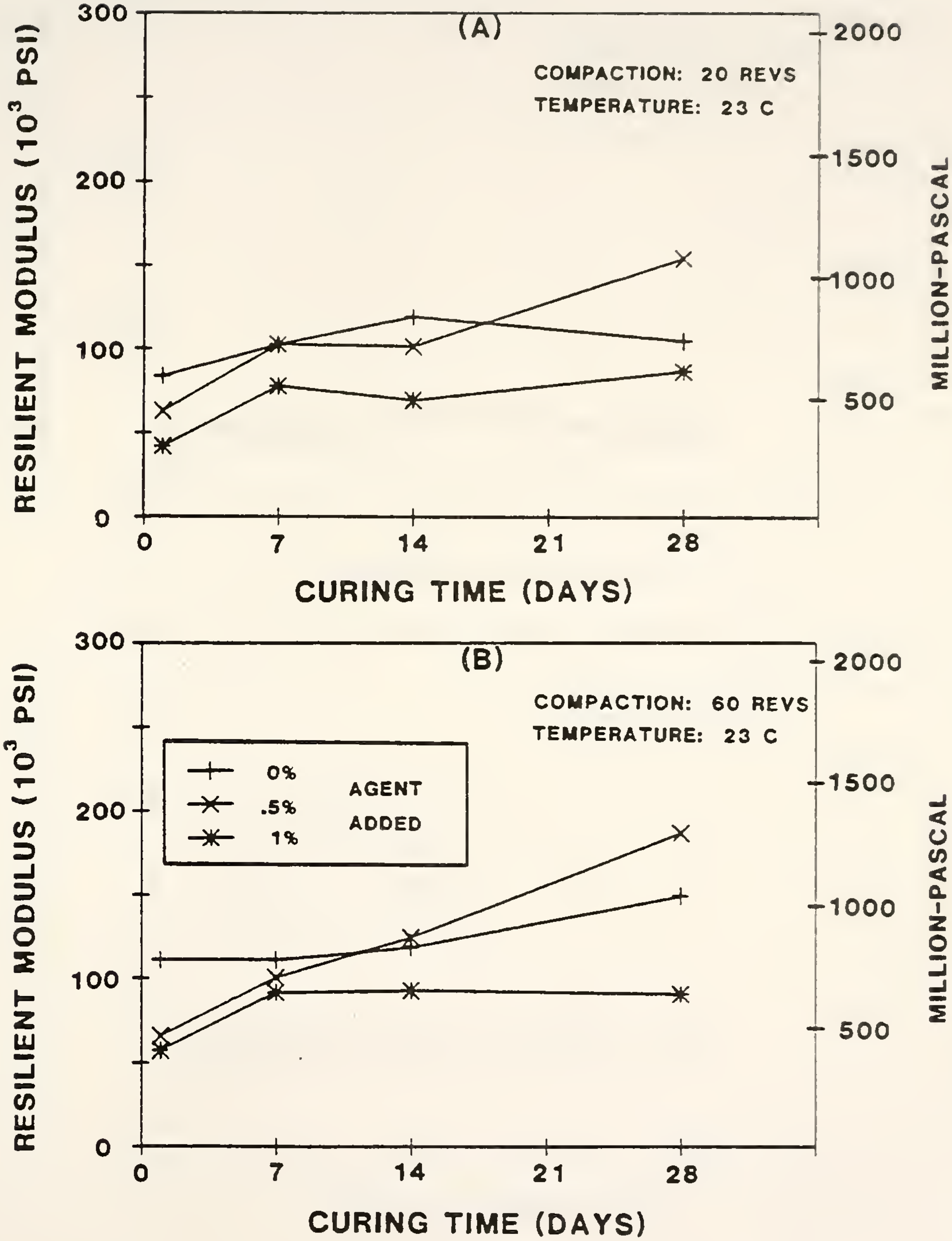


FIGURE 8.1 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF ARTIFICIALLY AGED PAVING MIXTURES WITH RECLAMITE ADDED (DESIGN NO.6)

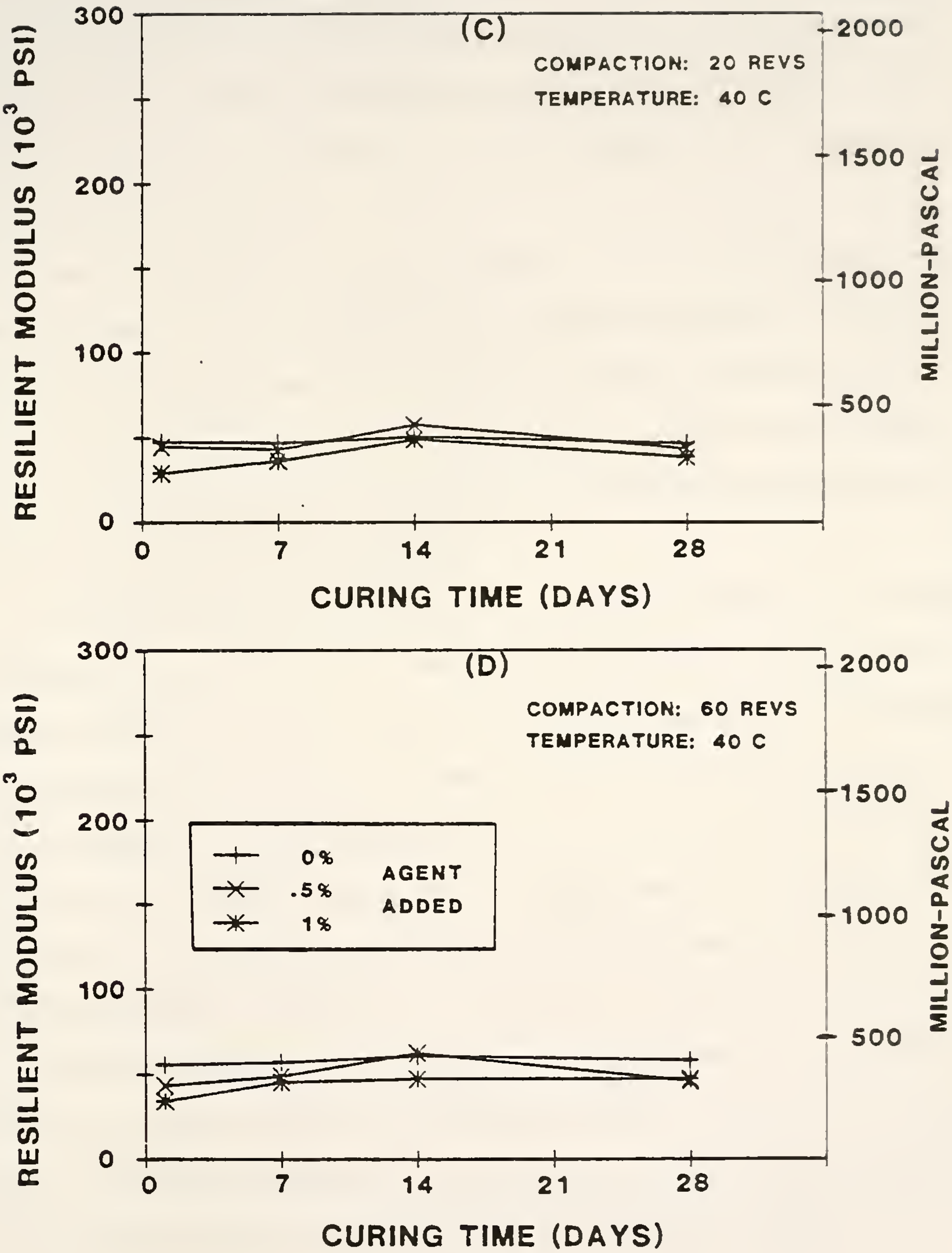


FIGURE 8.1 (Continued)

Figure 8.2 presents the resilient moduli of the recycled mixes with Mobilsol added. It can be noted that the resilient modulus increased significantly with curing time from 1 day to 14 days and leveled off thereafter. Similarly, this was due to the evaporation of the water from the Mobilsol emulsion.

Figure 8.3 presents the resilient moduli of the recycled mixes with DUTREX 739 added. It can be seen that the resilient modulus generally increased with curing time from 1 day to 14 days and leveled off thereafter. The rejuvenating agent, DUTREX 739, was in the form of a heavy oil. The stiffening of the binder might be caused by the evaporation of the volatile substance from the agent.

The resilient moduli of these mixes at ultimate curing are presented in Figures 8.4, 8.5 and 8.6. It can be observed that, for all cases, the optimum percent agent added increased as the testing temperature decreased. The comparison of the effects of these three rejuvenating agents are shown in Figure 8.7. Significant differences in resilient modulus can be observed at .5% agent added. At 1% agent added, the difference is not significant. It is also noted that the difference between 28 days curing and ultimate curing was not significant for the mixes with Reclamite or Mobilsol added. For the mixes with DUTREX added, the resilient moduli at ultimate curing was significantly higher than those at 28 days curing. This might be caused by the evaporation of the volatile substance from the agent during the heating process of ultimate curing.

8.2.2 Hveem R-Value and Marshall Variables

The Hveem R-values and Marshall variables measured at 28 days and ultimate curing were analyzed with the aid of the ANOVA statistical

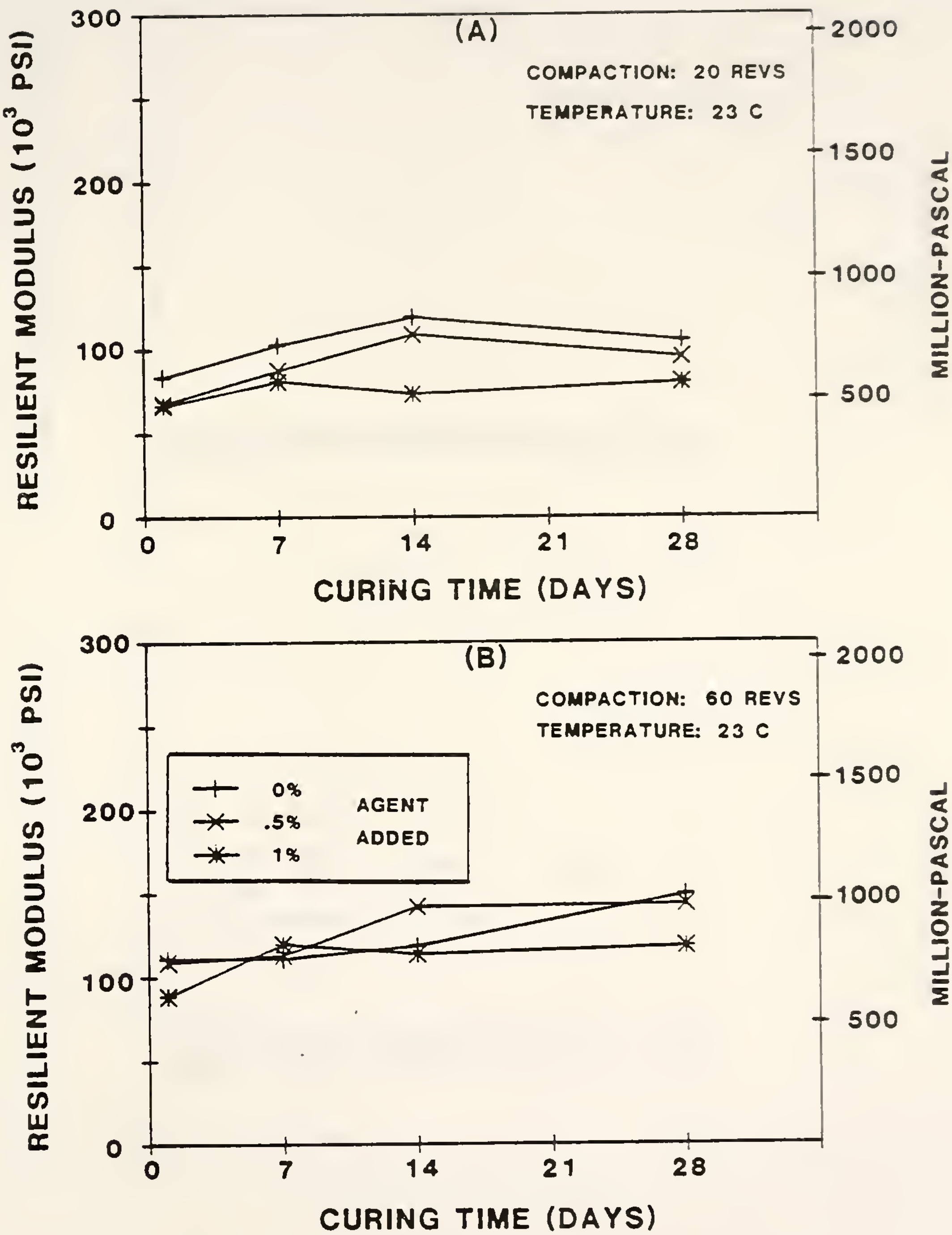


FIGURE 8.2 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF ARTIFICIALLY AGED PAVING MIXTURES WITH MOBILSOL ADDED (DESIGN NO.6)

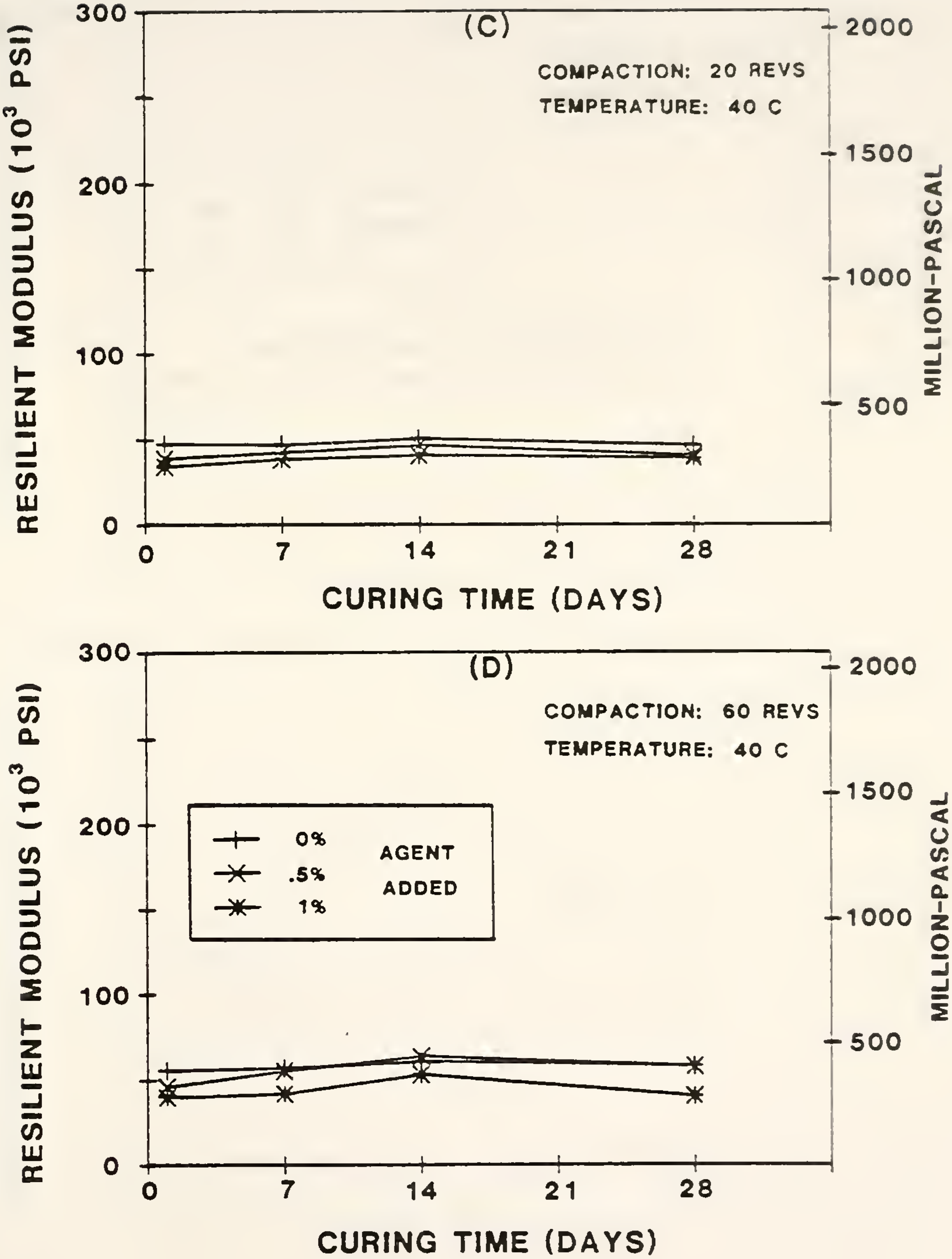
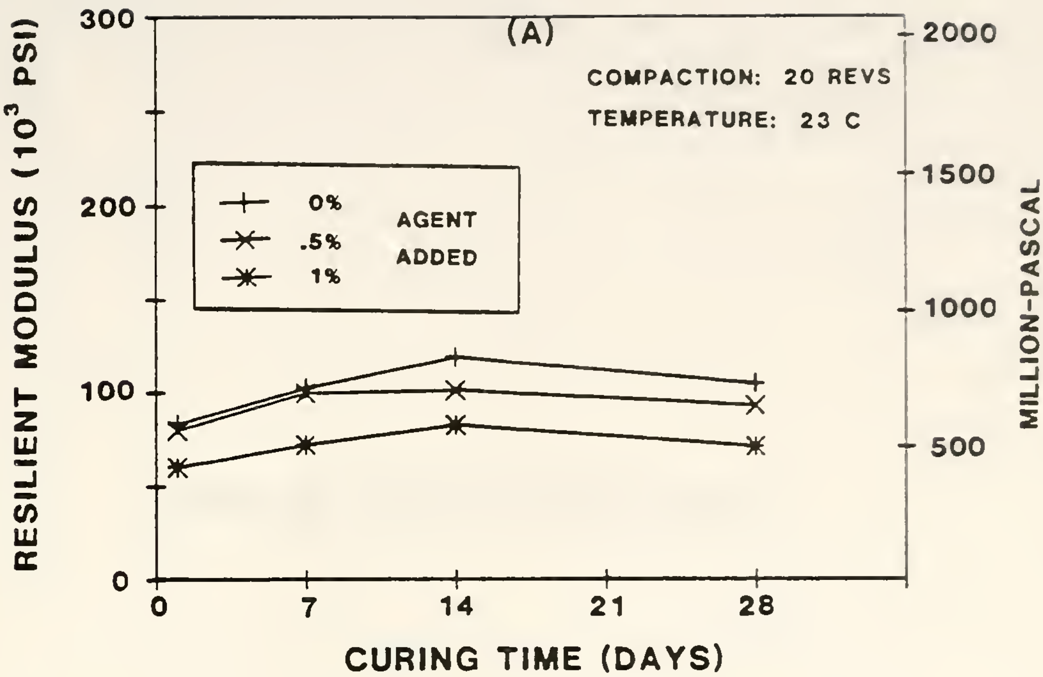


FIGURE 8.2 (Continued)



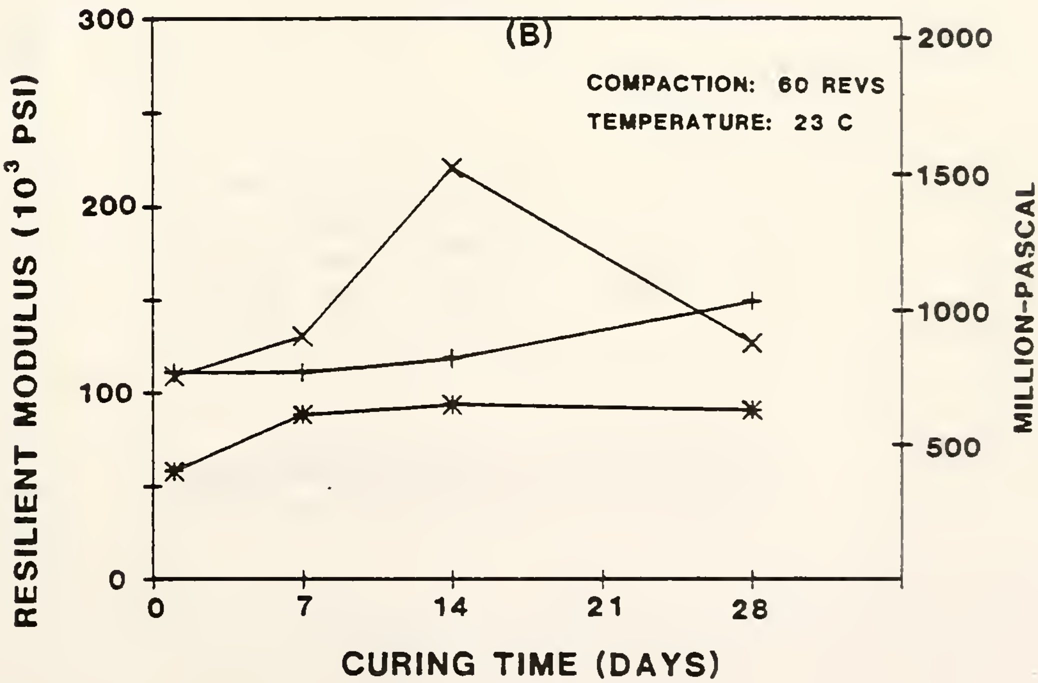
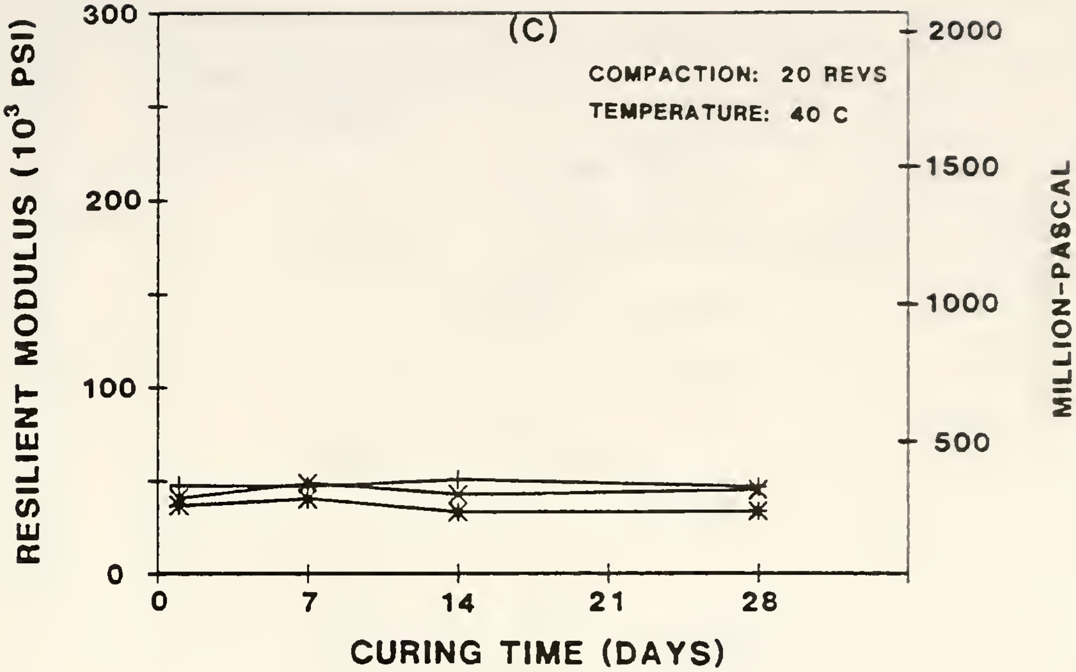


FIGURE 8.3 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF ARTIFICIALLY AGED PAVING MIXTURES WITH DUTREX 739 ADDED (DESIGN NO.6)



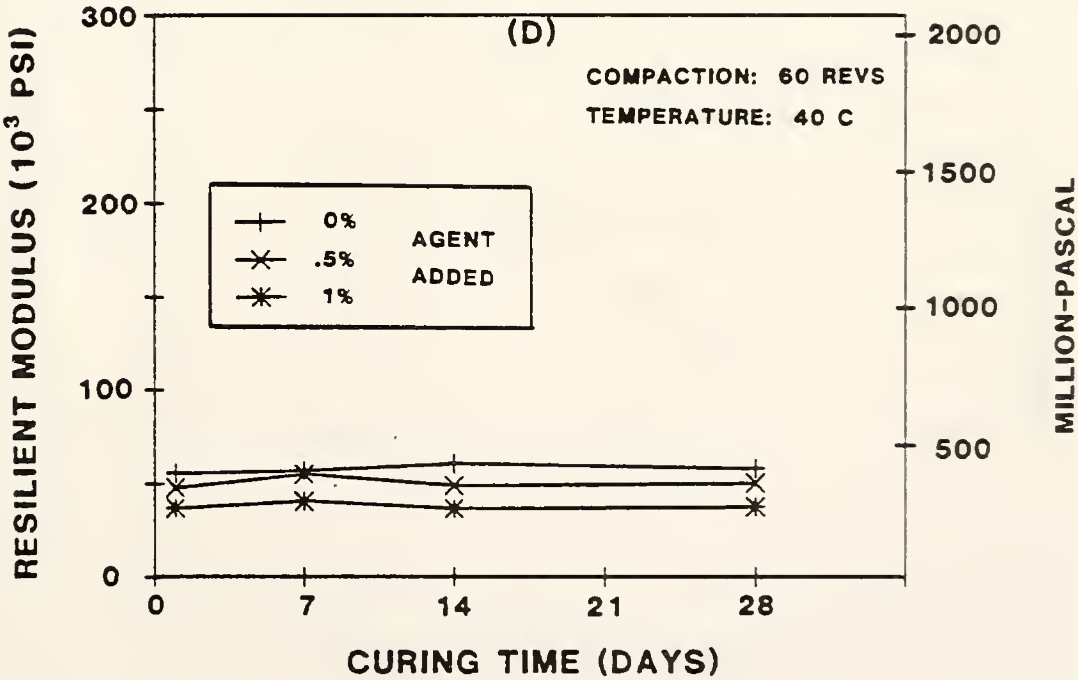


FIGURE 8.3 (Continued)

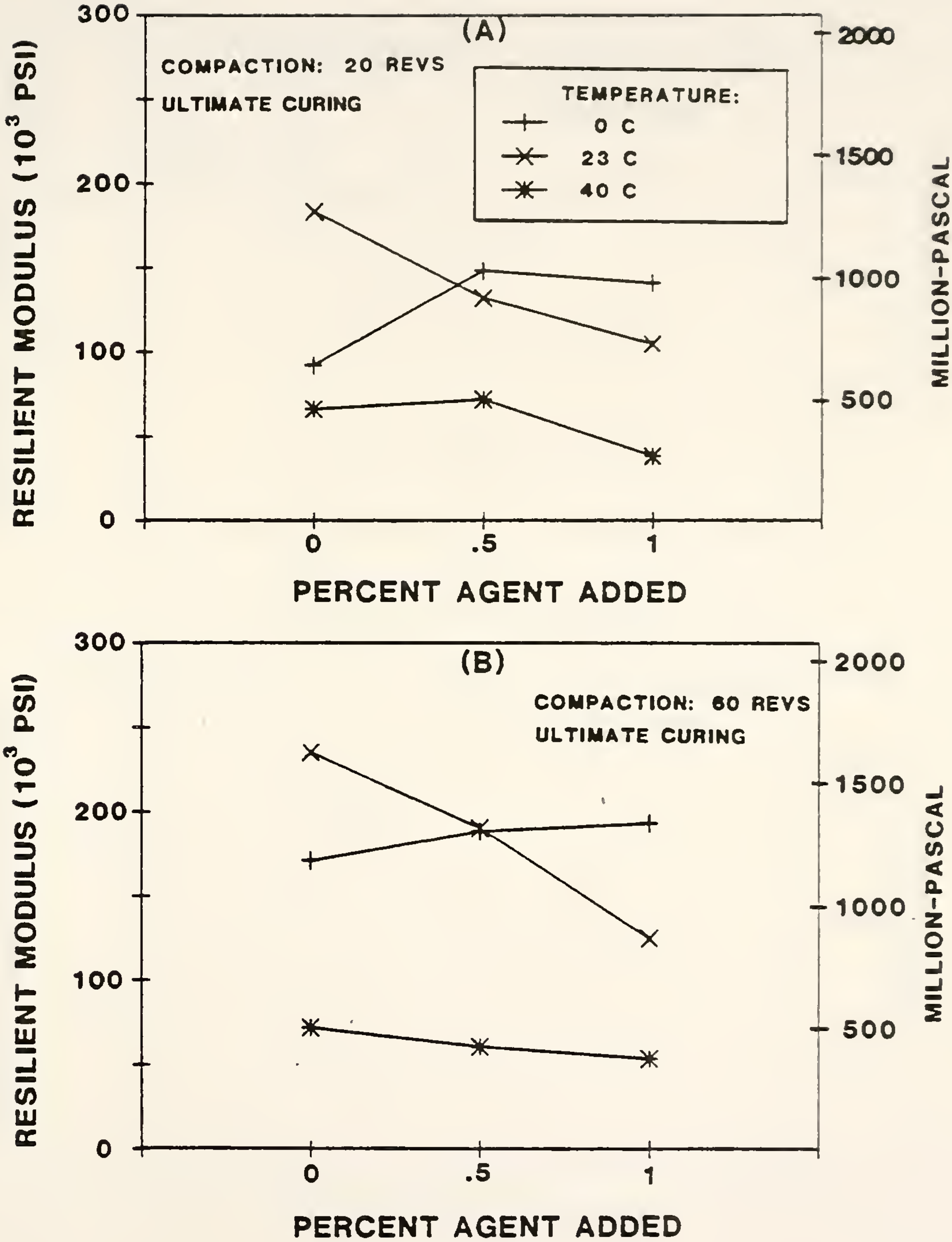


FIGURE 8.4 RESILIENT MODULI AT ULTIMATE CURING FOR ARTIFICIALLY AGED PAVING MIXTURES WITH RECLAMITE ADDED (DESIGN NO.6)

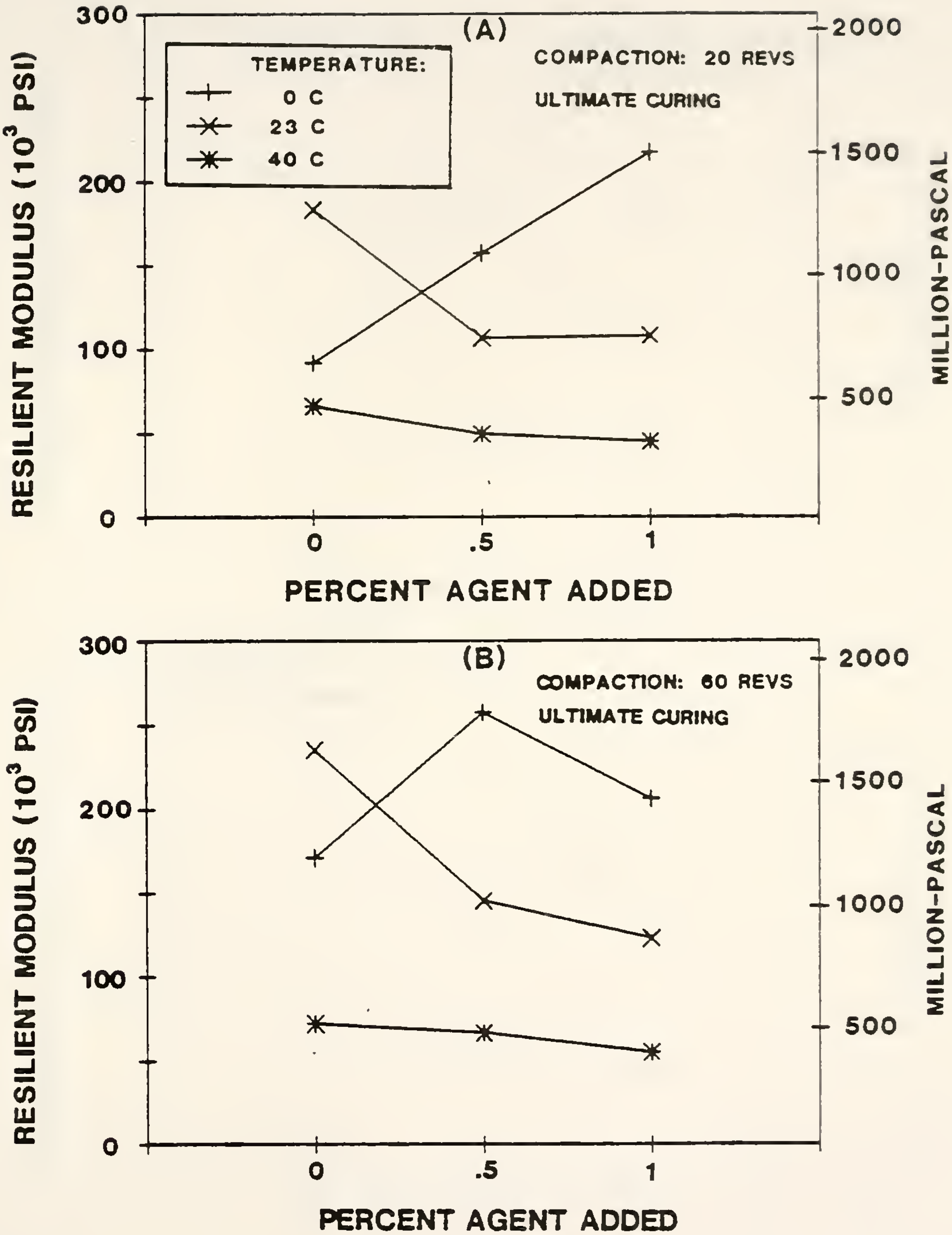
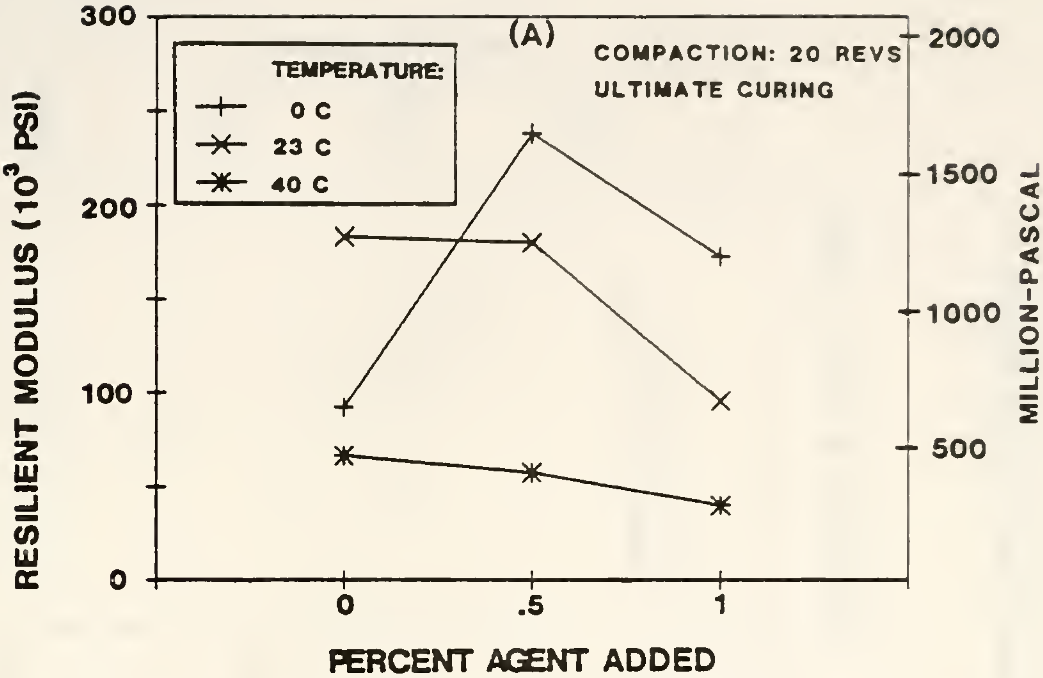


FIGURE 8.5 RESILIENT MODULI AT ULTIMATE CURING FOR ARTIFICIALLY AGED PAVING MIXTURES WITH MOBILSOL ADDED (DESIGN NO.6)



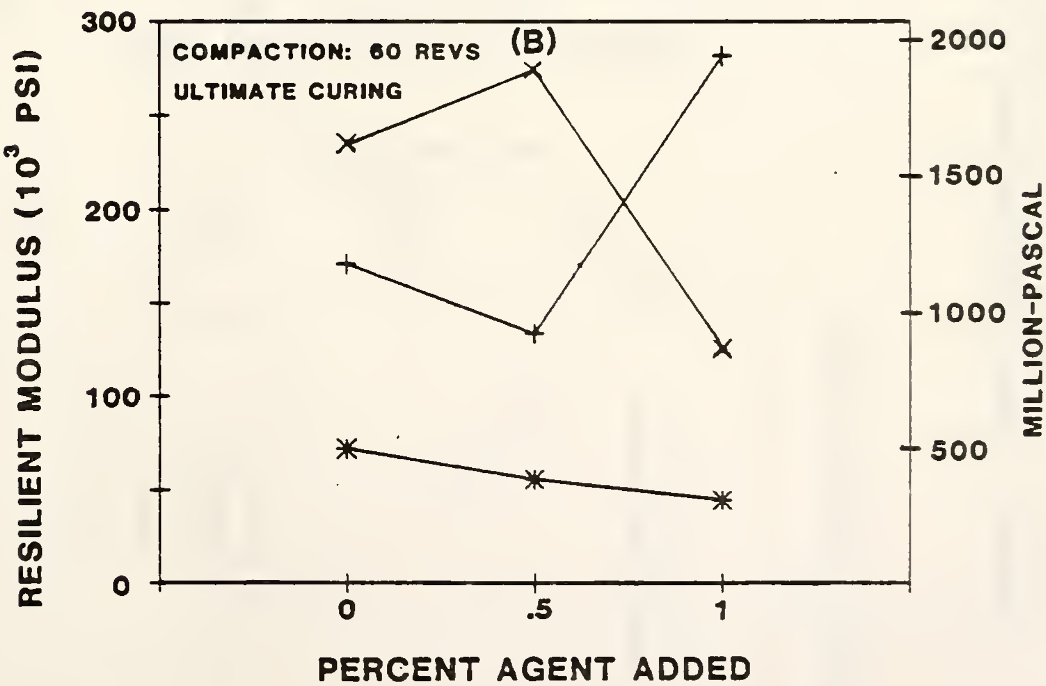


FIGURE 8.6 RESILIENT MODULI AT ULTIMATE CURING FOR ARTIFICIALLY AGED PAVING MIXTURES WITH DUTREX 739 ADDED (DESIGN NO.6)

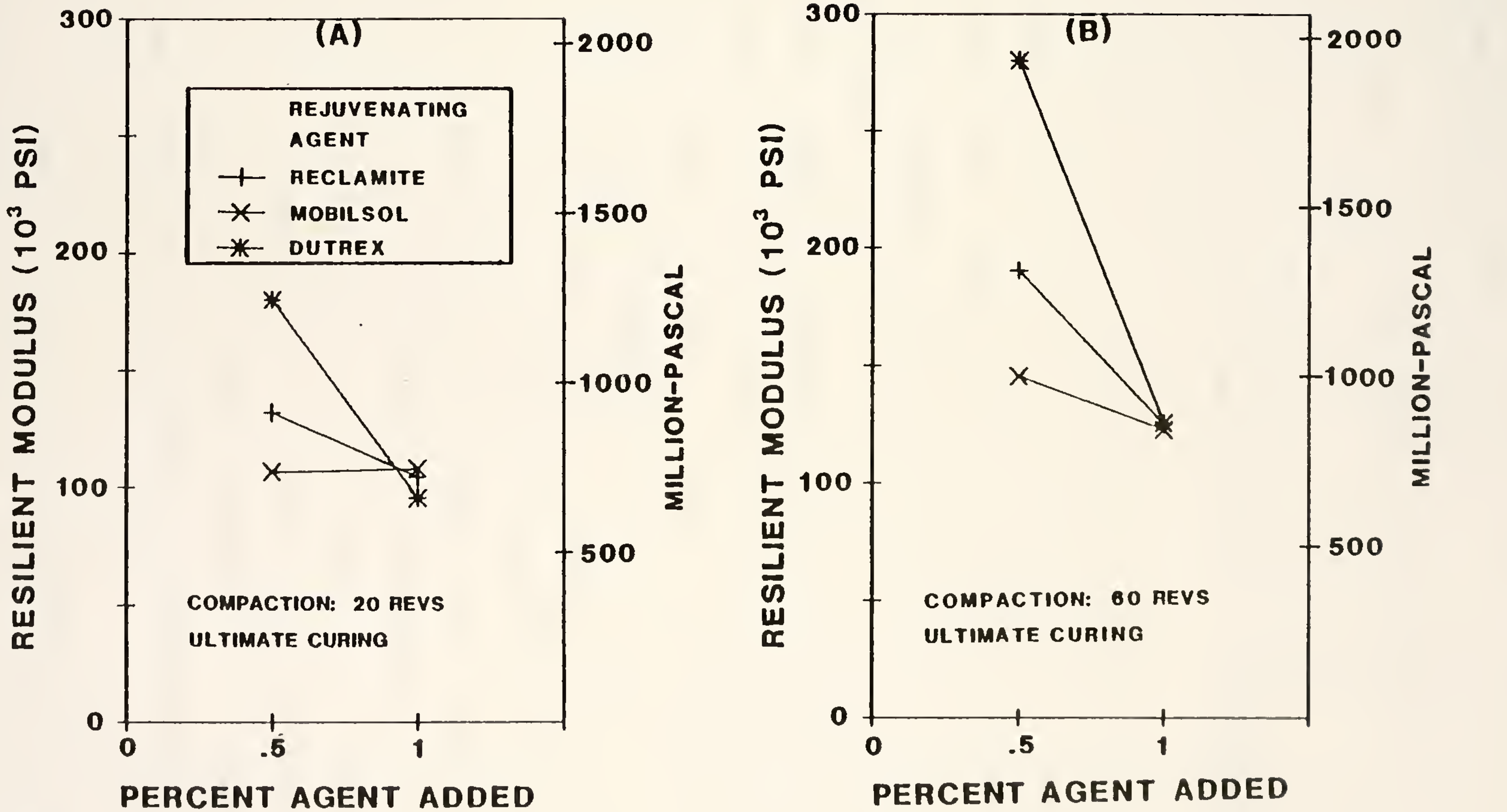


FIGURE 8.7 EFFECTS OF DIFFERENT REJUVENATING AGENTS ON THE RESILIENT MODULI OF RECYCLED MIXES IN DESIGN NO.6

method using the following model:

$$Y_{ijk\ell} = \mu + C_i + R_j + P_k + B_\ell + CR_{ij} + CP_{ik} + CB_{i\ell} + RP_{jk} + RB_{j\ell} + PB_{k\ell} + \varepsilon_{(ijk\ell)}$$

This is a completely randomized design. The ANOVA results are displayed in Table 8.2.

Figures 8.8, 8.9 and 8.10 present the Hveem R-values of the recycled mixes in design no. 6. It can be noted that the difference between 28 days curing and ultimate curing was not significant. R-values were generally lower at the lower compactive efforts. The optimum level of agent added was between 0% and .5%. The comparison of the effects of the three rejuvenating agents on the R-values are shown in Figure 8.11. It can be observed that their differences were greater at 1% level than at .5% level. The ANOVA result indicated that their differences were not significant.

The Marshall stabilities of the recycled mixes in desig no. 6 are presented in Figure 8.12, 8.13 and 8.14. It can be noted that the Marshall stability was generally higher at the higher compactive effort. The optimum level of agent added was between 0% and .5%. The difference between 28 days curing and ultimate curing was not significant, according to the ANOVA result. The comparison of the effects of these rejuvenating agents on the Marshall stabilities of the recycled mixes are shown in Figure 8.15. The ANOVA result indicated that their differences were insignificant.

The Marshall indices of these recycled mixes are presented in Figures 8.16, 8.17 and 8.18. It can be noted that the Marshall index

TABLE 8.2: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 6

Source of Variation	Response Variable:	R-Value	S_M	I_M	F_M
C		N.S.	N.S.	N.S.	N.S.
R		S.	S.	S.	N.S.
P		S.	S.	S.	S.
B		N.S.	N.S.	N.S.	S.
CR		N.S.	N.S.	N.S.	N.S.
CP		N.S.	N.S.	N.S.	N.S.
CB		N.S.	N.S.	N.S.	N.S.
RP		N.S.	N.S.	N.S.	N.S.
RB		N.S.	N.S.	N.S.	N.S.
PB		N.S.	N.S.	N.S.	N.S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$

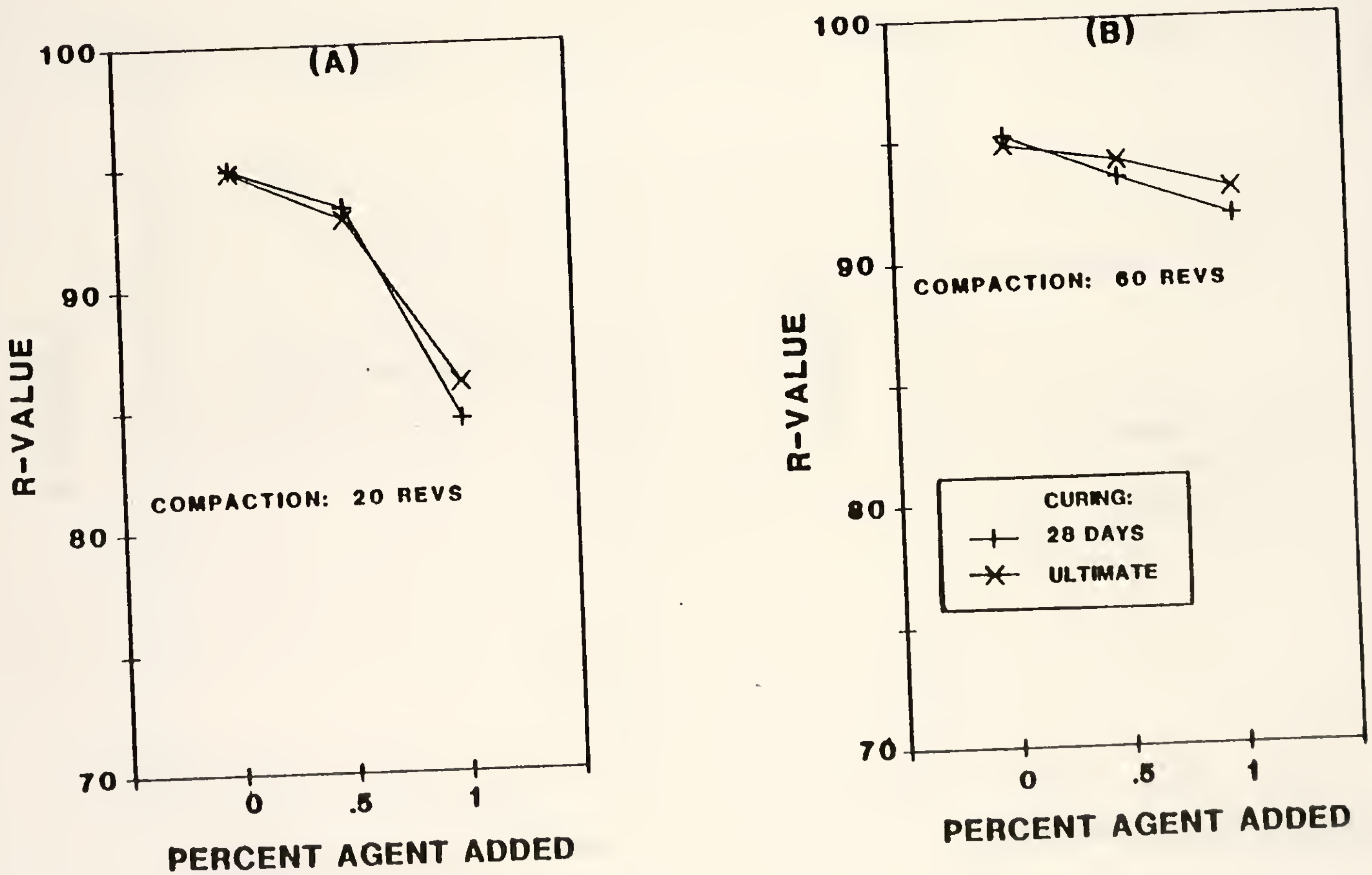


FIGURE 8.8 HVEEM R-VALUES OF ARTIFICIALLY AGED PAVING MIXTURES WITH RECLAMITE ADDED (DESIGN NO.6)

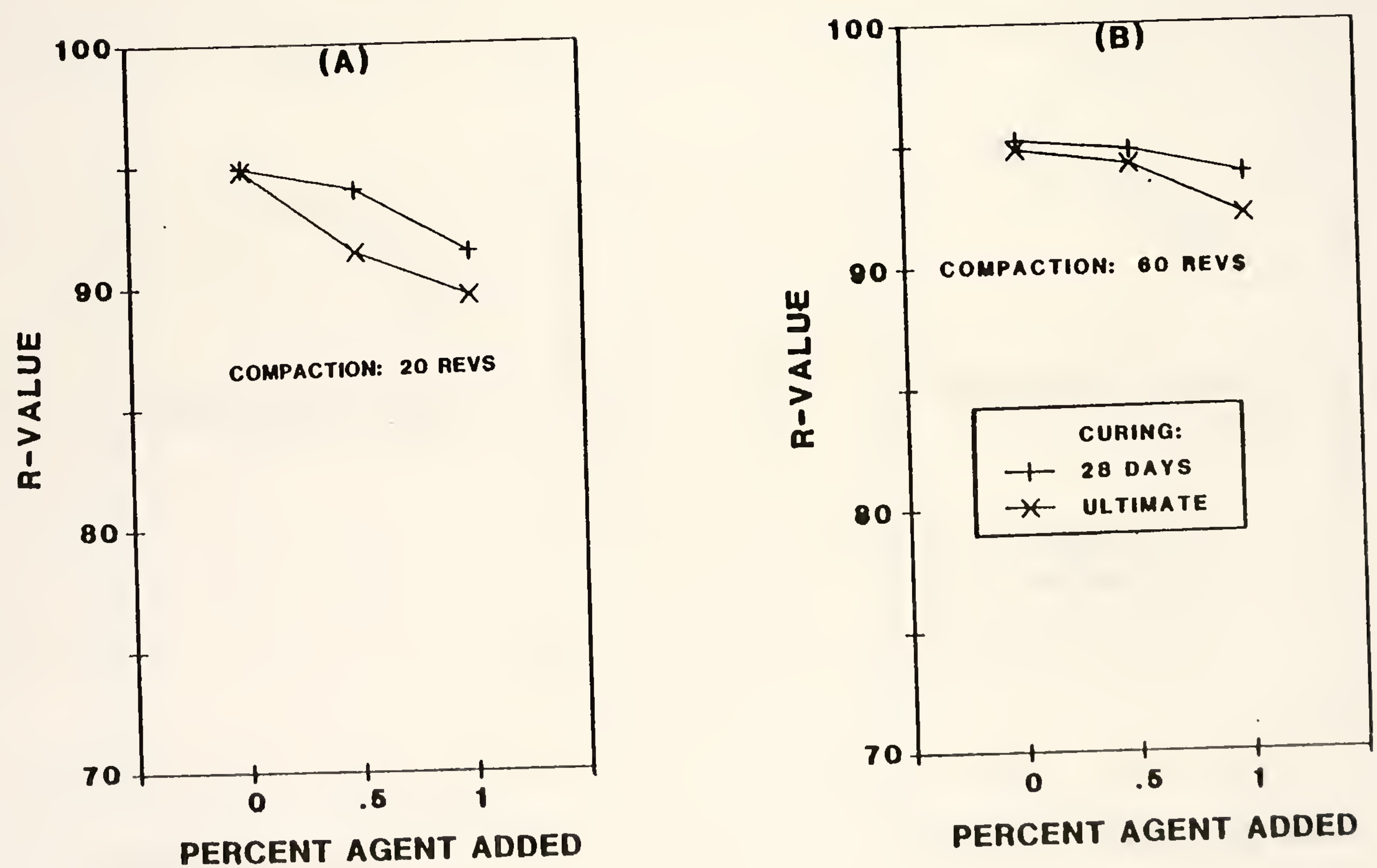


FIGURE 8.9 HVEEM R-VALUES OF ARTIFICIALLY AGED PAVING MIXTURES WITH MOBILSOL ADDED (DESIGN NO.6)

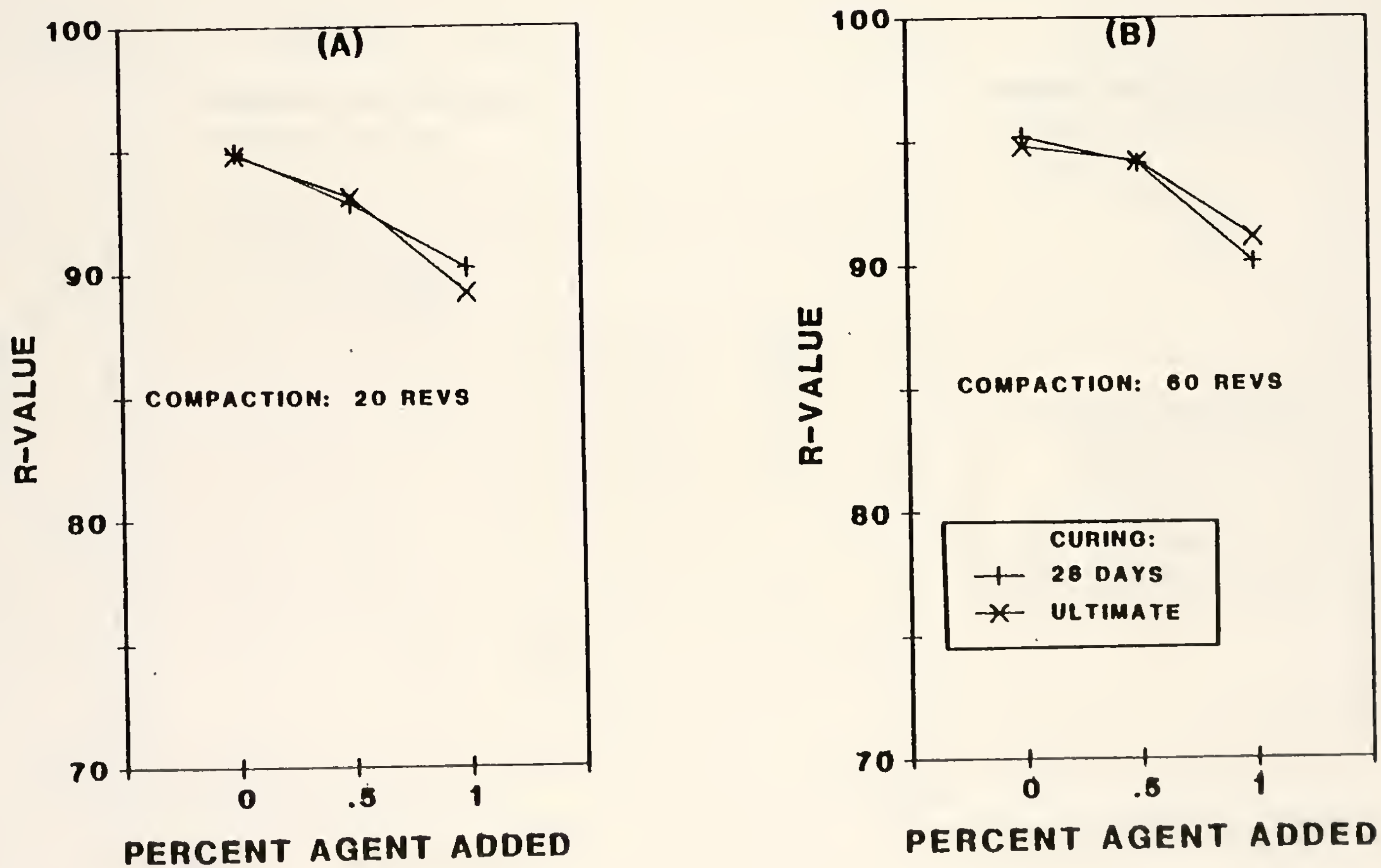


FIGURE 6.10 HVEEM R-VALUES OF ARTIFICIALLY AGED PAVING MIXTURES WITH DUTREX 739 ADDED (DESIGN NO.6)

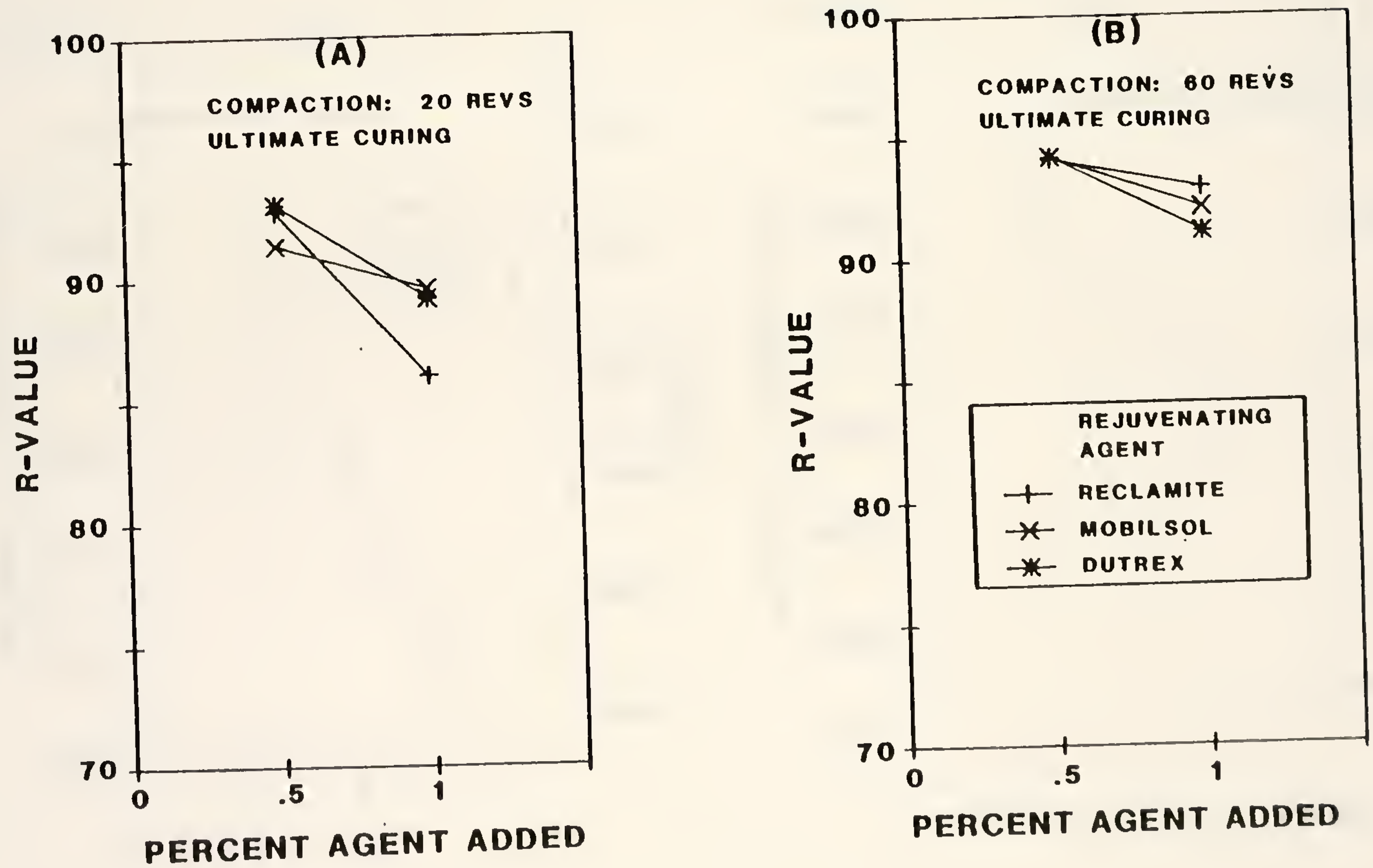


FIGURE 8.11 EFFECTS OF DIFFERENT REJUVENATING AGENTS ON THE HVEEM R-VALUES OF RECYCLED MIXES IN DESIGN NO.6

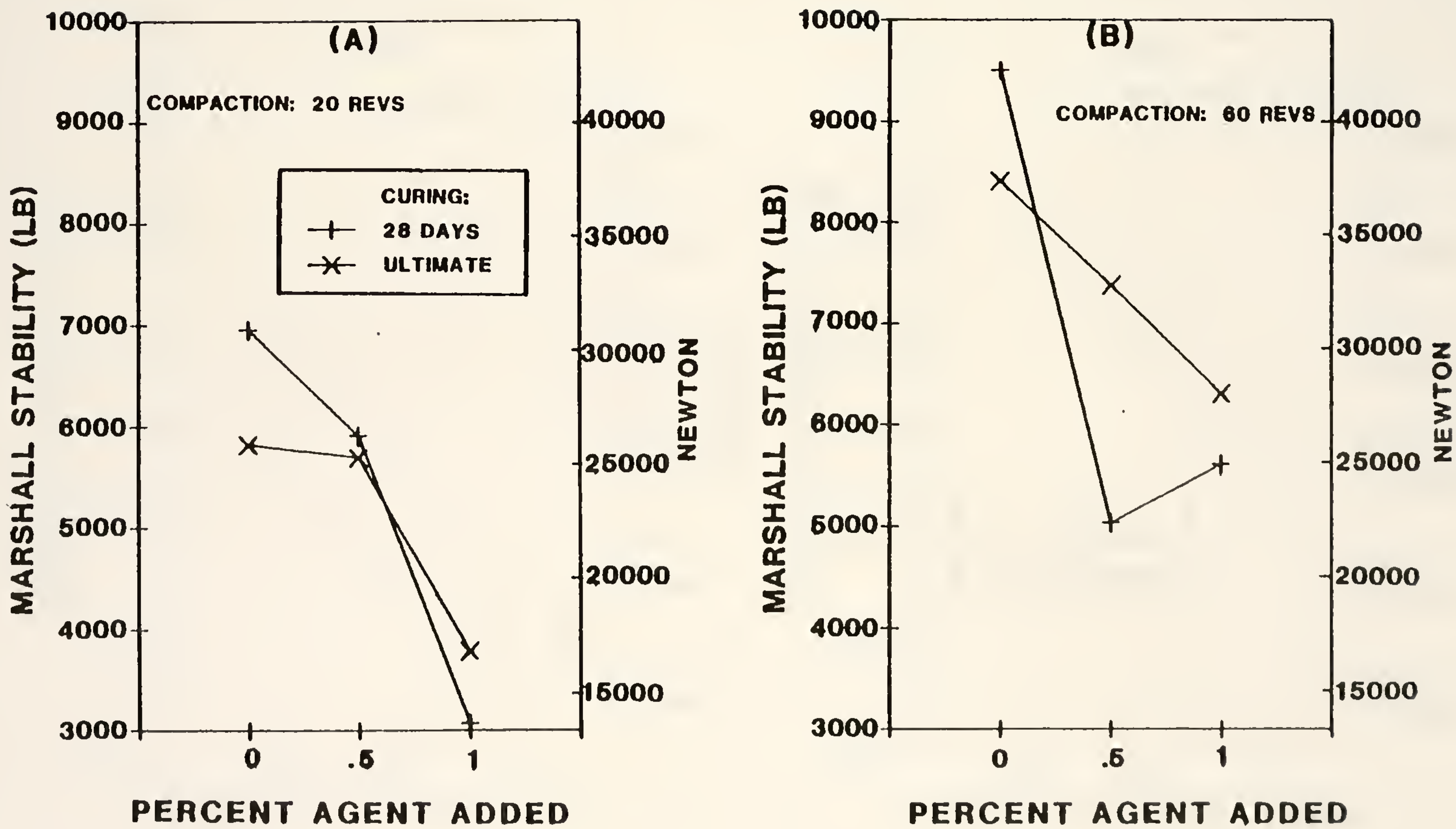


FIGURE 8.12 MARSHALL STABILITIES OF ARTIFICIALLY AGED PAVING MIXTURES WITH RECLAMITE ADDED (DESIGN NO.6)

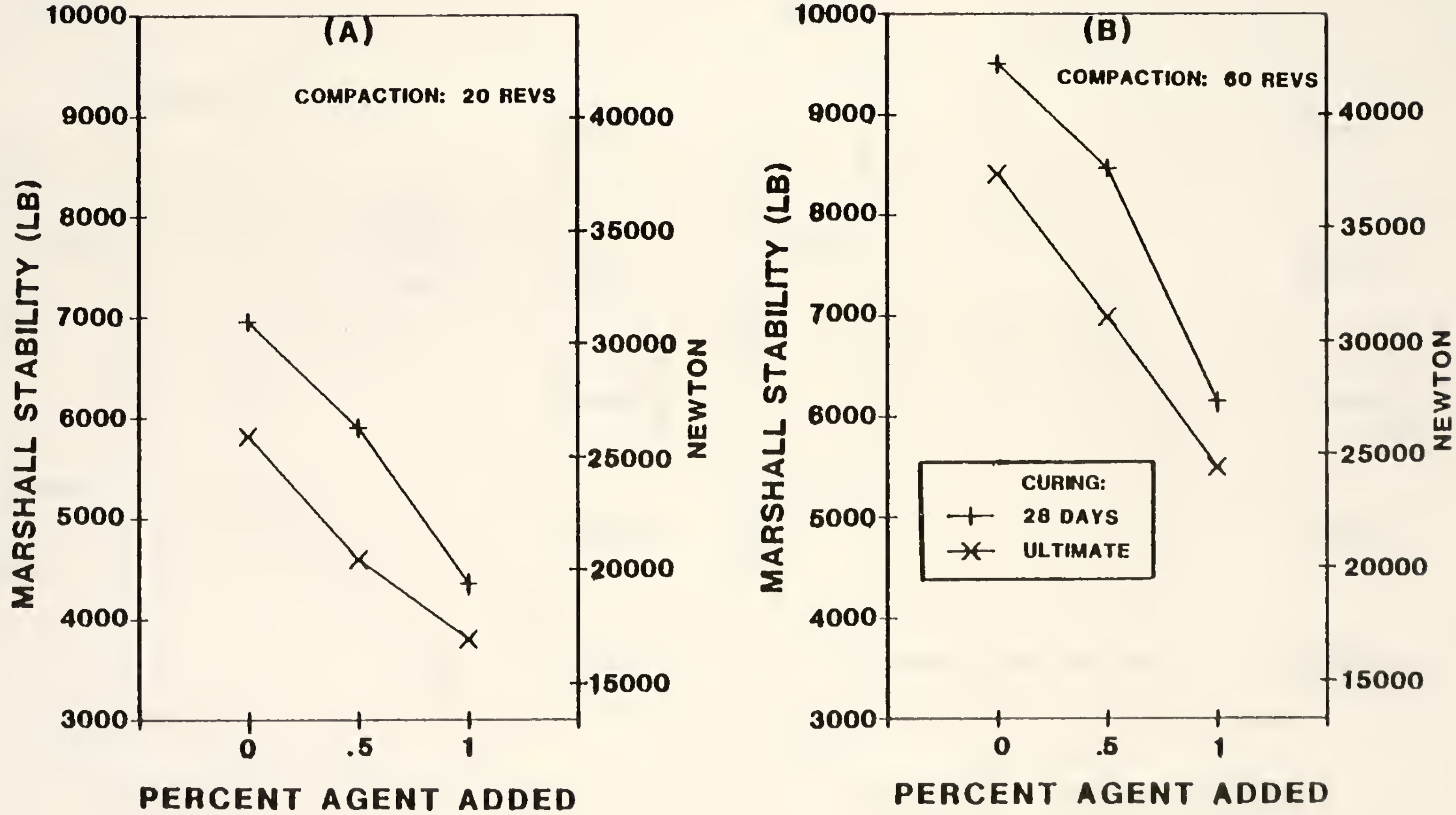


FIGURE 8.13 MARSHALL STABILITIES OF ARTIFICHALLY AGED PAVING MIXTURES WITH MOBILSOL ADDED (DESIGN NO.6)

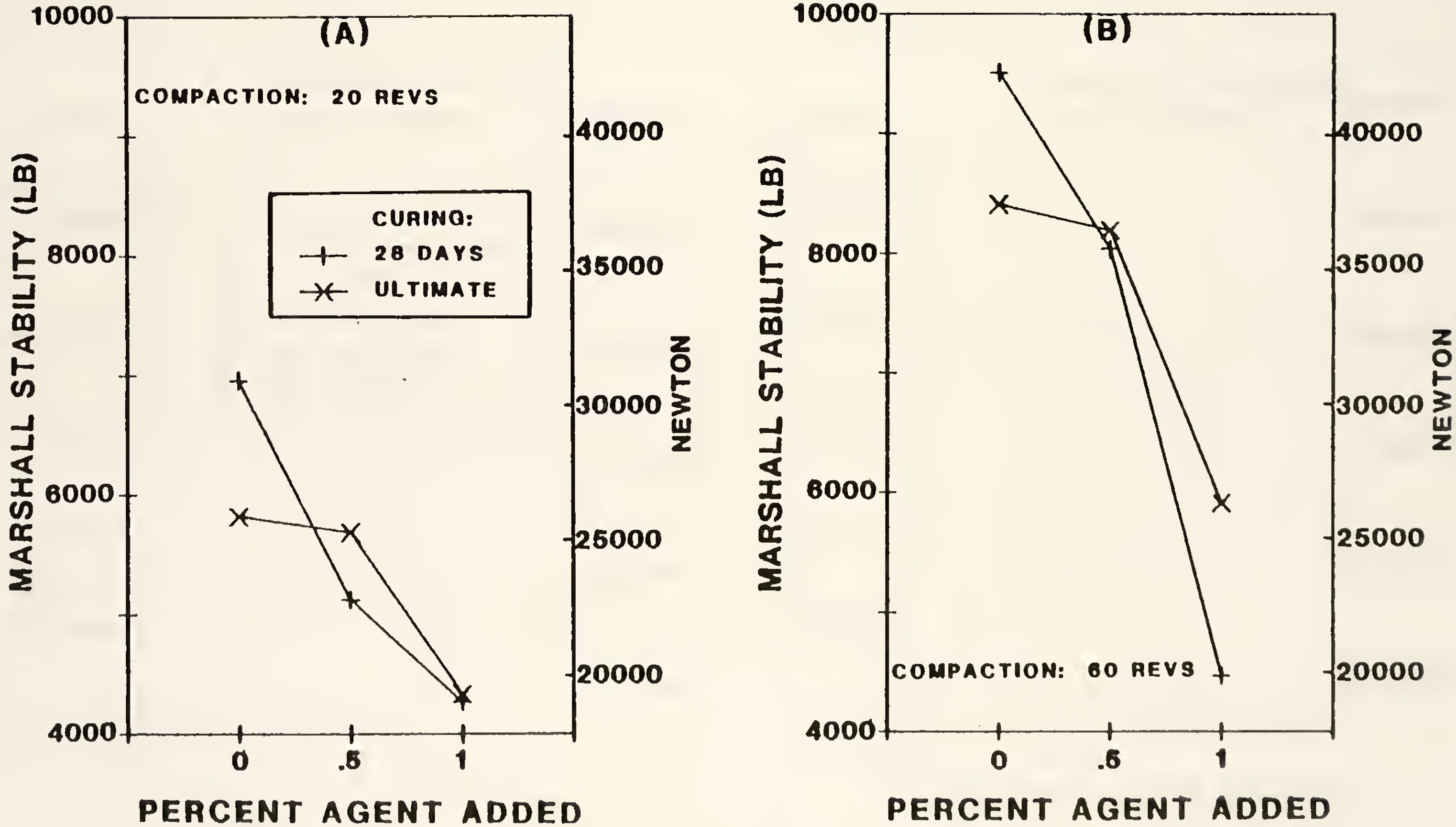


FIGURE 8.14 MARSHALL STABILITIES OF ARTIFICIALLY AGED PAVING MIXTURES WITH DUTREX 739 ADDED (DESIGN NO.6)

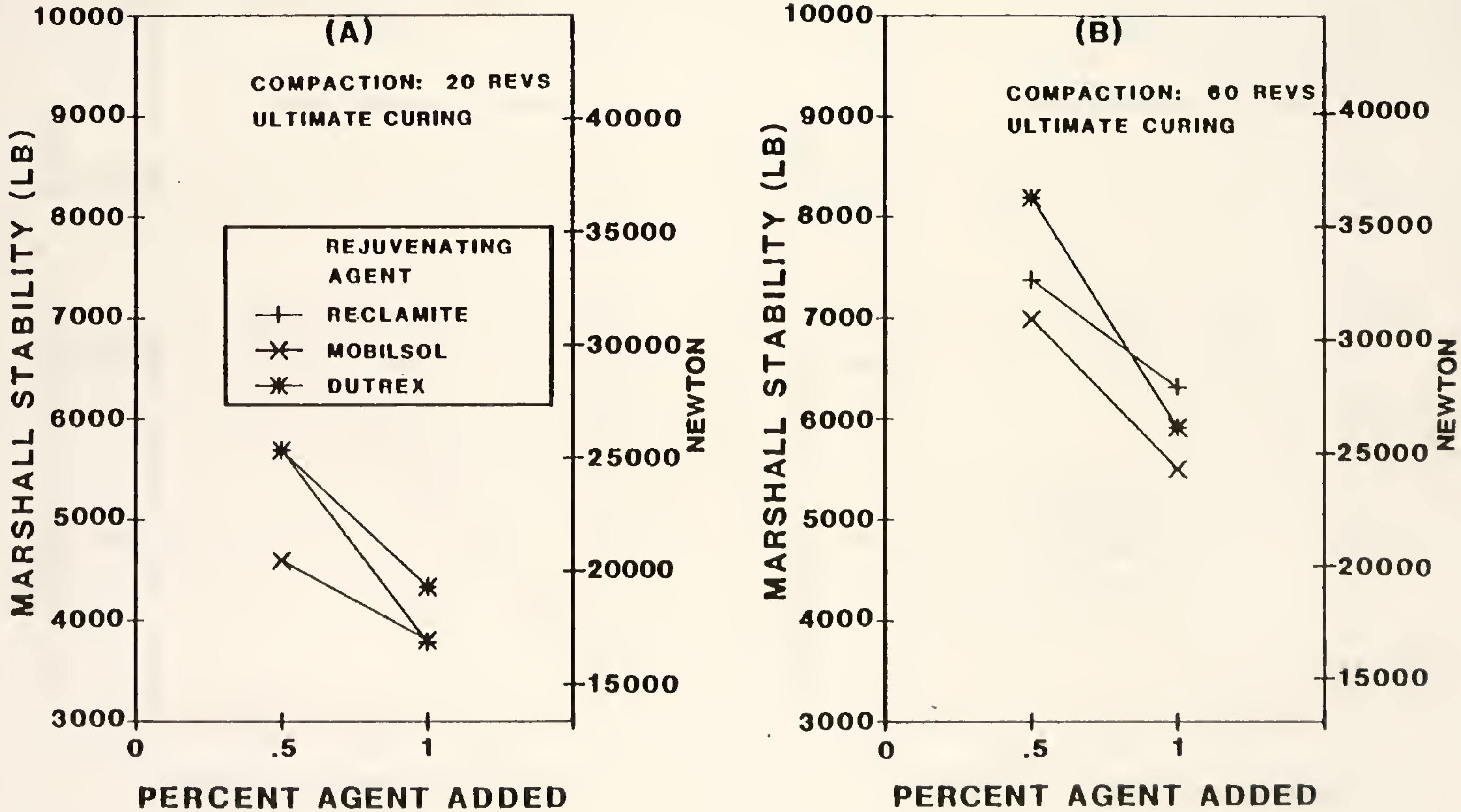


FIGURE 8.15 EFFECTS OF DIFFERENT REJUVENATING AGENTS ON THE MARSHALL STABILITIES OF THE RECYCLED MIXES IN DESIGN NO.6

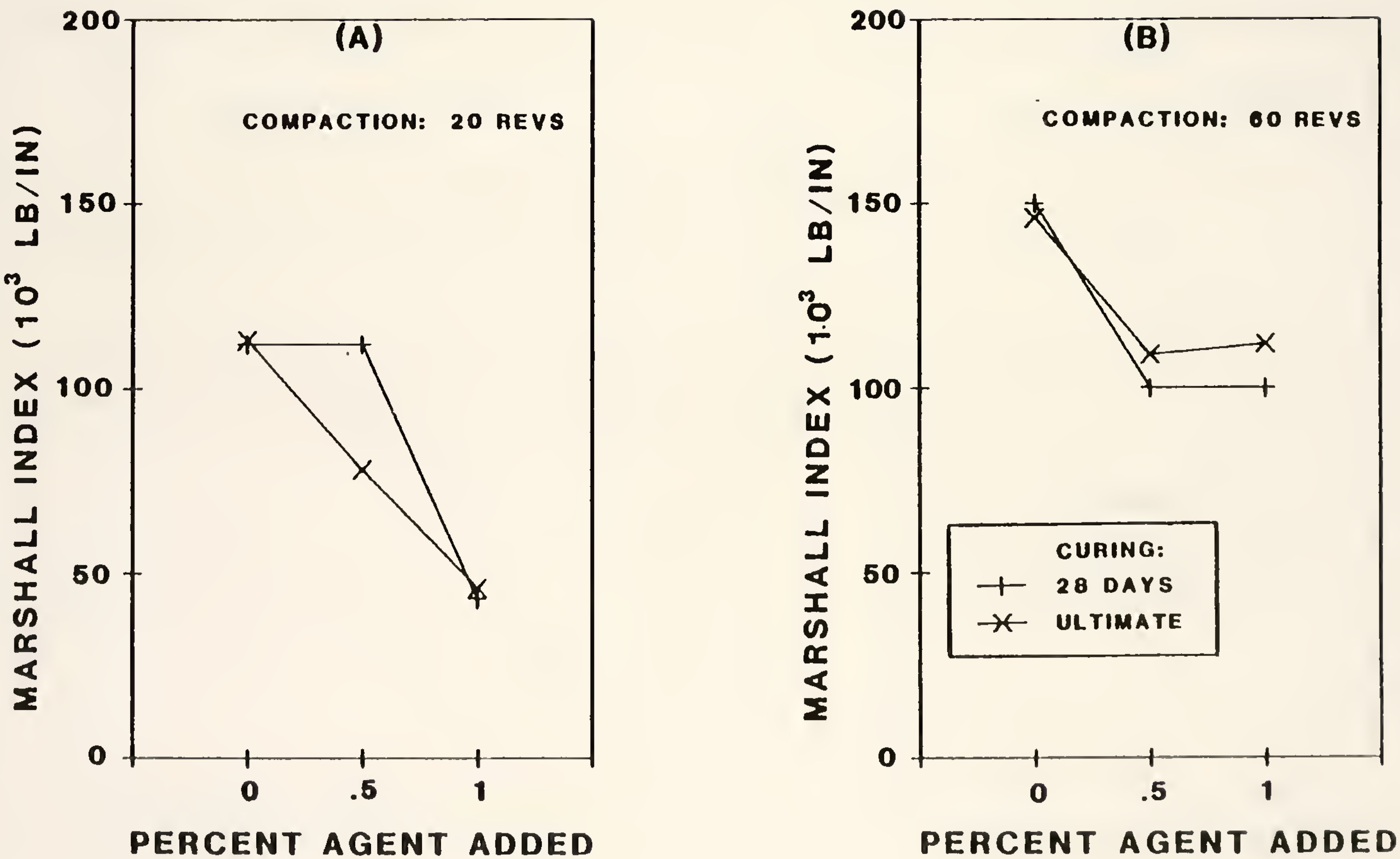


FIGURE 8.16 MARSHALL INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH RECLAMITE ADDED (DESIGN NO.6)

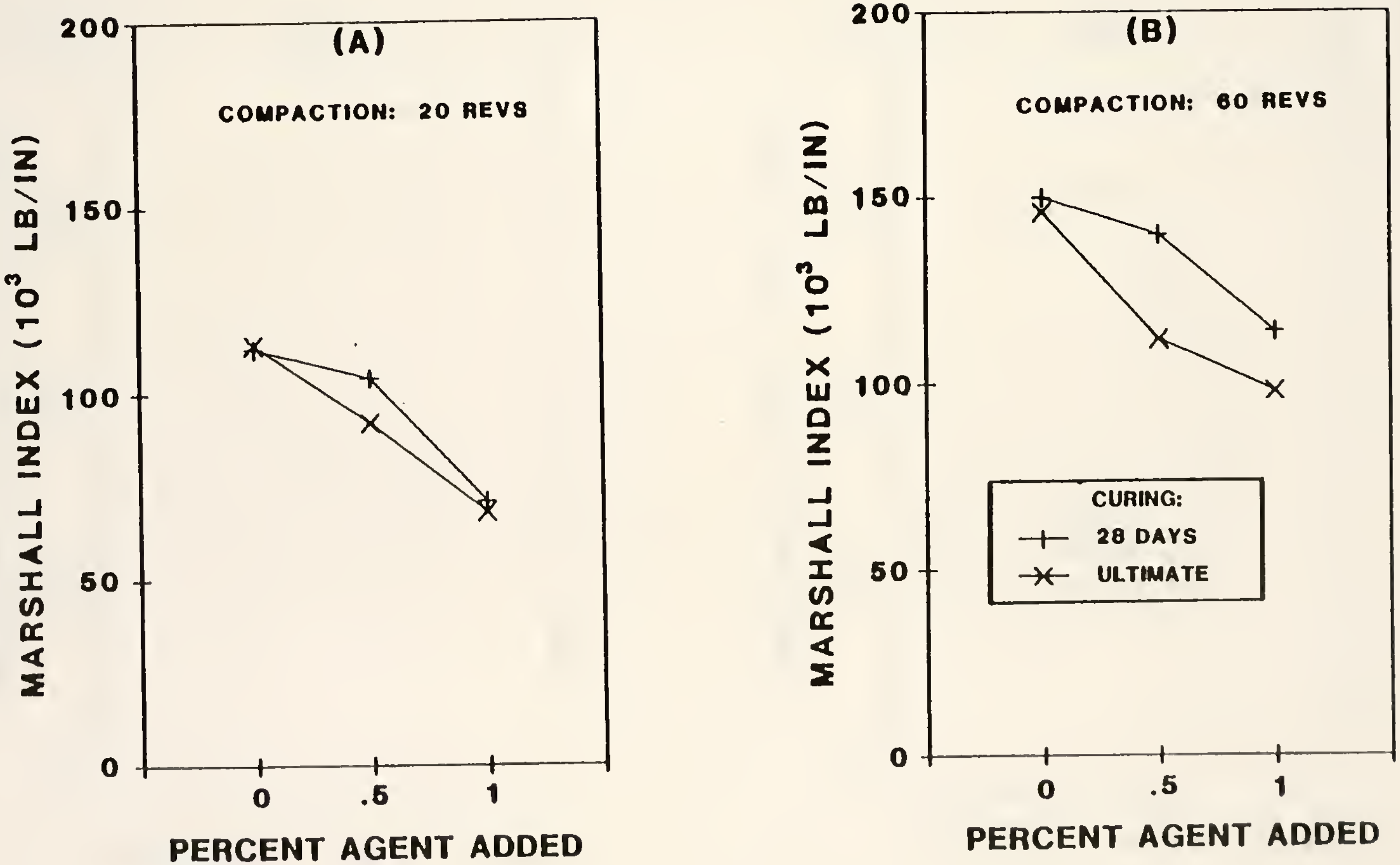


FIGURE 8.17 MARSHALL INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH MOBILSOL ADDED (DESIGN NO.6)

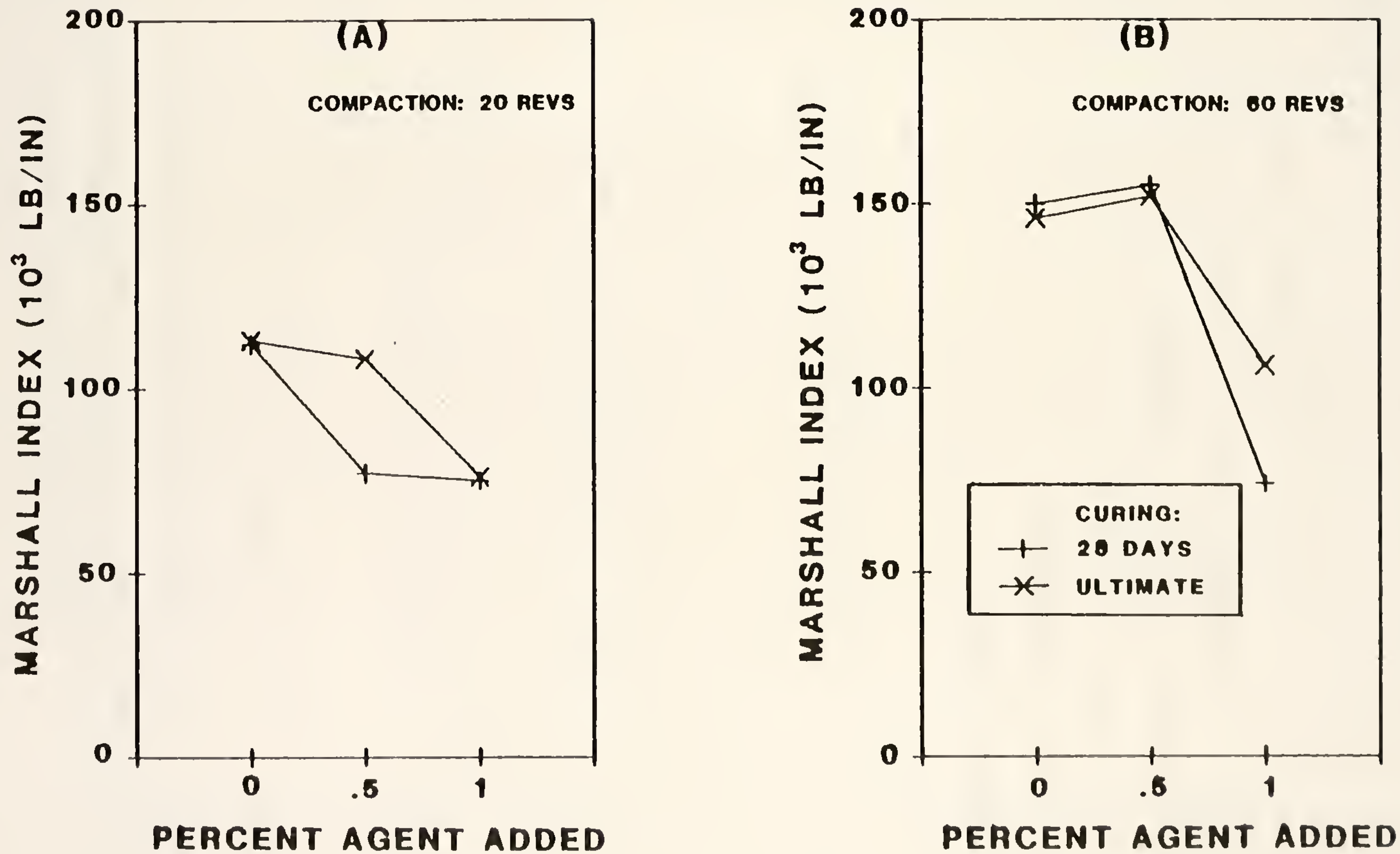


FIGURE 8.18 MARSHALL INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH DUTREX 739 ADDED (DESIGN NO.6)

was generally higher at the higher compactive effort and the optimum level of agent added was between 0% and .5%. The difference between 28 days curing and ultimate curing was not significant, as indicated by the ANOVA result.

8.2.3 Gyratory Indices

The gyratory indices for the recycled mixes in design no. 6 are presented in Figures 8.19, 8.20 and 8.21. It can be noted that the gyratory compactibility indices (GCIs) were insensitive to the changes in percent agent added. For the small range of percent agent added, no distinct trend can be observed from the gyratory stability index (GSI) and the elasto-plastic index (GEPI).

8.3 Results of Experimental Design No. 7

8.3.1 Resilient Modulus

The resilient moduli of the recycled mixes in design no. 7 are presented in Figure 8.22 as functions of curing time, from 1 day to 28 days. It can be observed that the resilient modulus increased significantly from 1 day to 7 days and leveled off thereafter.

The resilient modulus data were analyzed in the ANOVAs using the following model:

$$Y_{ijk} = \mu + P_i + S(P)_{(i)j} + \delta_{(ij)} + C_k + CP_{ik} + \varepsilon_{(ijk)}$$

The terms in the model are as defined earlier on page 143. ANOVA was performed on the data for curing times of 1 day to 28 days. The results are displayed in Table 8.3.

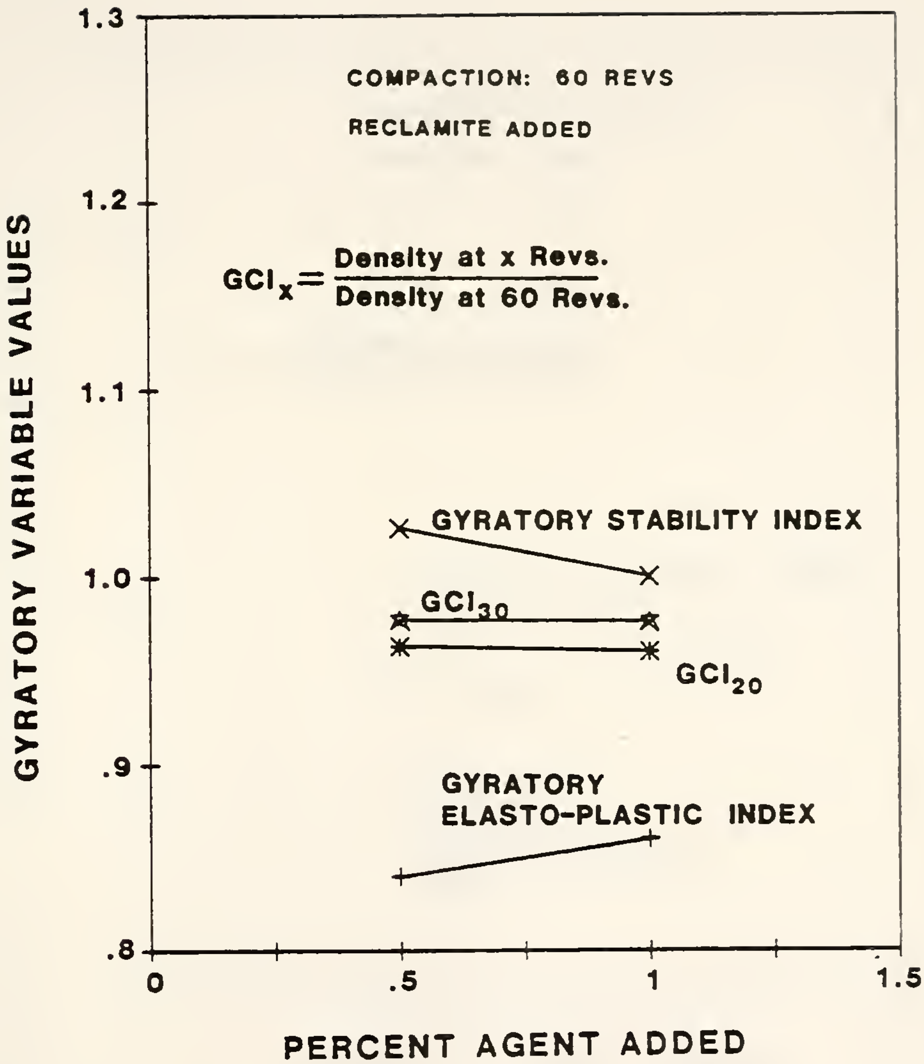


FIGURE 8.19 GYRATORY INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH RECLAMITE ADDED (DESIGN NO.6)

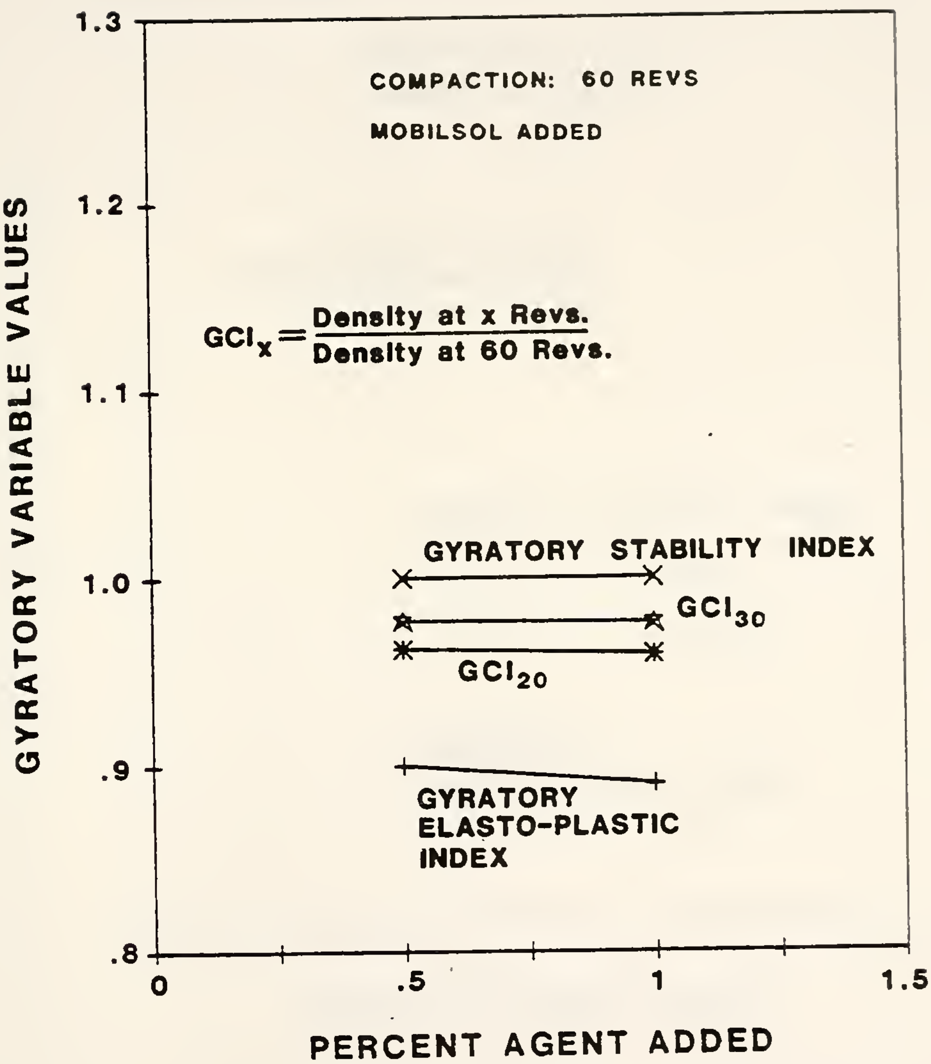


FIGURE 8.20 GYRATORY INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH MOBILSOL ADDED (DESIGN NO.6)

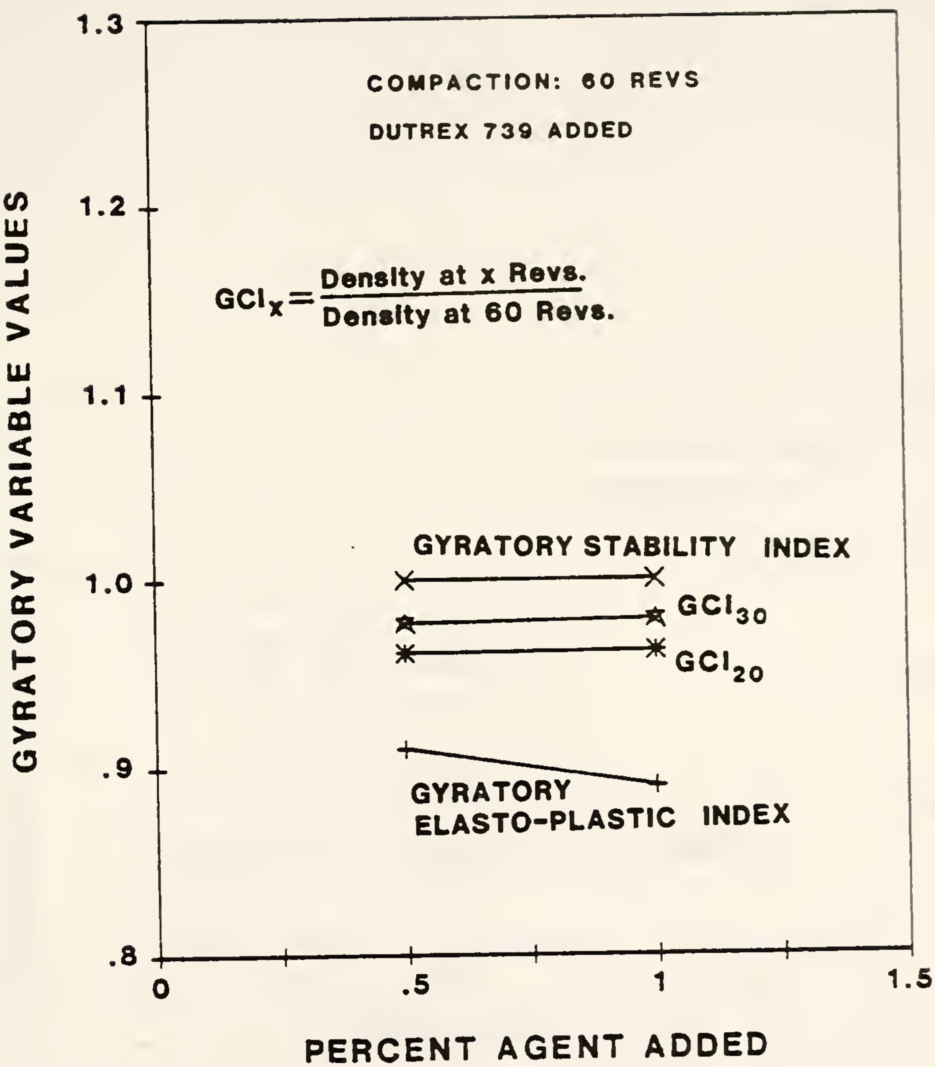


FIGURE 8.21 GYRATORY INDICES OF ARTIFICIALLY AGED PAVING MIXTURES WITH DUTREX 739 ADDED (DESIGN NO.6)

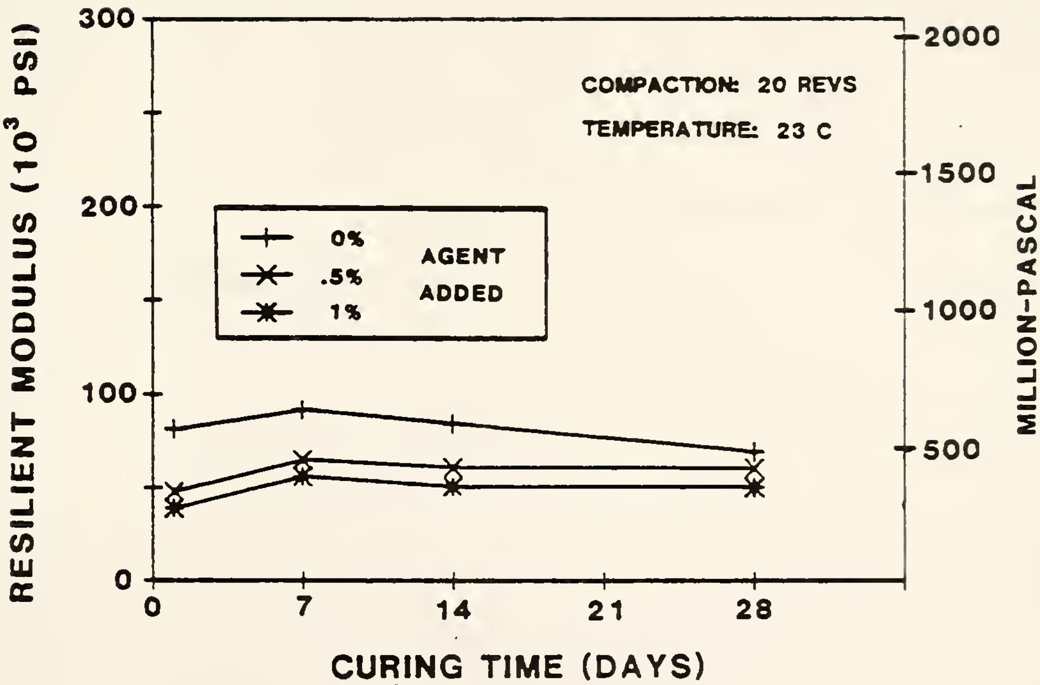


FIGURE 8.22 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF OLD PAVEMENT MATERIAL WITH RECLAMITE ADDED (DESIGN NO.7)

TABLE 8.3: ANOVA RESULTS FOR THE RESILIENT MODULUS IN DESIGN NO. 7

Factor	d.f.	S.S.	M.S.	F
P	1	362.9	362.9	2.9
S(P)	2	251.3	125.7	
C	3	633.8	211.3	9.5*
CP	3	1.5	.5	.02
ε	6	133.2	22.2	

* Significant at α = 0.05

8.3.2 Hveem R-Value and Marshall Variables

The Hveem R-values of the mixes in design no. 7 are depicted in Figure 8.23. It can be noted that the optimum level of agent added was between 0% and .5%.

Figure 8.24 presents the Marshall stabilities and indices of these recycled mixes. They indicated that the optimum level of agent added was between 0% and .5%.

8.4 Summary of Results

The findings presented in this chapter, on the behavior of the recycled mixes with rejuvenating agents added, are summarized as follows:

1. When Reclamite or Mobilsol was used as the added agent, the resilient modulus of the mixture generally increased with time. This was due to the stiffening of the binder caused by the evaporation of water from the emulsion. At 28 days curing, most of the water had evaporated. Thus, the difference between 28 days curing and ultimate curing was not significant.
2. When DUTREX 739 was used as the added agent, the resilient modulus of the mixture increased with curing time in the first 7 days, and leveled off thereafter. The stiffening of the binder was caused by the evaporation of the volatile substance in the agent. When the mix was subjected to ultimate curing at 140°F (60°C), the binder was further stiffened when more volatile fractions in the agent evaporated.

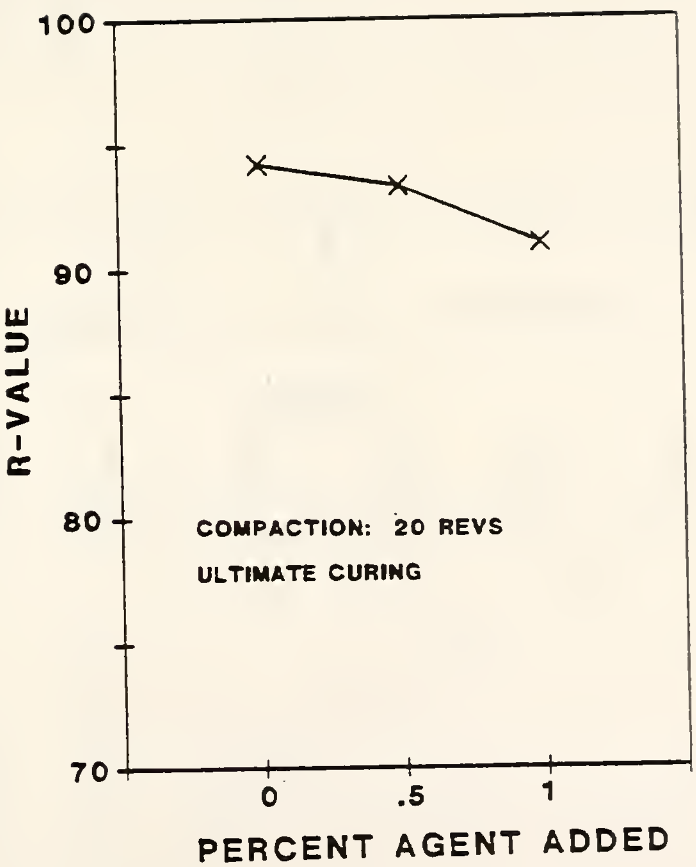


FIGURE 8.23 HVEEM R-VALUES OF OLD PAVEMENT MATERIAL WITH RECLAMITE ADDED (DESIGN NO.7)

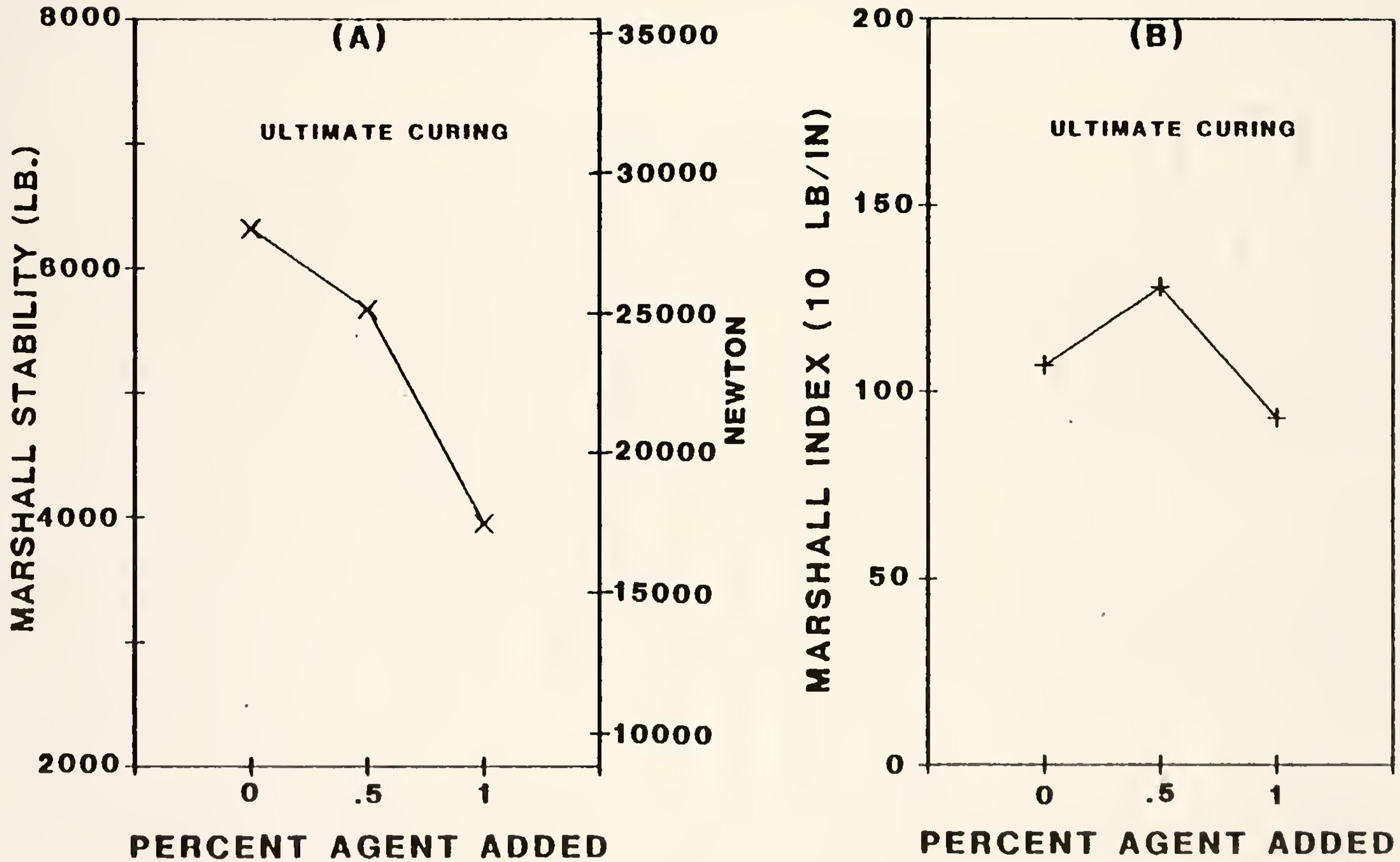


FIGURE 8.24 MARSHALL STABILITIES AND INDICES OF OLD PAVEMENT MATERIAL WITH RECLAMITE ADDED (DESIGN NO.7)

3. The level of rejuvenating agent added had significant effect on the resilient modulus, R-value, Marshall stability and index.
4. The resilient modulus, R-value, Marshall stability and index generally increased with higher compactive effort.
5. The optimum level of agent added increased as the testing temperature decreased.
6. The difference between 28 days curing and ultimate curing was not significant for the Hveem R-value, Marshall stability and index.
7. The gyratory stability index and elasto-plastic index did not show any distinct trend for the levels of added agent considered. The gyratory compactibility index was insensitive to the changes in the level of added agent.
8. The effects of the three rejuvenating agents considered were not significantly different.

CHAPTER 9

RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED

9.1 Introduction

This chapter presents the results of Design 8, which dealt with the behavior of the recycled mixtures with virgin aggregate added. The experimental design is shown in Table 4.9. The recycled mixes were made by adding 25% of virgin crushed limestone to an artificially aged paving mixture and by using AE-150 as the added binder. The general laboratory procedure described in Chapter 5 was used to prepare and to test the recycled mixes. One percent water (by weight of the aggregate) was added to the virgin aggregate and the aged mixture before the mixing process. The required amount of asphalt emulsion was added to the virgin aggregate and mixed for one minute with a mechanical mixer. The aggregate coated with asphalt emulsion was then added to the aged mixture and mixed for another one minute. The method of analysis was similar to that described in Chapter 6.

9.2 Resilient Modulus Results

The resilient moduli of the recycled mixes in design No. 8 are presented in Figure 9.1 as functions of curing time, from 1 day to 28 days. It can be noted that the resilient modulus generally increased as the curing time increased.

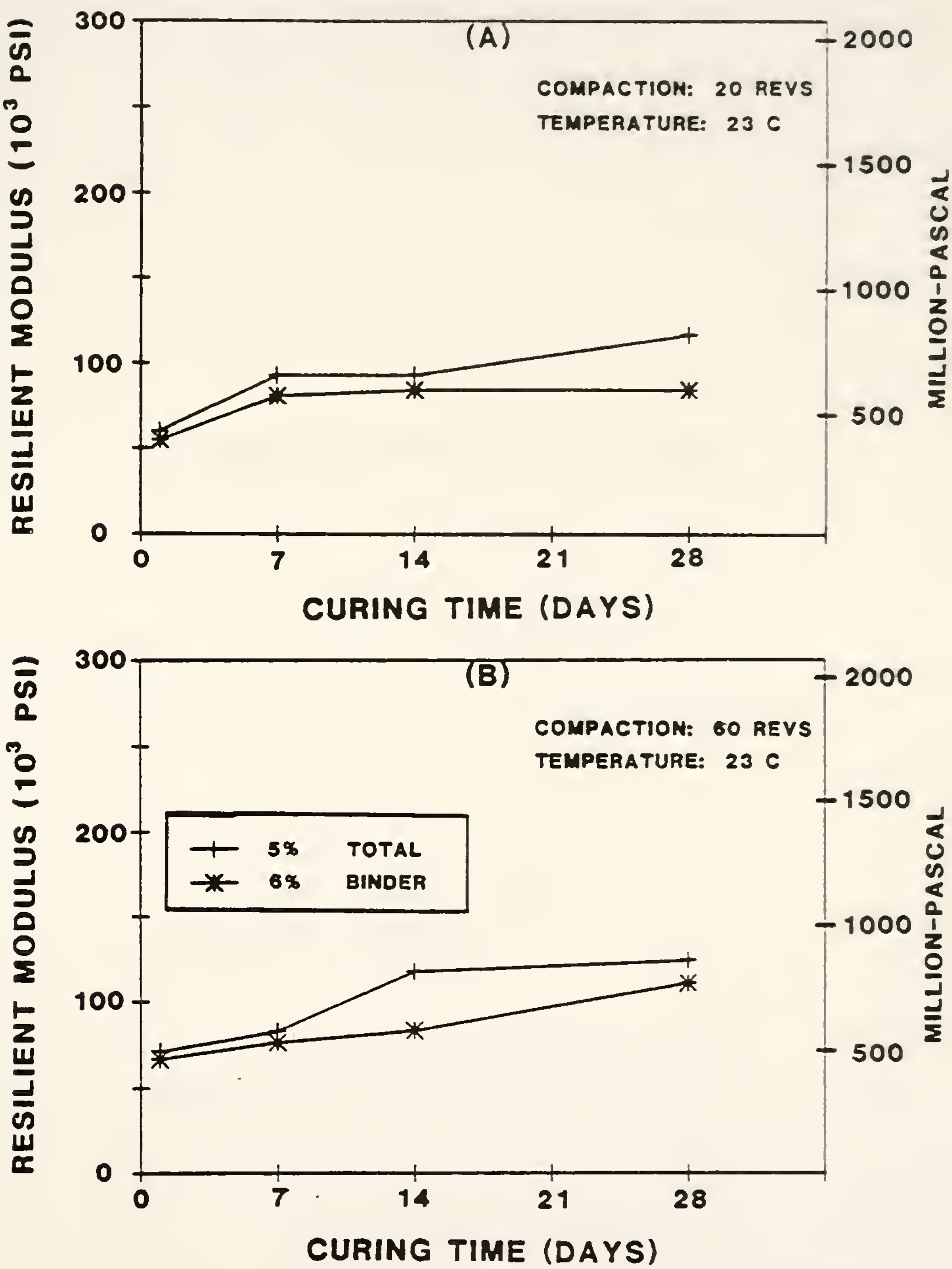


FIGURE 9.1 EFFECTS OF CURING TIME ON THE RESILIENT MODULI OF RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED (DESIGN NO.8)

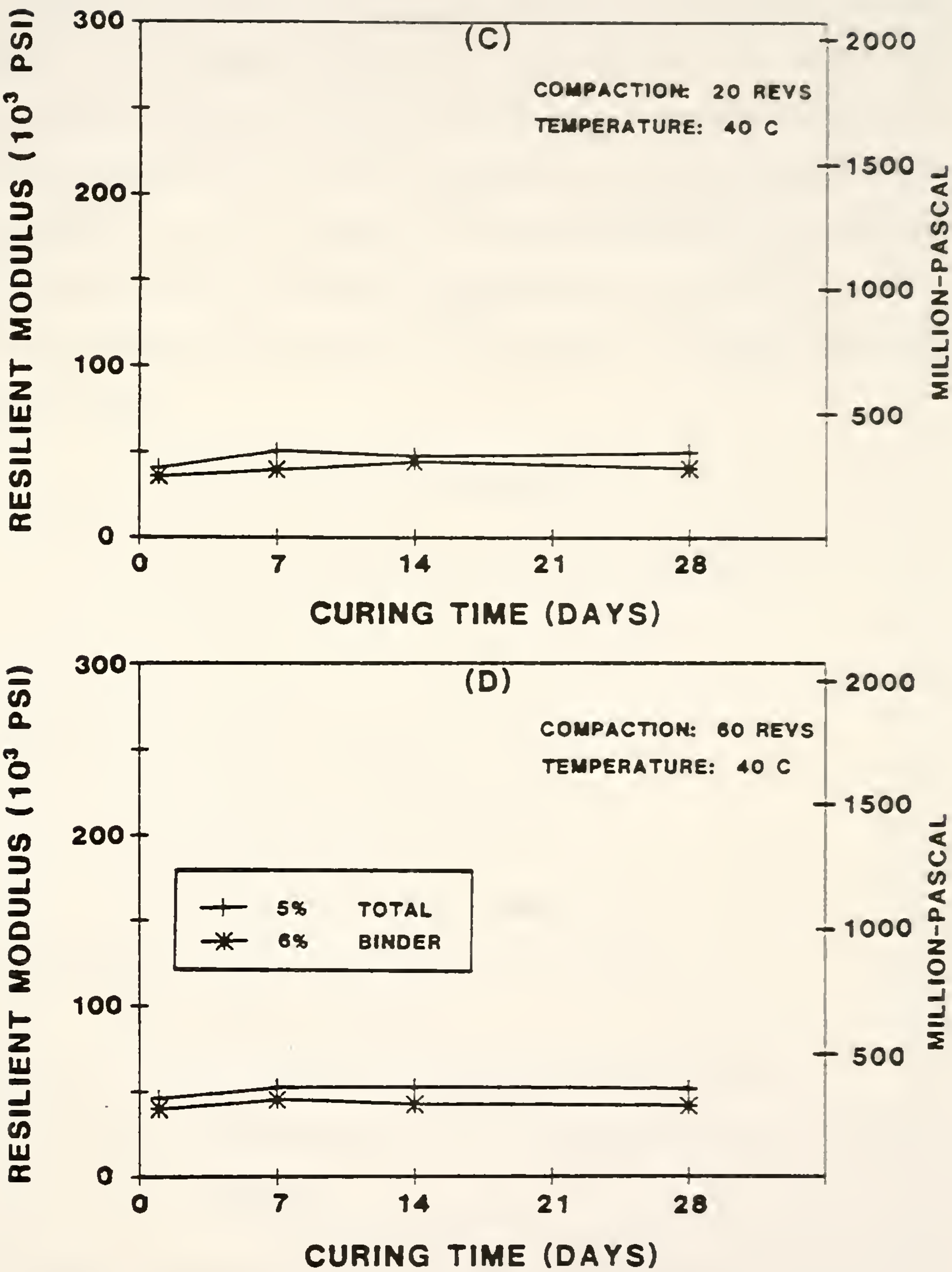


FIGURE 9.1 (Continued)

Figure 9.2 depicts the resilient moduli of these mixes at ultimate curing. For the compactive effort of 20 revolutions, the higher resilient modulus occurred at 5% total binder for all testing temperatures. For the compactive effort of 60 revolutions, the higher resilient modulus occurred at 6% total binder for a testing temperature of 0%C, and at 5% total binder for testing temperatures of 23^{o} and 40^{o}C.

The resilient modulus data were analyzed in the ANOVA using the following model:

$$Y_{ijk\ell m} = \mu + P_i + R_j + PR_{ij} + S(P\text{-}R)_{(ij)k} + \delta_{(ijk)} + C_\ell + T_m + PC_{i\ell} + RC_{j\ell} + PT_{im} + RT_{jm} + CT_{\ell m} + \varepsilon_{(ijk\ell m)}$$

where P_i = Effect of percent total binder

R_j = Effect of compactive effort

C_ℓ = Effect of curing time

T_m = Effect of testing temperature

$S(P\text{-}R)_{(ij)k}$ = Within error of P-R combinations

δ = Restriction error

PR_{ij}, $PC_{i\ell}$ ... $CT_{\ell m}$ = Effect of interaction of two factors.

$\varepsilon_{(ijk\ell m)}$ = Experimental error + interaction of three or more factors.

ANOVA was performed on the data for curing times of 1 day to 28 days. The results are displayed in Table 9.1.

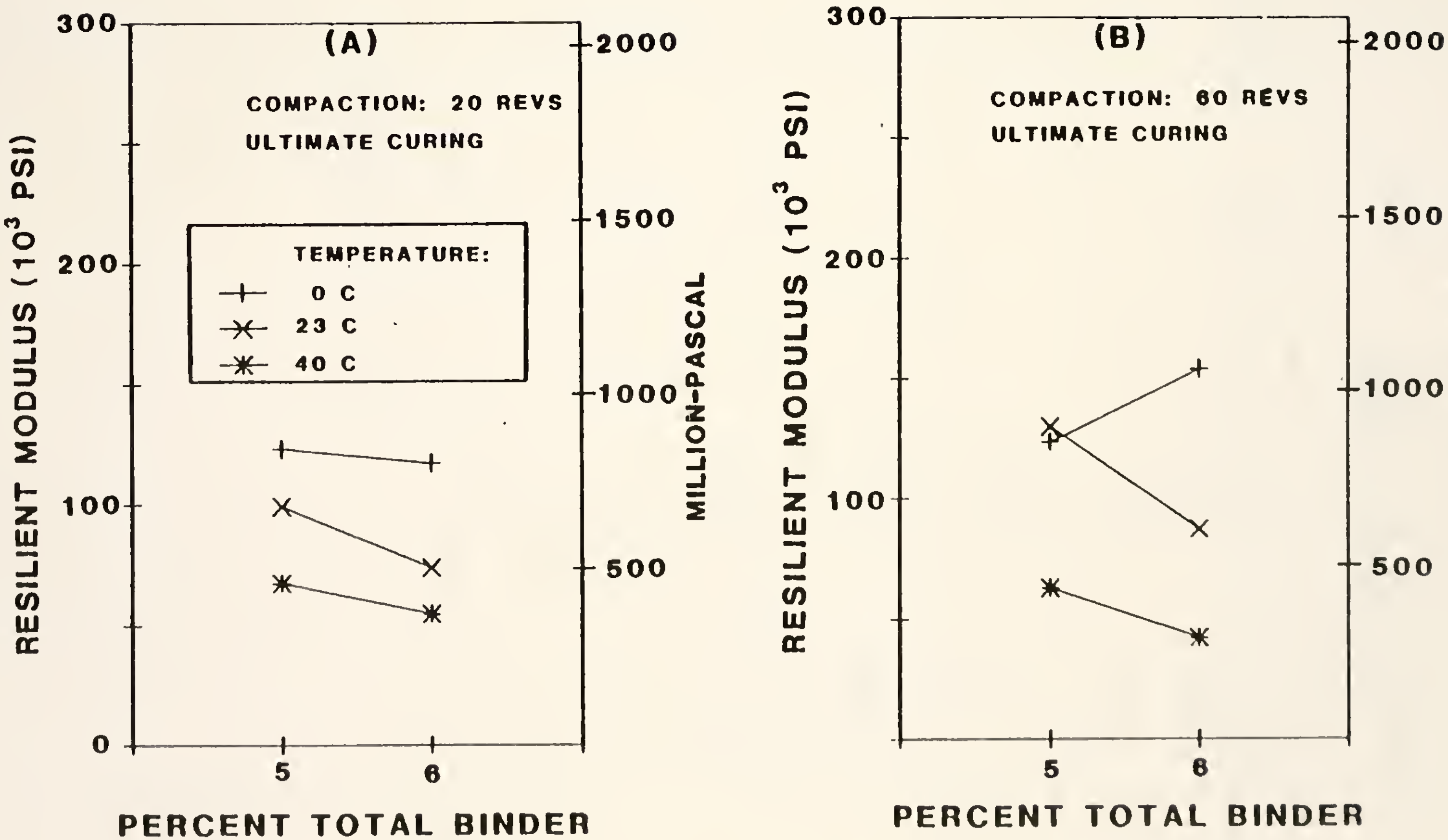


FIGURE 9.2 RESILIENT MODULI AT ULTIMATE CURING FOR RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED (DESIGN NO.8)

TABLE 9.1: ANOVA RESULTS FOR THE RESILIENT MODULUS IN DESIGN NO. 8

Factor	d.f.	S.S.	M.S.	F
P	1	2025.0	2025.0	2.7
R	1	467.6	467.6	.63
PR	1	1.9	1.9	.003
S(P-R)	4	2986.9	746.7	
C	3	5613.2	1871.1	24.8*
T	1	29044.7	29044.7	385.7*
CT	3	3587.5	1195.8	15.9*
CP	3	290.2	96.7	1.3
CR	3	288.5	96.2	1.3
TP	1	176.9	176.9	2.3
TR	1	110.8	110.8	1.5
ε	41	3087.3	75.3	

* Significant at α = 0.05

9.3 Hveem R-Value and Marshall Test Results

The Hveem R-value and Marshall variables of the mixes in design no. 8 are analyzed in the ANOVAs using the following model:

$$Y_{ijk} = \mu + C_i + R_j + P_k + CR_{ij} + CP_{ik} + RP_{jk} + \varepsilon_{(ijk)}$$

The terms in the model are as defined earlier (in section 9.2). This is a completely randomized design. The ANOVA results are shown in Table 9.2.

Figure 9.3 presents the Hveem R-values of the mixes as functions of percent total binder. It can be noted that the R-value was higher at 5% total binder.

The Marshall stabilities and indices of these mixes are presented in Figure 9.4 and 9.5. It can be observed that the Marshall stability and index were generally higher at 5% total binder and at the higher compactive effort. The ANOVA results, however, indicated that these differences were insignificant.

9.4 Gyratory Compaction Results

The gyratory indices of the recycled mixes in design no. 8 are presented in Figure 9.6. It can be noted that the gyratory compactibility indices (GCIs) were insensitive to the changes in percent total binder. The gyratory stability index (GSI) was significantly higher at 6% total binder, at which the mix was less stable. The gyratory elasto-plastic index (GEPI) did not vary much from 5% to 6% total binder.

TABLE 9.2: ANOVA RESULTS FOR THE R-VALUE AND MARSHALL VARIABLES IN DESIGN NO. 8

Source of Variation	Response Variable:	R-Value	S_M	L_M	F_M
C		N.S.	N.S.	N.S.	N.S.
R		N.S.	N.S.	N.S.	N.S.
P		S.	N.S.	N.S.	N.S.
CR		N.S.	N.S.	N.S.	N.S.
CP		N.S.	N.S.	N.S.	N.S.
RP		N.S.	N.S.	N.S.	N.S.

S. = Significant at $\alpha = 0.05$

N.S. = Not Significant at $\alpha = 0.05$

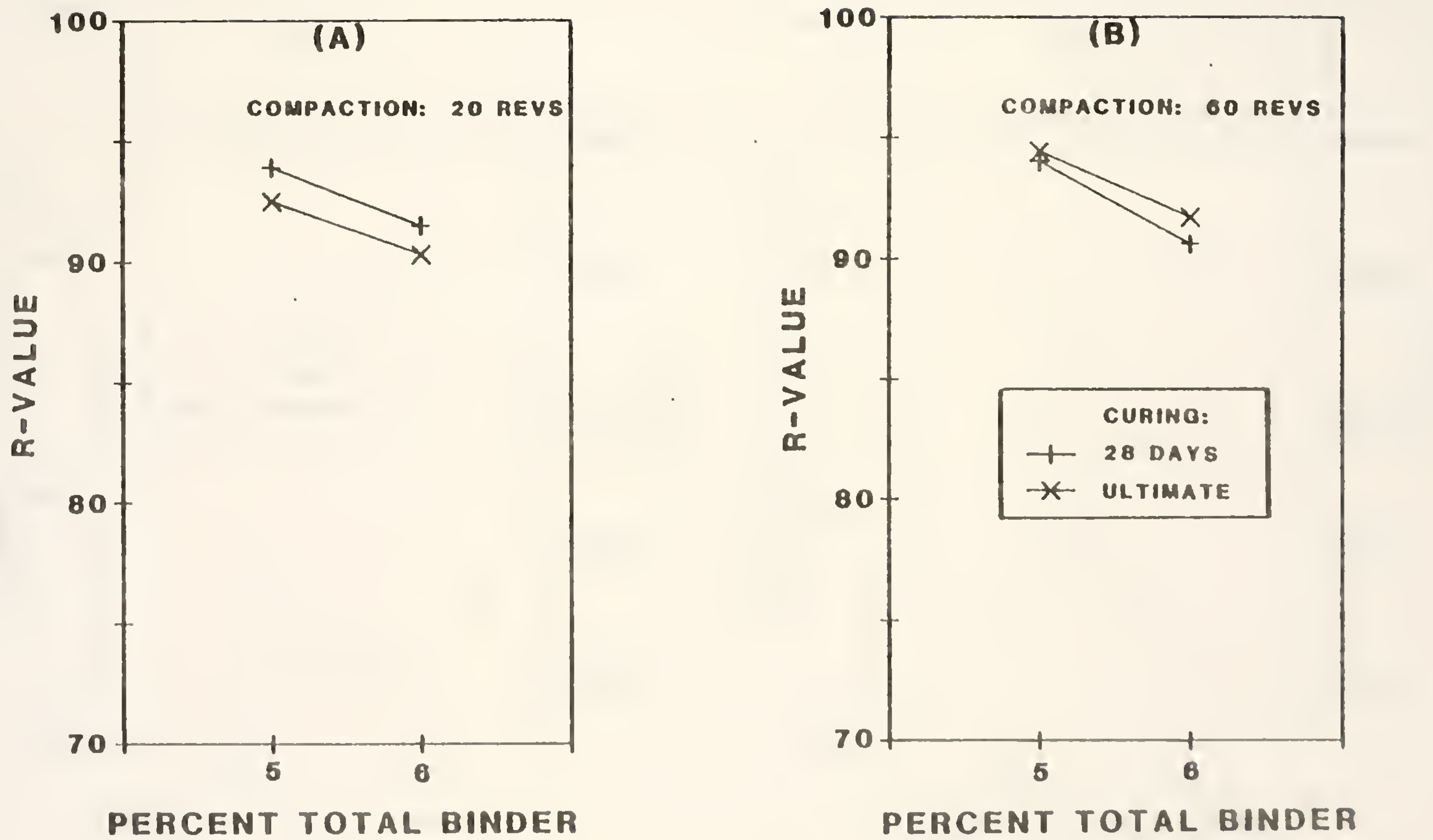


FIGURE 9.3 HVEEM R-VALUES OF RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED (DESIGN NO.8)

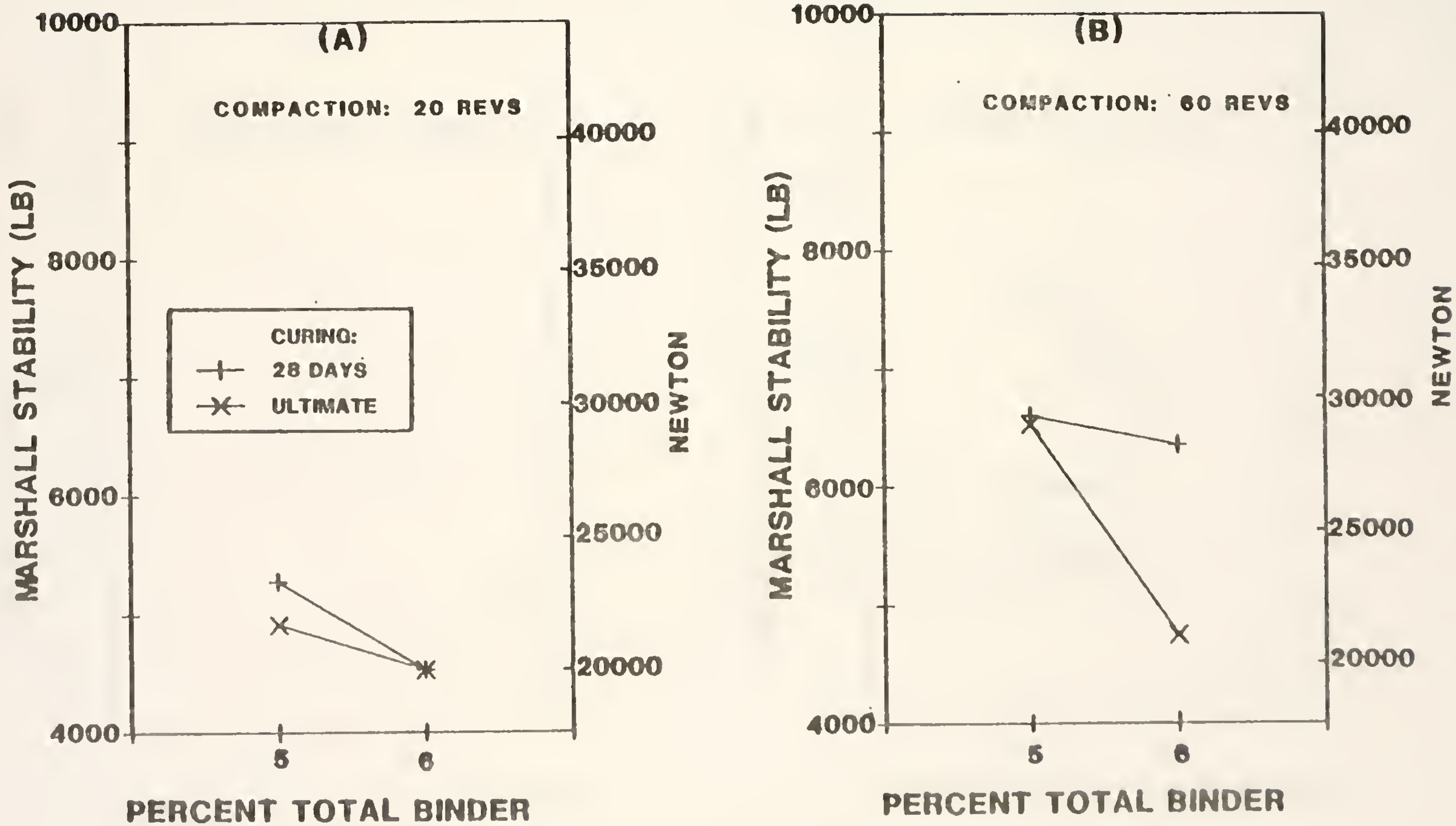


FIGURE 9.4 MARSHALL STABILITIES OF RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED (DESIGN NO.8)

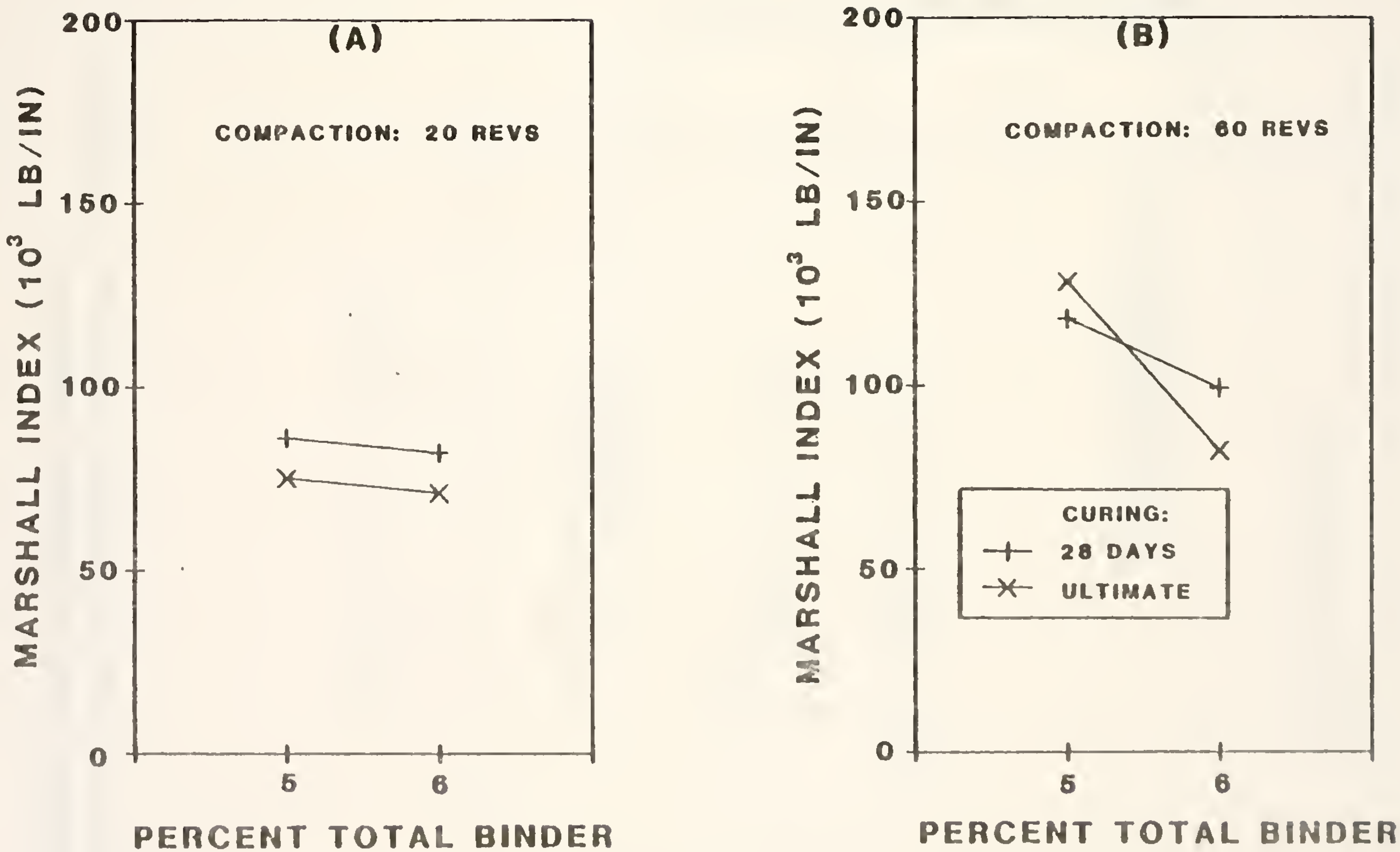


FIGURE 9.5 MARSHALL INDICES OF RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED (DESIGN NO.8)

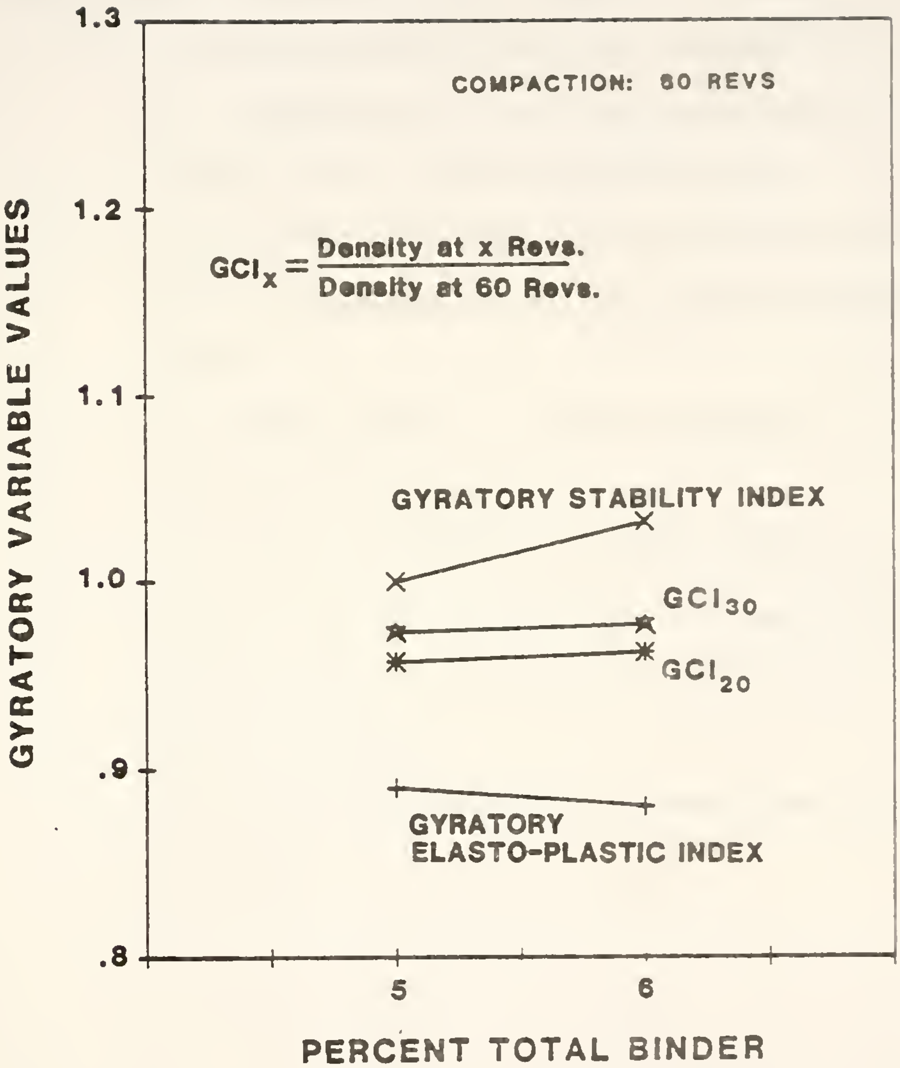


FIGURE 9.6 GYRATORY INDICES OF RECYCLED MIXTURES WITH VIRGIN AGGREGATE ADDED (DESIGN NO.8)

9.5 Summary of Results

The findings presented in this chapter, on the behavior of the recycled mixes with virgin aggregate added, are summarized as follows:

1. The resilient modulus generally increased with curing time. The stiffening of the binder was caused by the evaporation of water from the asphalt emulsion added.
2. The difference between 28 days curing and ultimate curing was not significant for all the response variables considered.
3. The optimum percent total binder increased as the testing temperature decreased.
4. The gyratory compactibility index was insensitive to the changes in percent total binder. The gyratory elasto-plastic index did not vary much for the levels of total binder considered.
5. The gyratory stability index increased when the mix became less stable.

CHAPTER 10

EFFECTS OF WATER ON THE RECYCLED MIXTURES

10.1 Introduction

This chapter presents the results of Design 9, which studied the effect of water on the recycled mixtures. The experimental layout is shown in Table 4.10. The recycled mixtures were made from an old pavement material. The two added binders used were AE-150 and a foamed asphalt (made from AC-2.5). The susceptibility of the recycled mixtures to the action of water was evaluated by subjecting the mixtures to a 24-hour water soaking (Water Sensitivity Test) and testing them in the resilient modulus, Hveem R-value and Marshall tests. The general laboratory procedure described in Chapter 5 was used to prepare and to test the mixes.

10.2 Resilient Modulus Results

Figure 10.1 presents the resilient moduli of the recycled mixtures with AE-150 added under the wet (water sensitivity test) and the dry conditions. It can be noted that the water sensitivity test significantly reduced the resilient modulus of these mixes. It can also be noted that the "wet" resilient modulus increased with curing time.

Figure 10.2 presents the resilient moduli of the recycled mixtures with foamed asphalt added, under the wet and the dry condition. It can be observed that the "wet" resilient modulus increased significantly with

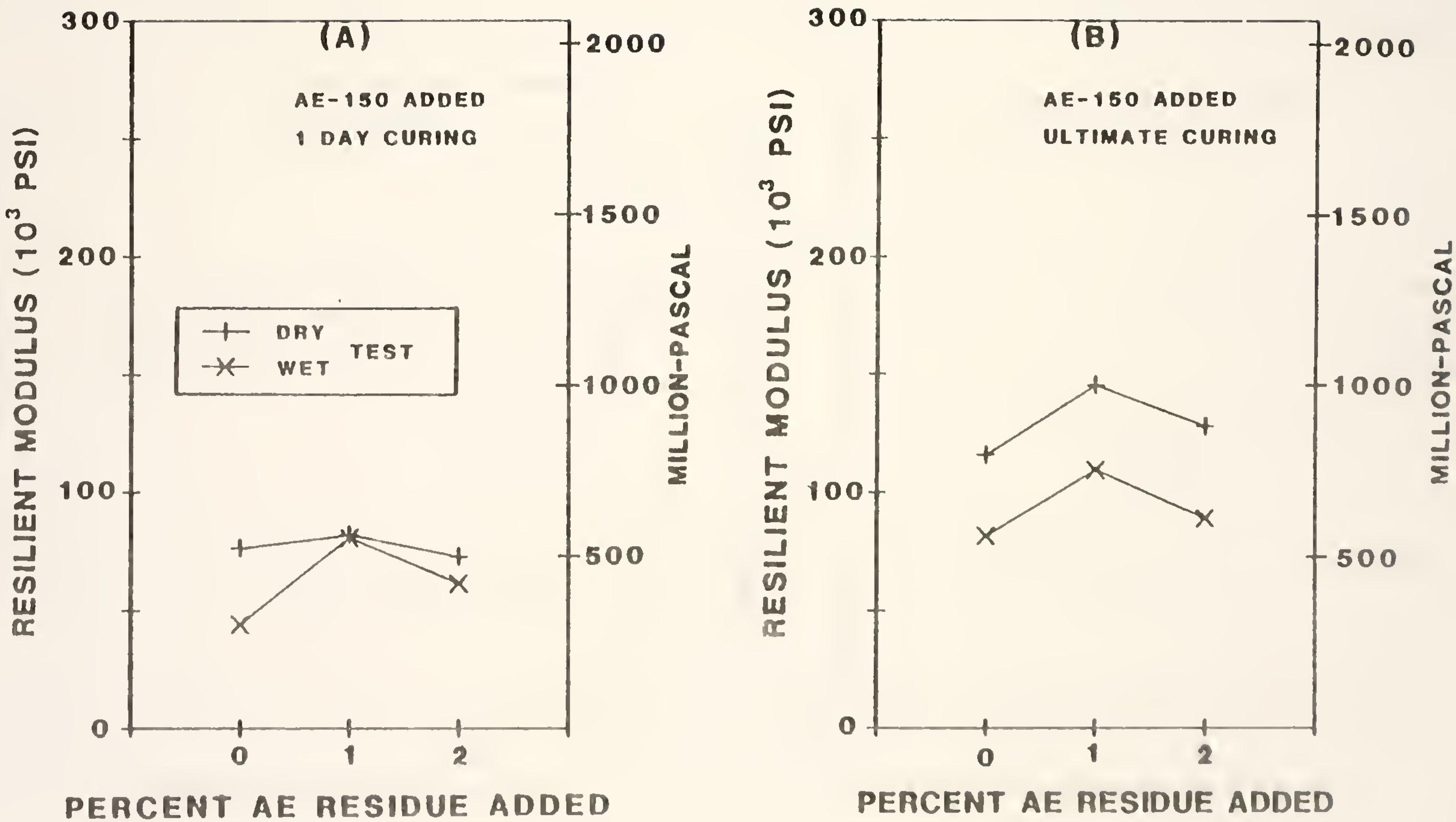


FIGURE 10.1 EFFECT OF WATER SENSITIVITY TEST ON THE RESILIENT MODULUS OF RECYCLED MIXTURES WITH AE-150 ADDED (DESIGN NO.9)

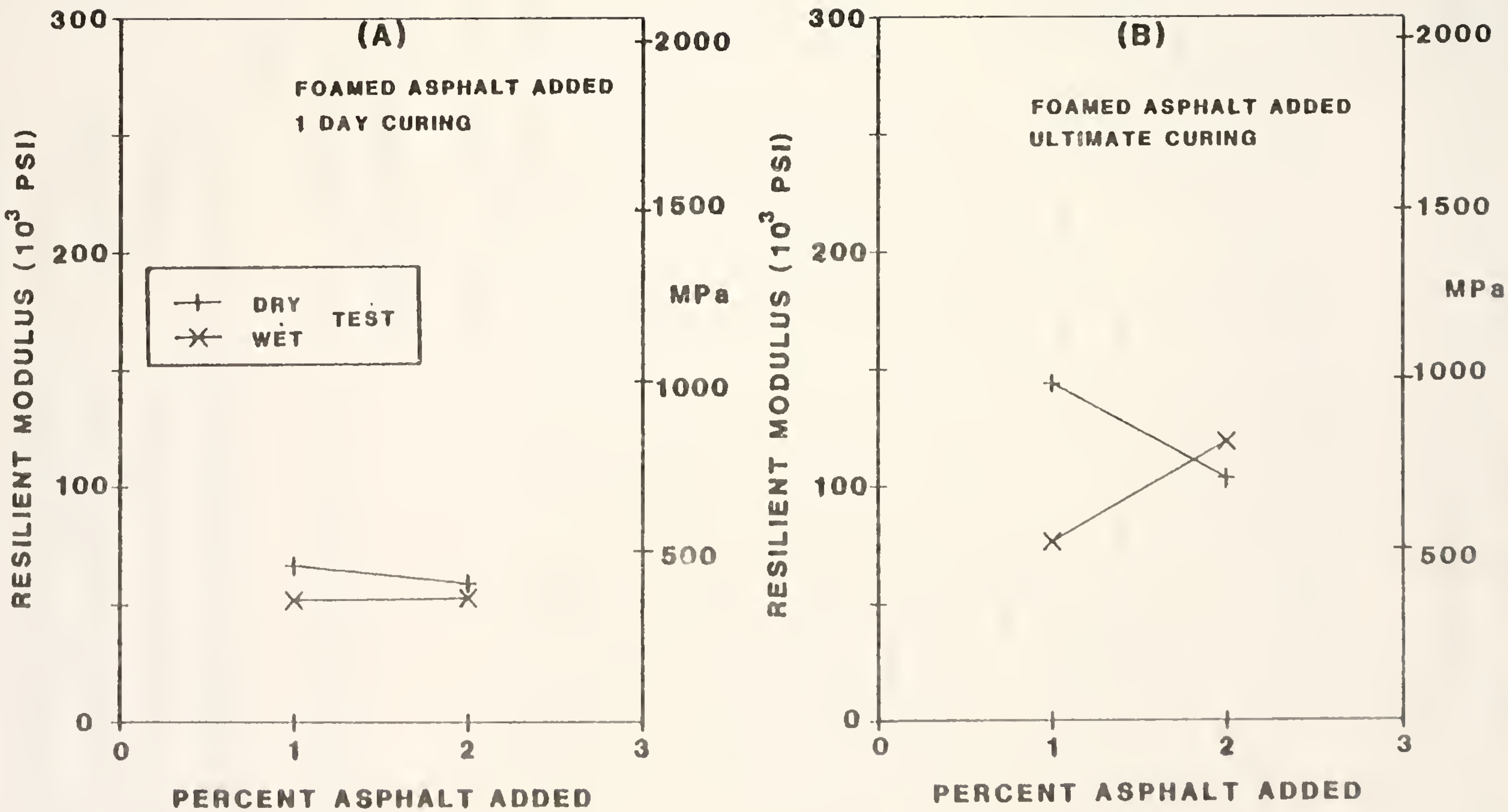


FIGURE 10.2 EFFECT OF WATER SENSITIVITY TEST ON THE RESILIENT MODULUS OF RECYCLED MIXTURES WITH FOAMED ASPHALT ADDED (DESIGN NO.9)

curing time. It can also be observed that the effect of water to the recycled mixtures decreased as the amount of added foamed asphalt increased.

10.3 Hveem R-Value and Marshall Test Results

The Hveem R-values of the recycled mixtures in design no. 9 are presented in Figure 10.3, for the dry and the wet (water sensitivity test) conditions. It can be noted that the water sensitivity test significantly reduced the R-values of the mixtures with AE-150 added, but had no significant effect on the mixtures with foamed asphalt added.

Figure 10.4 presents the Marshall stabilities of these mixes under the dry and the wet conditions. It can be observed that the water sensitivity test significantly reduced the Marshall stabilities of these mixes. For both the dry and the wet conditions, the recycled mixtures with foamed asphalt added had higher Marshall stability values.

Figure 10.5 presents the Marshall indices of these mixes under the dry and the wet conditions. Similarly, it can be observed that the water sensitivity test significantly reduced the Marshall indices of these recycled mixtures.

10.4 Summary of Results

The findings presented in this chapter are summarized as follows:

1. The resilient modulus, Hveem R-value, Marshall stability and Marshall index could be significantly reduced in the wet condition. Thus, a water sensitivity test is needed to evaluate the properties of the recycled mixtures under a wet condition.

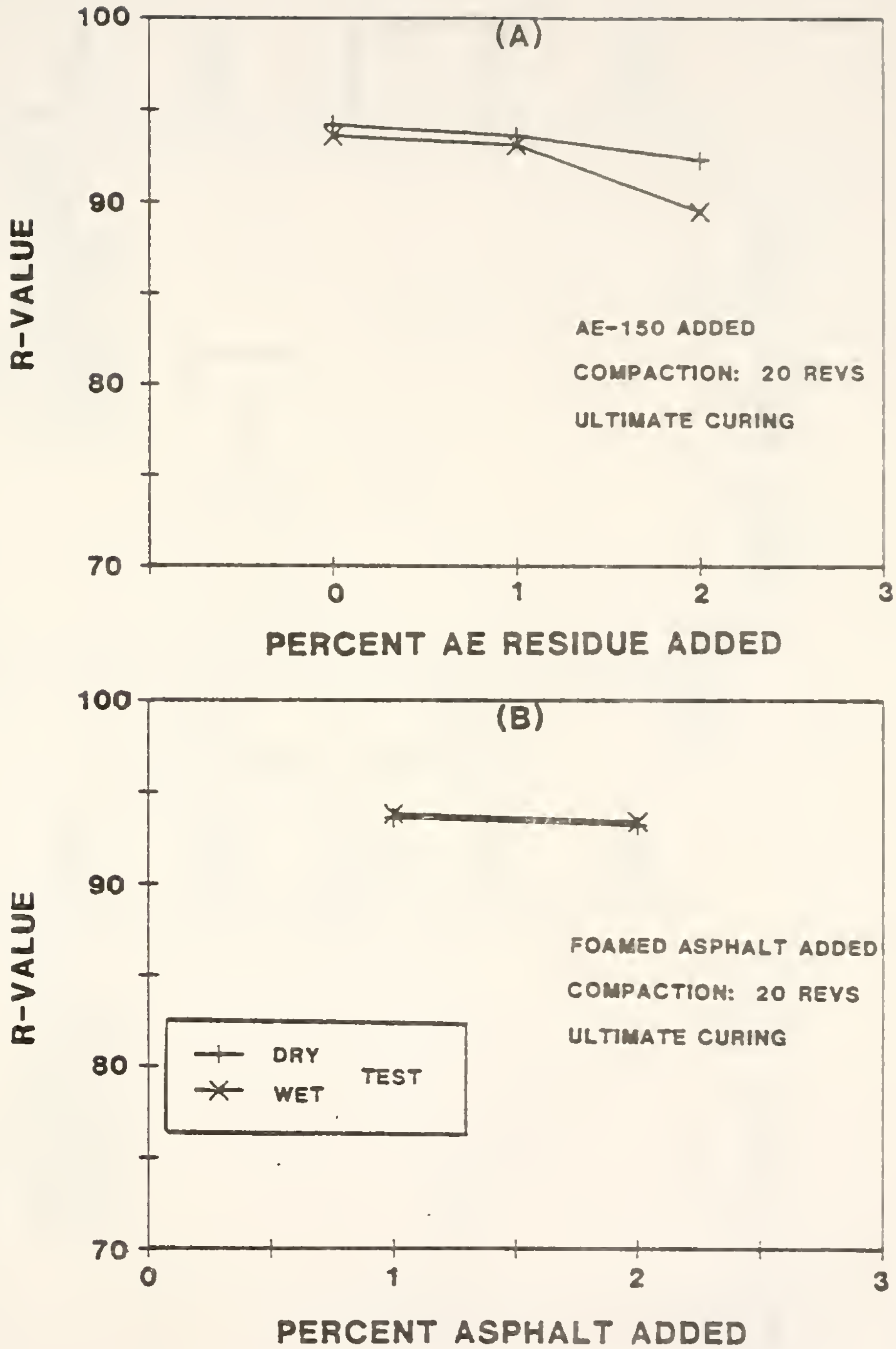


FIGURE 10.3 EFFECT OF WATER SENSITIVITY TEST ON THE HVEEM R-VALUE OF RECYCLED MIXTURES AT ULTIMATE CURING (DESIGN NO.9)

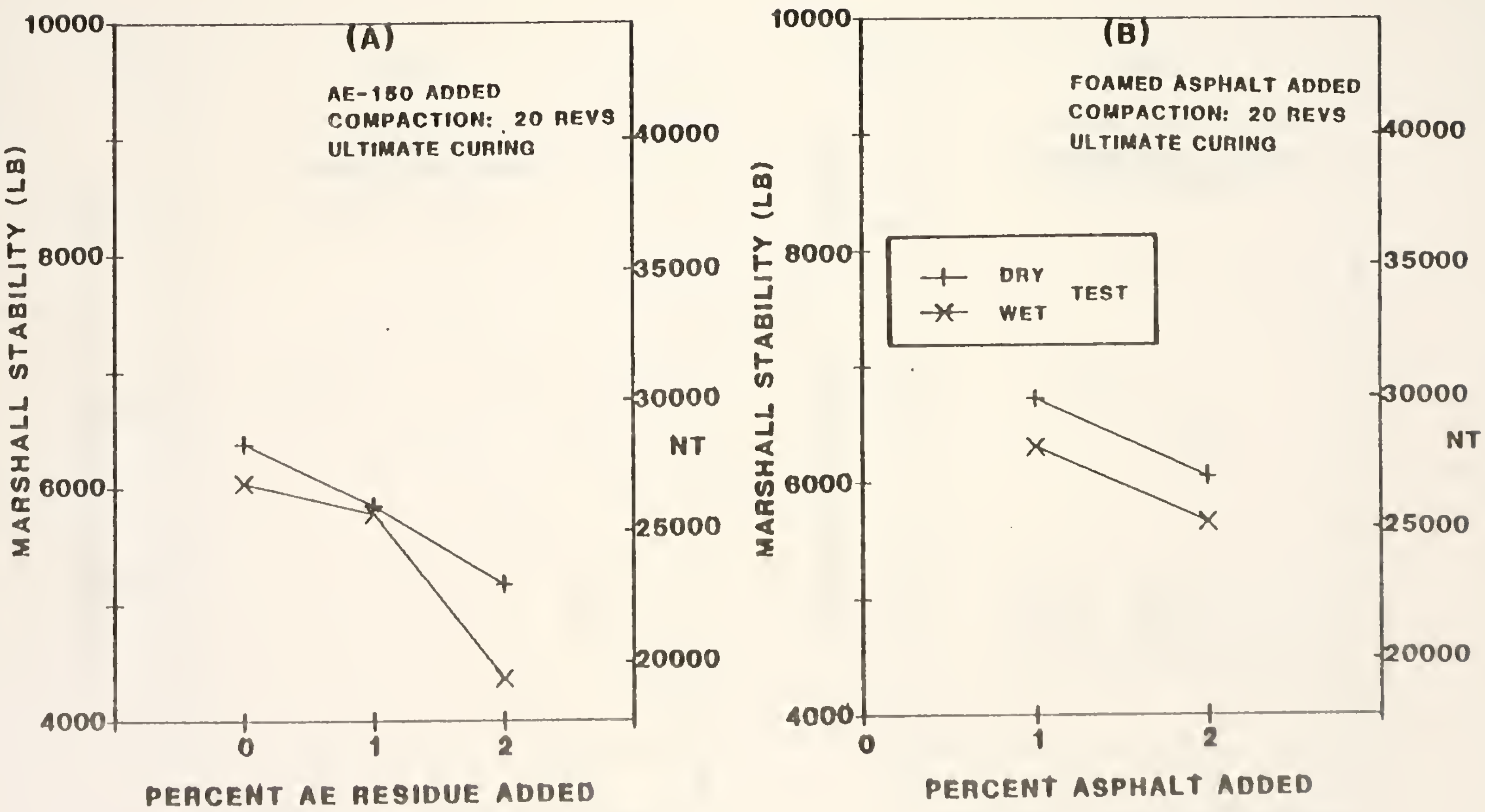


FIGURE 10.4 EFFECT OF WATER SENSITIVITY TEST ON THE MARSHALL STABILITY OF RECYCLED MIXTURES AT ULTIMATE CURING (DESIGN NO.9)

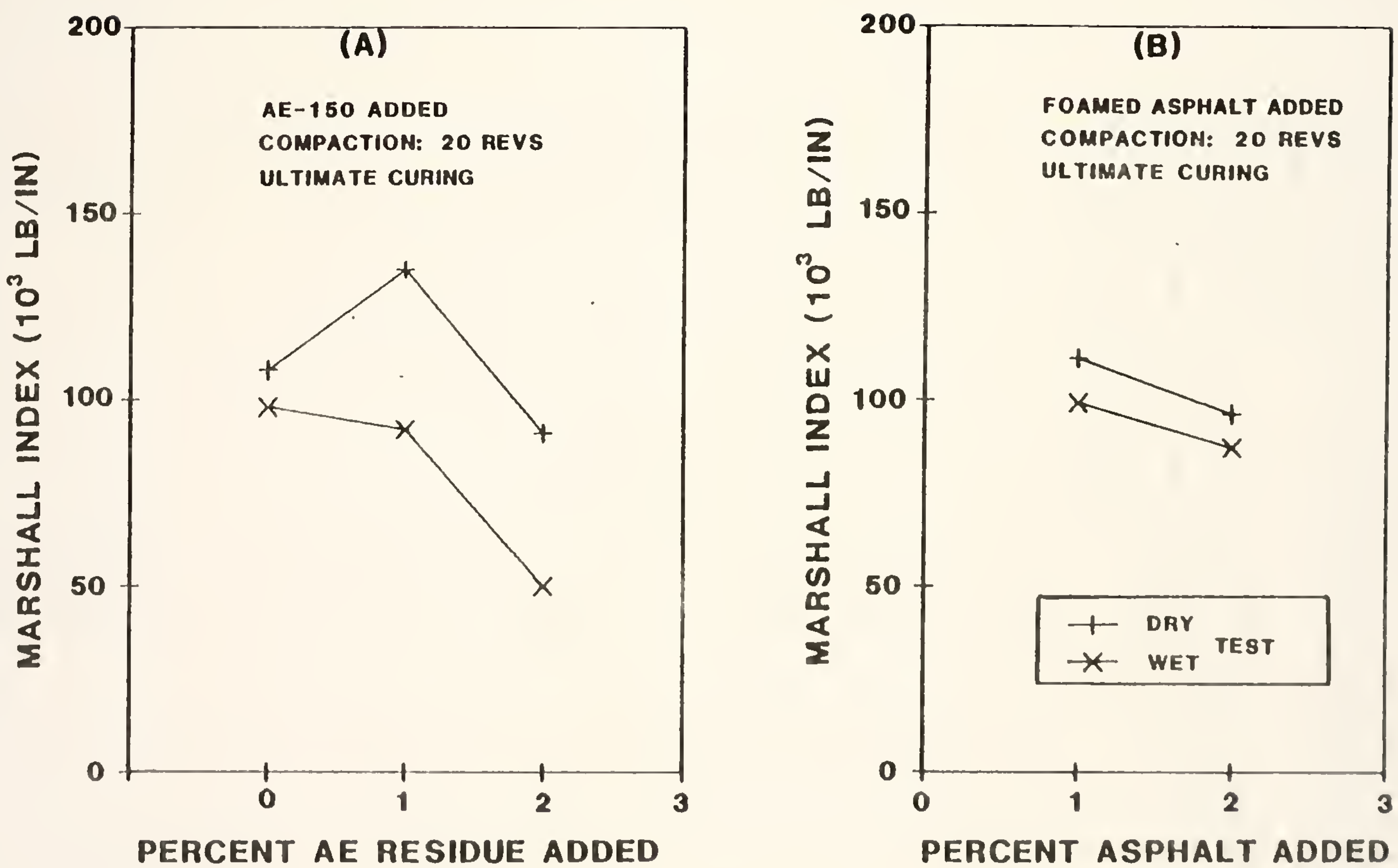


FIGURE 10.5 EFFECT OF WATER SENSITIVITY TEST ON THE MARSHALL INDEX OF RECYCLED MIXTURES AT ULTIMATE CURING (DESIGN NO.9)

2. The "wet" resilient modulus increase with curing time.

3. When foamed asphalt was used as the added binder, the effect of water decreased with increasing amount of asphalt added.

4. The recycled mixtures with foamed asphalt added showed higher Hveem R-value and Marshall stability for both the dry and the wet condition.

CHAPTER 11

COMPARISON AND DISCUSSION OF TEST RESULTS

11.1 Introduction

The results of an extensive laboratory study on the long term behavior of various cold recycled asphalt mixtures have been presented in the previous chapters. In this chapter, these results are compared and evaluated in accordance with the objectives of this study. The behavior of the various recycled mixtures under study are compared. The structural characteristics of these mixes are evaluated. Finally, a study is made to see how well the gyratory indices can predict the performance of recycled mixes.

11.2 Comparison of the Various Recycled Mixtures

The scope of this laboratory study was quite broad. It included two types of pavement material, three levels of oxydized condition of the old binder, five kinds of virgin binders or rejuvenating agents and one type of virgin aggregate. In this section, the behavior of these different recycled mixes are compared.

11.2.1 Effect of Curing Time

In the recycling process, virgin binder or rejuvenating agent is added to the old pavement material to soften the old asphaltic binder. This softening or rejuvenating action was postulated to be a function of curing time, compactive effort and temperature. For the levels of compactive effort used in this study, it was observed that most of the rejuvenating action took place during the compaction process. After the initial softening action during compaction, the binders began to increase in stiffness with time, as evidenced by the increase in resilient moduli of the compacted specimens. This was caused by the evaporation of water or volatile fractions from the mixtures.

11.2.2 Effect of Temperature.

Some of the recycled mixtures under study were subjected to the ultimate curing of 24-hours heating in a forced-draft oven at 60°C (140°F). For most cases, there was no significant difference between 28 days curing and ultimate curing. Heating at 60°C (140°F) had the effect of accelerated curing. For the case with the rejuvenating agent DUTREX 739 as the added binder, the mixtures at ultimate curing were significantly stiffer than those at 28 days curing. This could be explained by the fact that a certain volatile fraction evaporated only at the elevated temperature.

The optimum binder content increased as the testing temperature decreased, for all cases. Thus, an appropriate testing temperature has to be used in the determination of the optimum binder content of the recycled mixes.

11.2.3 Effect of Compaction

As mentioned earlier, the rejuvenating action of the new binder on the old binder took place during the compaction process. Thus, for higher compactive effort, the old and the new binder should be better blended together, and the stiffness and stability should be higher at its optimum binder content. This was evidenced by the higher resilient moduli and Marshall stabilities at the higher compactive efforts. The Hveem R-value, however, was not sensitive to the changes in compactive effort for stable mixes. When the binder content was too high, the higher compactive effort produced significantly lower Hveem R-values. Thus, it can be concluded that a high compactive effort is useful for detecting excessive asphalt content.

11.2.4 Comparison of Mix Performance

The effectiveness of the different added virgin binders or rejuvenating agents can be evaluated by the performance of the recycled mixes produced. The comparison of the properties of the mixes using the various added binders or agents are shown in Table 11.1. The values shown are those of the recycled mixes made from the artificially aged paving mixture, compacted at 20 revolutions and ultimately cured. It can be noted that the mixes with foamed asphalt added had comparable performance to that of the mixes with asphalt emulsion added. However, slightly more added binder is needed when foamed asphalt is used as the binder. Results from the water sensitivity tests (presented in Chapter 10) also indicated that the recycled mixes with foamed asphalt added had comparable resistance to water as that of the mixes with asphalt emulsion added.

The recycled mix with 25% virgin aggregate added had lower resilient modulus, Hveem R-value and Marshall stability than those of the recycled mix without any virgin aggregate. This indicates that, in cold mixing, the asphalt emulsion can adhere to the old pavement material better than to the virgin aggregate. Unless the added virgin aggregate can improve the gradation of the recycled material significantly, virgin aggregate will not improve the performance of a cold recycled asphalt mix.

TABLE 11.1: COMPARISON OF THE PROPERTIES OF RECYCLED MIXTURES WITH DIFFERENT VIRGIN BINDERS ADDED

Binder or Agent Added	Amount Added (%)	M_R (10^3 psi)	S_M (lb.)	Hveem R-Value
AE-150	.5	224.9	6041	94.8
Foamed Asphalt	1	203.9	6742	94.7
Reclamite	.5	132.0	5689	92.8
Mobilsol	.5	106.8	4591	91.4
DUTREX 739	.5	180.0	5686	93.1
25% Virgin Aggregate AE-150 Added 5.0% Total Binder		99.3	4909	92.5

NOTE: Recycled Material: Artificially aged paving mixtures
Compaction: 20 revolutions at 200 psi
Curing: ultimate

Among the three rejuvenating agents used, DUTREX 739 produced the stiffest mixes (i.e., with the highest resilient modulus), while Mobilsol produced the softest mixes. This can be noted from the values given in Table 11.1.

The artificially aged paving mixture was a laboratory controlled material and thus showed less variability in material property than that of the old pavement material. For the recycled mixes made from the old pavement material, there was usually great scattering of data, and the significance of some factors could not be effectively tested in the ANOVAs. However, the recycled mixes made from these two materials showed similar trends in their properties.

Darter et al [75] and Mamlouk [21] had performed some material characterization of asphalt emulsion treated base course materials. When compared to the properties of those stabilized base mixes, the recycled mixes in this study showed comparable or better performances.

11.3 Structural Characteristics of the Recycled Mixes

The resilient modulus, which was measured most extensively throughout this laboratory study, was an essential input parameter to the analytical pavement design method, such as the multilayer elastic analysis. In this section, the structural characteristics of the recycled mixes in this study are compared to that of a conventional asphalt cement using a linear elastic multilayer analysis. From the results of this analysis, the AASHTO structural coefficients of these recycled mixes are estimated.

11.3.1 Linear Elastic Multilayer Analysis

The resilient moduli of the recycled mixes in this study ranged from 50,000 psi (345 MPa) to 300,000 psi (2069 MPa) at 23°C (73°F). The structural performance of these mixes (with the resilient moduli in this range) as stabilized bases was evaluated using a hypothetical pavement system. The pavement system used in this analysis is depicted in Figure 11.1. This is a typical pavement structure for a low volume road. The condition of the subgrade in this pavement structure is representative of the subgrade condition of State Road 16 in Indiana, where a recycling project has recently been completed. The pavement system was to be subjected to an arbitrary wheel load of 4500 lbs (20,000 NT) with a tire pressure of 80 psi (552 kPa) and a circular contact area.

The BISTRO (Bitumen Structures in Roads) computer program developed by Shell Research N.V. [74] was used to make the multilayer analysis. The program calculated stresses, strains and displacements in a linear elastic multilayer system, induced by axisymmetric surface loads uniformly distributed over circular areas. The method of analysis was based on Boussinesq's equations for stresses in a semi-infinite elastic medium under compressive loads at the surface. The contact between the layers was assumed to be continuous.

The induced vertical subgrade deformation was used as a means of measuring and comparing the structural performance of different pavement materials. Asphalt concrete of 4 inches (10.2 cm) in thickness was used as a reference base course in this hypothetical pavement system. The vertical subgrade deformation for this reference system was calculated to be .00745 in. (.189 mm). The recycled mixtures (with resilient modulus of 50,000 to 300,000 psi) was then used as the stabilized

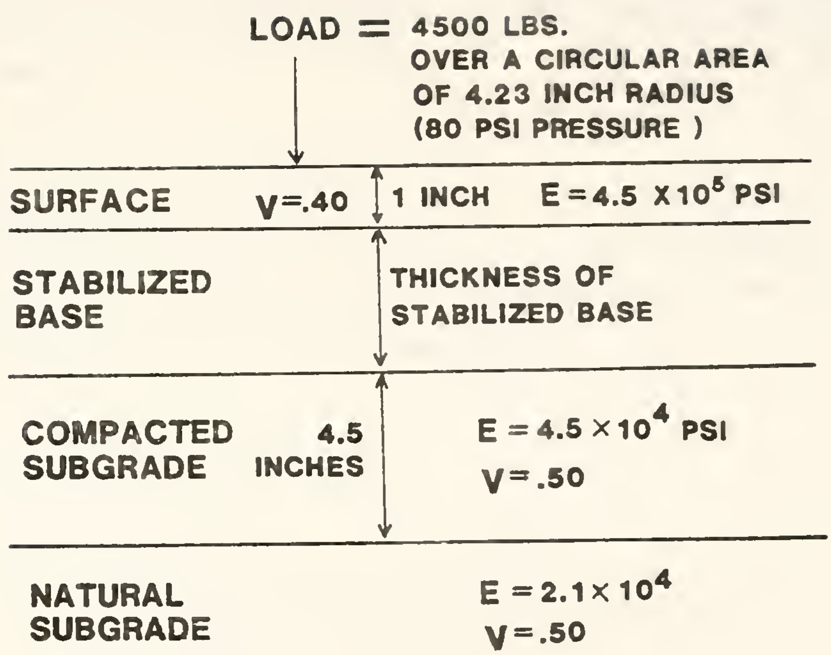


FIGURE 11.1 PAVEMENT SYSTEM FOR LINEAR ELASTIC MULTILAYER ANALYSIS

base of this hypothetical system, and the vertical subgrade deformations were calculated for various thicknesses of the stabilized base. For the range of resilient modulus considered, determination was made of the required thicknesses of the stabilized base for the vertical subgrade deformation to be the same (.00745 in.). Table 11.2 shows the required thicknesses of the stabilized base for the range of resilient modulus considered.

11.3.2 AASHTO Structural Coefficient

In the AASHTO pavement design method [5] , the performance of a pavement section can be directly related to the structural number SN, which can be expressed by the general equation:

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

where a_1, a_2, a_3 = structural coefficients

D_1 = thickness of surface course, in inches

D_2 = thickness of base course, in inches

D_3 = thickness of subbase, in inches

The structural performance can be measured by a combination of several variables. However, the most important variable is the vertical subgrade deformation. The study by Little et al [51] indicated that there was good correlation between the vertical subgrade deformation and the number of load repetitions to failure. Thus, when two pavement systems have the same subgrade deformations under the same loading condition, it is assumed that they have the same structural number.

TABLE 11.2: REQUIRED THICKNESSES OF THE STABILIZED BASE FOR THE SAME VERTICAL SUBGRADE DEFORMATION

Resilient Modulus (psi)	Thickness Required (inch)
5×10^4	7.6
1.0×10^5	6.4
1.5×10^5	5.5
2.0×10^5	5.0
2.5×10^5	4.7
3.0×10^5	4.4
4.5×10^5 (Asphalt Concrete)	4.0

The structural coefficient of the reference asphalt concrete was known to be 0.44 [5]. For the pavement systems with the same subgrade deformations and with everything else the same except for the stabilized base course, the following relationship can be established:

$$a_2 D_2 = (0.44)(4 \text{ in.})$$

where a_2 = structural coefficient of the recycled material

D_2 = required thickness

Using the above relationship and the results in the previous section, the structural coefficients of the recycled materials can be estimated. Figure 11.2 presents the estimated structural coefficients of the recycled materials for the range of resilient modulus considered. It should be noted that using the calculated subgrade deformation to measure the structural performance of a pavement system was a simplified method. The derived structural coefficients were thus only estimated values.

11.4 Prediction of Mix Performance from Gyratory Indices

One of the main objectives of this study was to evaluate the feasibility of using the gyratory machine for designing cold recycled asphalt mixtures. Ideally, the gyratory machine would be used not only as a compactive machine but also as a testing machine. The gyratory compaction has been noted to be an effective technique, since most of the rejuvenating action of the new binder on the old binder took place during the compaction process. This section evaluates how effective a device the gyratory compactor is for evaluating recycled asphalt mixes.

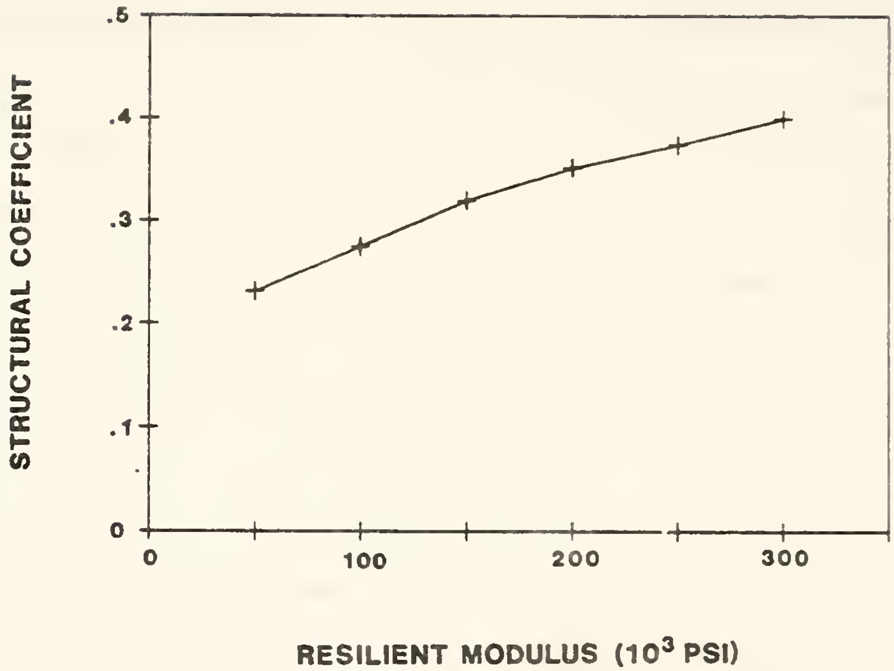
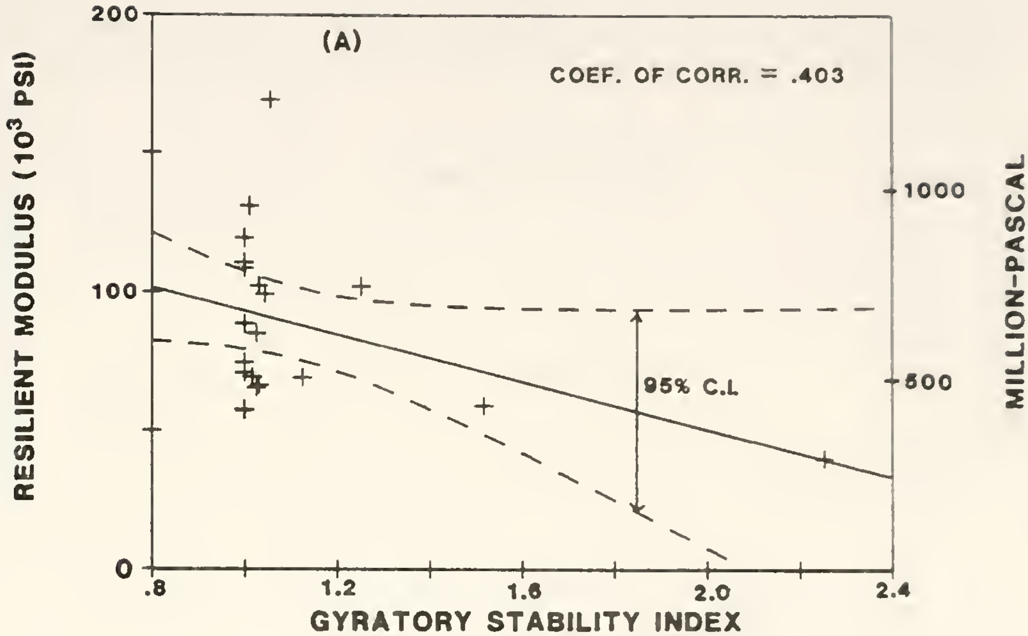


FIGURE 11.2 ESTIMATED AASHTO STRUCTURAL COEFFICIENTS OF THE RECYCLED MIXTURES

The question to be answered is how well the gyratory indices can predict the performance of the recycled mixes.

Correlation analyses were performed between the gyratory indices (GSI and GEPI) and the other response variables (M_R, S_M and Hveem R-values). Results of the analysis indicated that the GSI and GEPI correlated poorly with the resilient modulus and the Marshall stability, and correlated moderately well with the Hveem R-value. Figure 11.3 depicts the plots of resilient modulus at one day cure versus GSI and GEPI. Figure 11.4 depicts the plots of resilient modulus at ultimate curing versus GSI and GEPI. From these plots, it can be observed that the resilient modulus generally decreased with increasing GSI or GEPI. However, at low values of GSI or GEPI, there were wide ranges of possible resilient moduli. Figure 11.5 presents the plots of Marshall stability at ultimate curing versus GSI and GEPI. Similarly, it can be noted that there were wide ranges of possible Marshall stability values at low values of GSI or GEPI. Figure 11.6 shows the plots of Hveem R-value at ultimate curing versus GSI and GEPI. It can be observed that the Hveem R-value had a relatively better correlation with GSI and GEPI. The Hveem R-value generally decreased with increased GSI or GEPI.

From the results of these analyses, it can be concluded that the gyratory stability index and gyratory elasto-plastic index can be used to detect unstable mixtures when the binder content is too high. When the binder content is near or below the optimum level, the GSI and GEPI are close to 1.0 and they can not be used to estimate the absolute values of the resilient modulus or the Marshall stability. The R-value is relatively insensitive to mix parameters when the mixtures is relatively stable, but becomes very sensitive when the mixtures is



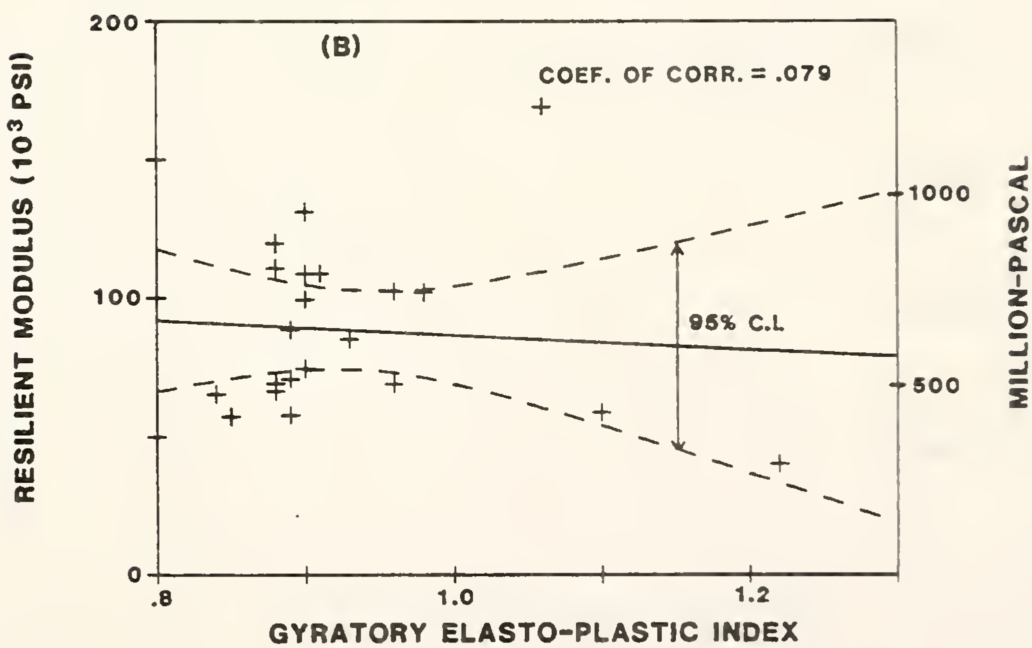


FIGURE 11.3 RELATIONSHIP BETWEEN THE RESILIENT MODULUS AT 1 DAY CURE AND THE GYRATORY INDICES

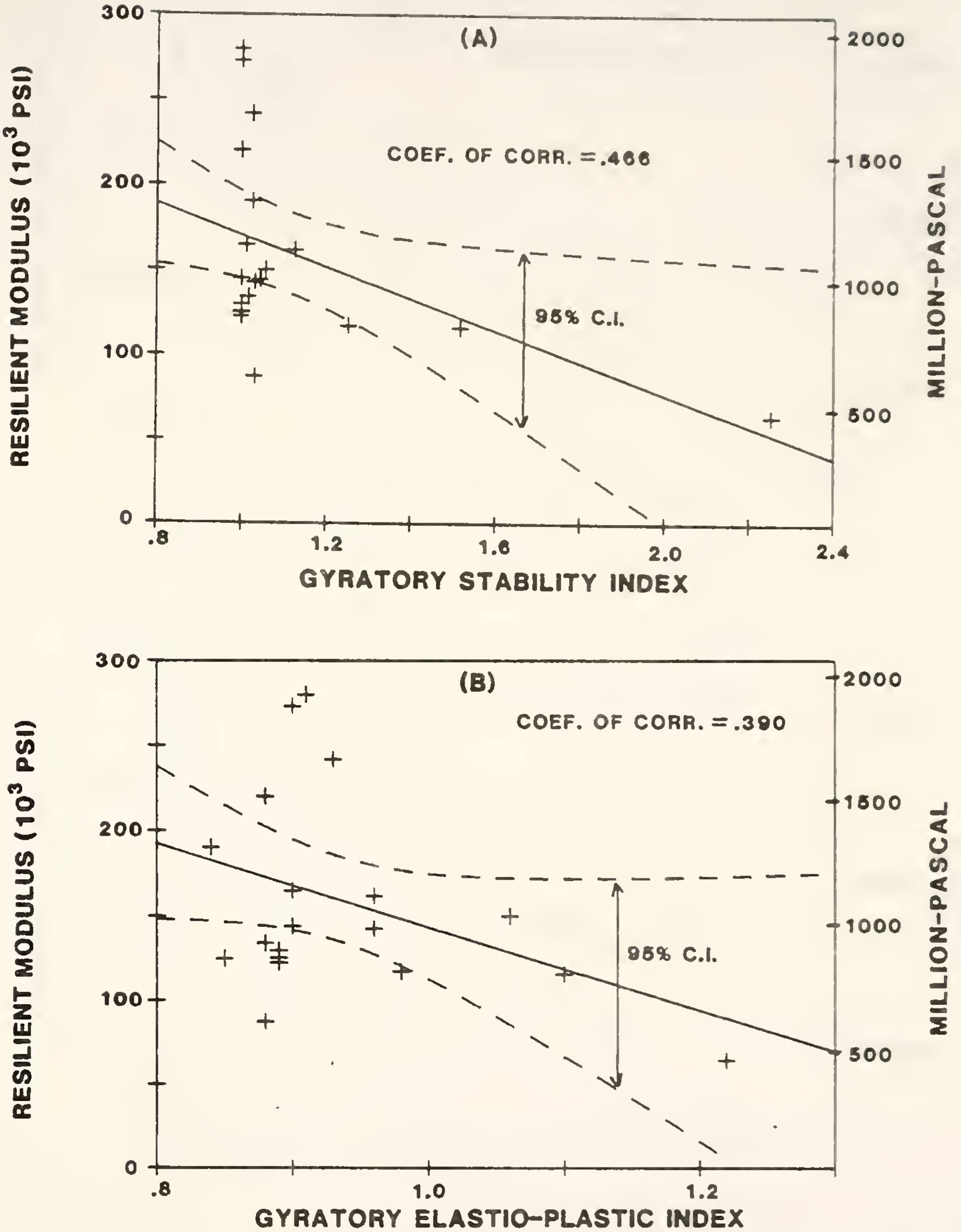


FIGURE 11.4 RELATIONSHIP BETWEEN THE RESILIENT MODULUS AT ULTIMATE CURING AND THE GYRATORY INDICES

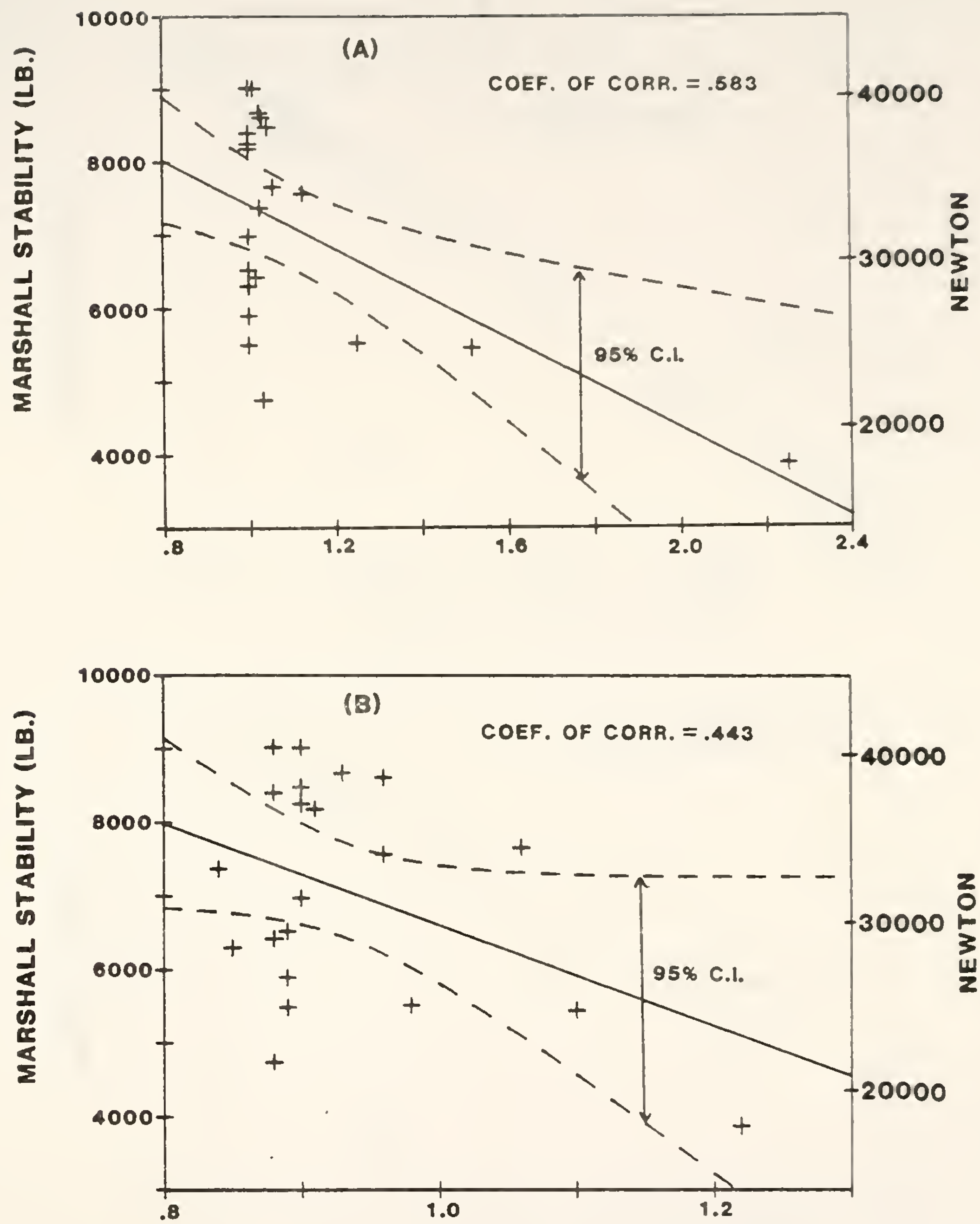


FIGURE 11.5 RELATIONSHIP BETWEEN THE MARSHALL STABILITY AND THE GYRATORY INDICES

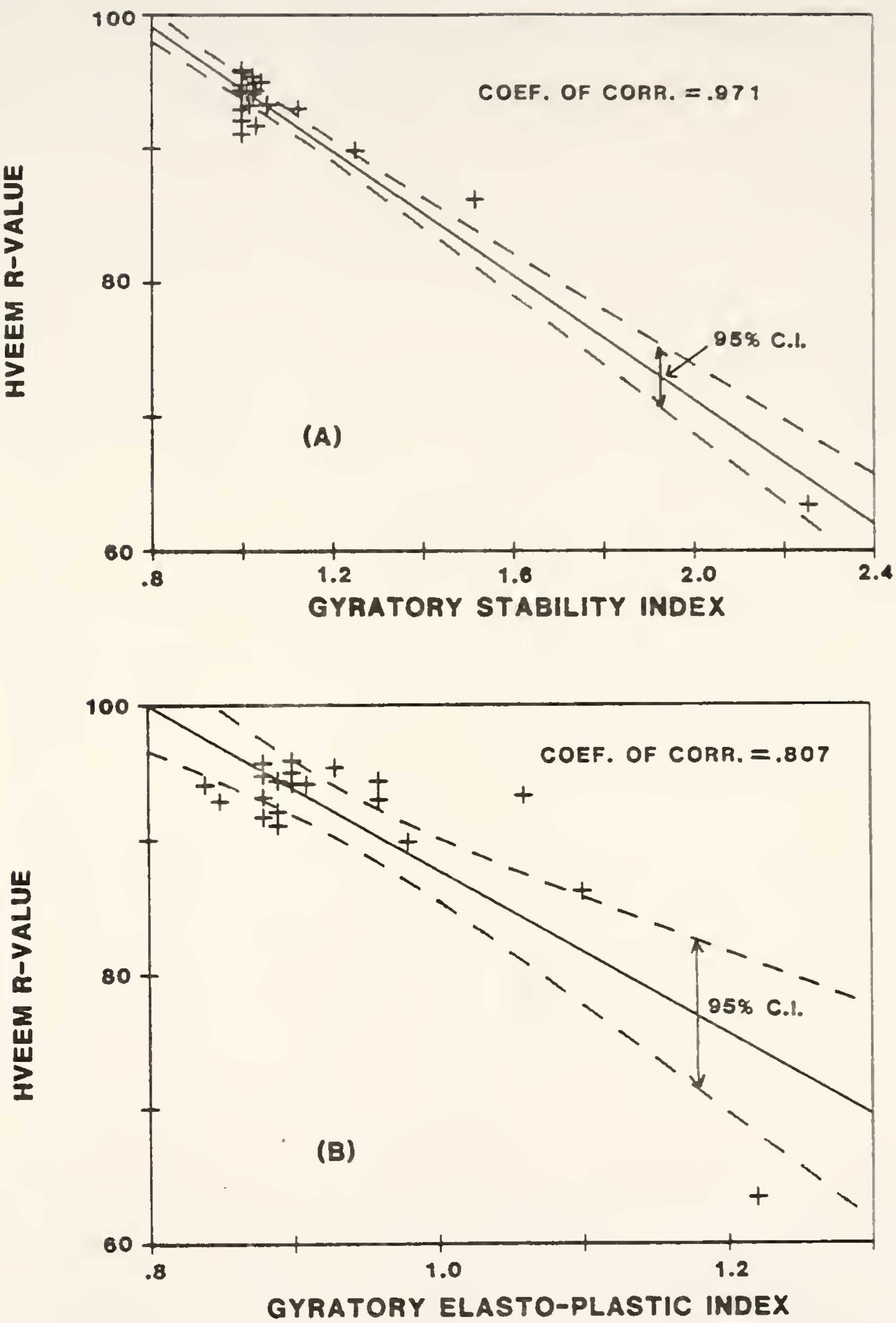


FIGURE 11.6 RELATIONSHIP BETWEEN THE HVEEM R-VALUE AND THE GYRATORY INDICES

relatively unstable. The characteristics of the Hveem R-value are similar to those of GSI and GEPI, and thus the Hveem R-value has relatively better correlations with GSI and GEPI.

CHAPTER 12

CONCLUSIONS AND RECOMMENDATIONS

12.1 Conclusions

An extensive in-depth study of the long-term behavior of cold-recycled asphalt mixtures has been conducted through nine sets of experiments. The scope of the study covered two types of pavement material, three levels of oxydized condition of the old binder, five kinds of added binder or rejuvenating agent, and one type of virgin aggregate. Major conclusions from this laboratory study are summarized as follows:

1. When a virgin binder or rejuvenating agent is added to the aged pavement material, most of the rejuvenating action of the new binder on the old binder will take place during the gyratory compaction process.
2. The binders of the recycled mixes which undergo the initial softening during the compaction process generally increase in stiffness with increasing curing time. This could be explained by the evaporation of the water or the volatile substance from the mixes.
3. Heating at a slightly elevated temperature generally has the effect of accelerated curing. This was true for the 24-hour heating at $60^{\circ}C$ ($140^{\circ}F$), which simulated the ultimate curing condition.

4. The optimum binder content increases with decreasing testing temperature.
5. Higher compactive effort generally produces higher resilient modulus and Marshall stability of the recycled mixture.
6. When the binder content is too high, higher compactive effort generally produces a lower Hveem R-value. When the mix is relatively stable, the Hveem R-value is insensitive to the changes in compactive effort.
7. The gyratory stability index (GSI) and gyratory elasto-plastic index (GEPI) can be used to determine the optimum binder content of a recycled mix. However, they can not be used to estimate the resilient modulus or the Marshall stability of the mix.
8. The effects of water on the properties of the recycled mixes can be evaluated using the Water Sensitivity Test. An increased curing time generally increased the "wet" strength as well as the dry strength of the recycled mix.
9. The recycled mix with foamed asphalt added had properties comparable to those of the mix with asphalt emulsion added, in both dry and wet testing conditions. However, slightly more added binder is needed when foamed asphalt is used. This indicated that the foamed asphalt had less rejuvenating effect on the old binder than that of the asphalt emulsion.

10. Among the three rejuvenating agents used, DUTREX 739 produced the stiffest mixes (e.i., with the highest resilient modulus), while Mobilsol produced the softest mixes. However, the differences were statistically insignificant.
11. When twenty five percent of virgin aggregate was added to the recycled mix, the recycled mix had relatively lower resilient modulus and Marshall stability. This indicated that the virgin binder could coat and adhere to the aged pavement material (aggregate coated with aged binder) better than it could with the virgin aggregate. However, the recycled mix with virgin aggregate added had similar characteristics as those of the other recycled mixes.

12.2 Recommendations

The main purpose of this study was to investigate a method that would allow a decision to be made from short term laboratory results concerning proportioning of ingredients in cold recycled asphalt paving mixtures. Based on the findings from this study, the following design procedures are recommended.

1. An extraction test should be performed on the old pavement material to be recycled. The amount and gradation of virgin aggregate to be added can be determined from the gradation of the recovered aggregate.
2. The gyratory machine can be used to effectively and efficiently determine the optimum amount of virgin binder or rejuvenating agent to be added. The recycled mixes with

various binder contents are to be compacted with the gyratory machine for 60 revolutions at 200 psi (1.38 MPa) and the gyratory indices (GSI and GEPI) are to be obtained from the gyrograph. The optimum binder content is the maximum binder content above which the gyratory stability index (GSI) and the gyratory elasto-plastic index (GEPI) will increase appreciably. (See section 5.4 for the detailed laboratory procedure.)

3. The recycled mixes of optimum binder contents can be characterized by means of the resilient modulus, Hveem R-value and Marshall tests. Since compactive effort and curing time can greatly effect the properties of the recycled mixes, the complete ranges of compactive effort and curing time should be considered for material characterization. The two recommended compactive efforts are 20 revolutions at 200 psi (to simulate initial construction condition) and 60 revolutions at 200 psi (to simulate ultimate traffic compaction). The two recommended curing times are 1 day curing and ultimate curing (by means of 24-hour heating at 60°C).
4. The Water Sensitivity Test as modified from the suggested Asphalt Institute method can be used to determine the effect of water on the recycled mixes. (See section 5.6 for the detailed laboratory procedure).
5. The choice of virgin binder or rejuvenating agent to be used can be determined from the comparison of the material properties of the various recycled mixes considered and from the comparison of their costs.

RECOMMENDATIONS FOR FURTHER RESEARCH

The author would like to make the following recommendations for further research:

1. The characterizations of the cold recycled asphalt mixes in this study were limited to the resilient modulus, the Hveem Stabilometer R-Value and the Marshall tests. The resilient modulus indicates the stress-strain characteristics of the mix and is an essential input parameter to the analytical pavement design methods. Both the Hveem R-Value and the Marshall stability are empirical values which indicate the stability of the mix. However, none of these variables gives any indication of the fatigue properties, which govern the service life of the pavement material. Thus, it is recommended that the fatigue properties of the cold recycled asphalt mixes should be studied. The relationship between the fatigue properties of various recycled mixtures and the parameters such as the viscosity and type of the recycling agent, the binder type and content and the compactive effort, should be established.
2. One of the major disadvantages of a cold recycled asphalt mix is its relatively inferior quality as compared to that of a hot recycled mix. Research should be conducted on

the production of a more stable cold recycled mix, by investigating different mixing and pre-compaction curing methods. The optimum mixing and curing procedures should then be studied as to their application to the actual field construction.

3. Different testing methods have been used by different researchers and engineers to characterize bituminous mixtures. A study should be conducted to relate these different variables to one another, using statistical models and appropriate viscoelastic models for the bituminous mixes.

REFERENCES

LIST OF REFERENCES

1. Phillips, B. A., and condensed by Beaman, R. T., "Dollar Needs to Preserve and Restore U.S. Roads", Transportation Research News, Number 93, pp. 2-5, March-April 1981.

2. Tia, M., "A Laboratory Investigation of Cold-Mix Recycled Bituminous Pavements", Research Report No. JHRP-78-23, Joint Highway Research Project, Purdue University, West Lafayette, Indiana, 1978.

3. Yoder, E. J. and Witczak, M. W., Principles of Pavement Design, Second Edition, John Wiley & Sons, Inc., 1975.

4. A Brief Introduction to Asphalt and Some of its Uses, The Asphalt Institute, Manual Series No. 5, Seventh Edition, 1974.

5. AASHTO Interim Guide for Design of Pavement Structures, American Association of State Highway Officials, Washington, D.C., 1972.

6. Thickness Design - Full-Depth Asphalt Pavement Structures for Highways and Streets, The Asphalt Institute, Manual Series No. 1, Revised Eighth Edition, 1970.

7. Flexible Pavement Guide for Highways, National Crushed Stone Association, Washington, D.C., 1972.

8. Testing Manual, Transportation Laboratory, California Department of Transportation, 1981.

9. Peattie, K. R., "Flexible Pavement Design", Developments in Highway Pavement Engineering - 1, Edited by Pell, P. S., Applied Science Publishers Ltd., London, 1978.

10. Chou, Y. T., An Interactive Layered Elastic Computer Program for Rational Pavement Design, Technical Report S-76-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 1976.

11. Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types, The Asphalt Institute, Fourth Edition, 1974.

12. Goetz, W. H., "Comparison of Triaxial and Marshall Test Results", Proc. AAPT, Vol. 20, 1951.

13. McLaughlin, J. F., and Goetz, W. H., "Comparison of Unconfined and Marshall Test Results", Proc. AAPT, Vol. 21, 1952.

14. Metcalf, C. T., "Use of Marshall Stability Test in Asphalt Paving Mix Design", HRB, Bulletin No. 234, 1959.

15. Brian, D., "A Design Method for Gap-Graded Asphaltic Mixes", Roads and Road Construction, Vol. 50, No. 593, May 1972.

16. Van de Loo, P. J., "Creep Testing, a Simple Tool to Judge Asphalt Mix Stability", Proc. AAPT, Vol. 43, 1974.

17. Darter, M. I., et al., "Factors Affecting the Response of Emulsified Asphalt Mixtures", Proc. AAPT, Vol. 45, 1976.

18. Gadallah, A. A., A Study of the Design Parameters for Asphalt Emulsion Treated Mixtures, Report No. JHRP-76-30, Joint Highway Research Project, Purdue University, West Lafayette, Indiana, 1976.

19. Stevens, D. E., "Fundamentals of Stability Testing of Asphalt Mixes", Proc. AAPT, Vol. 22, 1953.

20. Iida, A., The Effects of Added Softening Agents Upon the Behavior OF Cold Recycled Asphalt Mixtures, Report No. FHWA/IN/JHRP-80/13, Purdue University, West Lafayette, Indiana, 1980.

21. Mamlouk, M. S., Characterization of Cold Mixed Asphalt Emulsion Treated Bases, Report No. JHRP-79-19, Purdue University, West Lafayette, Indiana, 1979.

22. Wood, L. E., and Goetz, W. H., "The Rheological Characteristics of a Sand-Asphalt Mixture", Proc. AAPT, Vol. 28, 1959.

23. Kumar, A., and Goetz, W. H., "Asphalt Hardening as Affected by Film Thickness, Voids and Permeability in Asphalt Mixtures", Proc. AAPT, Vol. 46, 1977.

24. Moavenzadeh, F., and Ashton, J. E., "Analysis of Stresses and Displacements in a Three-Layer Viscoelastic System", Research Report No. R67-31, Materials Research Laboratory, Dept. of Civil Engineering, M.I.T., Cambridge, Massachusetts, 1967.

25. Soils Manuals for the Design of Asphalt Pavement Structures, The Asphalt Institute, Manual Series No. 10, 1978.

26. Schmidt, R. J., "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes", Highway Research Board, Record No. 404, 1972, pp. 22-32.

27. Timoshenko, S., and Goodier, J. N., Theory of Elasticity, 2nd Edition, McGraw-Hill, New York, 1951.

28. Kennedy, T. W., "Characterization of Asphalt Pavement Materials Using the Indirect Tensile Test", Proc. AAPT, Vol. 46, 1977.

29. Monismith, C. W., and Deacon, J. A., "Fatigue of Asphalt Paving Mixtures", Journal of Transportation Engineering, ASCE, Vol. 95, No. TE2, May 1969.

30. Epps, John A., Guidelines for Recycling Pavement Materials, National Cooperative Highway Research Program, Project No. 1-17.

31. Epps, John A. and O'Neal, R. J., "Recycling of Pavement Materials", Research Report 214-12, Cooperative Research Project 2-9-74-214, December 1975.

32. Dunning, R. L., Mendenhall, R. L., and Tischer, K. K., "Recycling of Asphalt Concrete, Description of Process and Test Sections", Proc. AAPT, Vol. 44, 1975.

33. Whitcomb, W. G., Beecroft, G. and Wilson, J. E., "Evaluation of Oregon's First Project in Hot-Mix Asphalt Recycling", Transportation Research Record, 712, 1979.

34. Dollaire, G., "Pavement Recycling Catching On", Civil Engineering, ASCE, pp. 45-49, November, 1980.

35. "In-Place Recycling Cuts Paving Cost, Time", Highway and Heavy Construction, pp. 78-80, June 1981.

36. "Old Hot Mix Slung into Drum Plant for Recycling", Highway and Heavy Construction, p. 108, January 1981.

37. "Thermal Surface Recycling Salvages Old Pavements", Highway and Heavy Construction, pp. 50-51, June 1981.

38. "International Aspects of Pavement Recycling", Rural and Urban Roads, pp. 22-25, July 1981.

39. "Rural Hot-Mix Recycling", Rural and Urban Roads, pp. 40-46, July 1981.

40. "Wis DOT Recycling Booms in '80 - Thanks to the Lessons of '79", Rural and Urban Roads, pp. 26-48, March 1981.

41. "Recycling with Asphalt Emulsions", Rural and Urban Roads, pp. 34-38, March 1981.

42. "County Recycles Soil-Cement Road", Rural and Urban Roads, pp. 30-47, March 1981.

43. "The Decision Process in Pavement Recycling", Rural and Urban Roads, pp. 32-34, July 1981.

44. "Florida's Diligent Move Into Hot-Mix Recycling", Rural and Urban Roads, pp. 28-30, July 1981.

45. "Cost Down, Paving Up in City Recycling Job", Rural and Urban Roads, pp. 37-38, July 1981.

46. "Ontario Plunges into 5-Year Recycling Plan", Rural and Urban Roads, pp. 26-44, July 1981.

47. Elkin, B. L., Evaluation of Recycled Bituminous Pavements, FHWA-DP-39-8, USDOT, FHWA, 1979.

48. Epps, J. A., O'Neal, R. J., and Gallaway, B. M., "A Review of Pavement Materials Recycling Techniques and Associated Laboratory Tests and Evaluation", Proc. AAPT, pp. 304-352, Vol. 45, 1976.

49. Gannon, C. R., Wombles, R. H., Ramey, C. A., Davis, J. P., and Little, W. V., "Recycling Conventional and Rubberized Bituminous Concrete Pavements Using Recycling Agents and Virgin Asphalt as Modifiers", Proc. AAPT, pp. 95-122, Vol. 49, 1980.

50, Tia, M., Wood, L. E., and Hancher, D. E., "The Effects of Added Virgin Binders on the Properties of Cold-Mix Recycled Asphalt Paving Mixtures", Proc. AAPT, pp. 199-218, Vol. 49, 1980.

51. Little, D. N. and Epps, J. A., "Evaluation of Certain Structural Characteristics of Recycled Pavement Materials", pp. 219-251, Vol. 49, 1980.

52. Terrel, R. L., "Laboratory Performance of Recycled Asphalt Concrete", presented at the Symposium on Recycling of Bituminous Pavements, ASTM, St. Louis, Missouri, December 1977.

53. Carpenter, S. H. and Wolosick, J. R., "Modifier Influence in the Characterization of Hot Mix Recycled Material", presented at the 59th Annual Meeting of T.R.B., January 1980.

54. Brennan, M., Tia, M., Altschaeffl, A., and Wood, L. E., "A Laboratory Investigation on the Use of Foamed Asphalt for Recycled Bituminous Pavements", presented at the Annual Meeting of T.R.B., January 1981.

55. Kari, W. J., Santucci, L. E. and Coyne, L. D., "Hot Mix Recycling of Asphalt Pavements", Proc. AAPT, Vol. 48, 1979.

56. Davidson, D. D., Canessa, W. and Escobar, S. J., "Recycling of Substandard or Deteriorated Asphalt Pavements - A Guideline for Design Procedures", Proc. AAPT, Vol. 46, 1977.

57. Tia, M., Wood. L. E., and Hancher, D. E., "The Influence of Certain Factors on the Properties of a Cold-Mix Recycled Asphalt Paving Mixture", Proc. of Canadian Technical Asphalt Association, Vol. 24, November 1979.

58. Terrel, R. L. and Fritchen, "Laboratory Performance of Recycled Asphalt Concrete", STP 662, ASTM, Edited by L. E. Wood, 1978.

59. McRae, J. L., Gyratory Testing Machine Technical Manual, Engineering Developments Company, Inc., Vicksburg, Mississippi, 1965, Revised 1970.

60. Khosla, N. P. and Goetz, W. H., "Tensile Characteristics of Bituminous Mixtures", Proc. AAPT, Vol. 48, 1979.

61. Indiana State Highway Commission, Standard Specifications, Indianapolis, Indiana, 1978.

62. Anderson, P. I., Peterson, D. E., Wiley, M. L., and Betenson, W. B., "Evaluation of Selected Softening Agents Used in Flexible Pavement Recycling", Report No. FHWA-TS-79-204, FHWA, April 1978.

63. Ruth, B. E., and Schaub, J. H., "Gyratory Testing Machine Simulation of Field Compaction of Asphalt Concrete", Proc. AAPT, Vol. 35, 1966.

64. Kumar, A., and Goetz, W. H., "The Gyratory Testing Machine as a Design Tool and as an Instrument for Bituminous Mixture Evaluation", Proc. AAPT, Vol. 43, 1965.

65. Frocht, M. M., "Photoelasticity", Vol. 2, John Wiley and Sons, Inc., 1967.

66. Hondros, G., "The Evaluation of Poisson's Ratio and the Modulus of Materials of a Low Tensile Resistance by the Brazilian Test with Partial Reference to Concrete", Australian Journal of Applied Science, Vol. 10, No. 3.

67. The Asphalt Institute, "Water Sensitivity Test for Compacted Bituminous Mixtures", The Asphalt Institute Laboratory, 1975.

68. Anderson, V. L., and McLean, R. A., Design of Experiments - A Realistic Approach, Marcel Dekker, Inc., New York, 1974, 418 pages.

69. Purdue University Computing Center, "Data Summarization with Homogeneity Tests", G4 DATASUM, 1971.

70. Purdue University Computing Center", SPSS Subprogram ANOVA: N-way Analysis of Variance", G4 SPSS20C, 1979.

71. Purdue University Computing Center, "Beginner's Guide to SPSS", GO SPSS, 19791.

72. Purdue University Computing Center, "Preface to the CDC 6500 Statistical Programs, GO STATPREF, 1977.

73. Finn, F., et al., "The Uses of Distress Prediction Subsystems for the Design of Pavement Structures", Proceedings of the Fourth International Conference on Structural Design of Pavement Structures", Ann Arbor, Michigan, 1977.

74. Shell Research N.V., "Computer Program for Layered Systems under Normal Surface Loads", Amsterdam, Netherlands.

75. Darter, M. I., et al., Development of Emulsified Asphalt-Aggregate Cold Mix Design Procedure, Report No. UILU-ENG-78-2006, University of Illinois, Urbana, Illinois, February, 1978.

APPENDICES

This copy of this report does not include the Appendices listed in the Table of Contents. These are identified as:

A copy of all or any of the above Appendices may be obtained for the cost of reproduction from:

Joint Highway Research Project
Civil Engineering Building
Purdue University
West Lafayette, Indiana 47907

COVER DESIGN BY ALDO GIORGINI