SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-78-23

A LABORATORY INVESTIGATION
OF COLD-MIX RECYCLED
BITUMINOUS PAVEMENTS

Mang Tia

PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

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A LABORATORY INVESTIGATION OF COLD-MIX RECYCLED BITUMINOUS PAVEMENTS

TO: H. L. Michael, Director
Joint Highway Research Project

December 12, 1978

File: 2-8-4

FROM: Leonard E. Wood, Research Engineer
Joint Highway Research Project

Project: C-36-21D

Attached is an Interim Report "A Laboratory Investigation of Cold-Mix Recycled Bituminous Pavements", 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 Professors Leonard E. Wood and Donn E. Hancher.

This report presents the findings of a detailed laboratory investigation of the effects of the amount and type of added binder, the amount of added moisture, the added virgin aggregate, the compactive effort and the curing time on the properties of a cold recycled asphalt mixture.

The report is offered as partial fulfillment of the objectives of the Research Project and will be submitted to ISHC and FHWA for review and acceptance.

Respectfully submitted,

Leonard E. Wood
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Interim Report

A LABORATORY INVESTIGATION OF COLD-MIX RECYCLED BITUMINOUS PAVEMENTS

by

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Joint Highway Research Project

Project No.: C-36-21D

File No.: 2-8-4

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission
and the
U.S. Department of Transportation
Federal Highway Administration

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

Purdue University
West Lafayette, Indiana
December 12, 1978

1. Report No. JHRP-78-23	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle A LABORATORY INVESTIGATION OF COLD-MIX RECYCLED BITUMINOUS PAVEMENTS		5. Report Date December 12, 1978	
		6. Performing Organization Code	
7. Author(s) Mang Tia		8. Performing Organization Report No. JHRP-78-23	
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(16) Part II	
12. Sponsoring Agency Name and Address Indiana State Highway Commission 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 <p>In this laboratory study, the effects of different factors on the properties of a cold-recycled asphalt mixture were investigated. The factors investigated were the amount and type of added binder, the amount of added moisture, the added virgin aggregate, the compactive effort and the curing time.</p> <p>A laboratory procedure for preparing and testing cold recycled mixtures was developed and used in the study. Specimens were compacted with the Gyratory machine and tested in the Hveem Stabilometer and Cohesimeter. The Water Sensitivity Test was used to evaluate the resistance of the recycled mixtures to water.</p> <p>The study indicated that the Gyratory machine could be a potentially valuable tool in the evaluation of long time performance of recycled mixtures. The shearing action and the high compactive effort of the gyratory compaction are believed to cause the old and the new binders to act together and thus the long term effect of the rejuvenating action could be detected during compaction.</p> <p>The total effective binder content was found to be the most important factor to the performance of a cold recycled mixture. It was hypothesized that different added virgin binders had different rejuvenating effects on the old binders. The resistance to water depended on the binder content and the type of added binder.</p> <p>A testing procedure for cold-recycled bituminous mixtures was recommended from the findings of this study.</p>			
17. Key Words Cold Recycling, Bituminous Mixture, Gyratory Compaction, Hveem Method, Curing, Water Resistance, Virgin Binder, Virgin Aggregate		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) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 176	22. Price

ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation to his co-major professors, Dr. Leonard E. Wood and Dr. Donn E. Hancher for their guidance, encouragement and advice during the entire study. He would like to convey his gratitude to Dr. L.E. Wood for the guidance in the laborator work, the long hours of discussion and constructive criticism, and the careful review and suggestions for revision of the manuscript. He was particularly grateful to Dr. D.E. Hancher for the assistance in choosing the research topic, its funding, and the advice given throughout the author's research and courseworks.

The author would like to express his special gratitude to Mr. James L. McKinney for the write-up of the proposal for this research project, the co-operation in obtaining the pavement materials for this study, and the assistance in the preliminary laboratory work of this study. He would like also to convey his appreciation to Mr. L.D. Tucker and Mr. Barry Elkin for serving as members of the Recycling Advisory Committee, and to Prof. Martin J. Gutzwiller for being a member of the advisory committee for the author's Master's degree program.

He would like to convey thanks to K.E. McConaughay, Inc. for supplying the asphalt emulsion, and to American Oil Co. for supplying the asphalt cement, to be used in the study. The valuable technical assistance given by the Research and Training Center, West Lafavette, was appreciated. Appreciation is also extended to Mr. Michel S. Mamlouk for obtaining the sand and gravel used in the study, to Mr. Dave White for his help in the laboratory, to Mr. David W. Bragg for the drafting work, and to Mr. Emmette L. Black for the photographs.

The financial support of this research from the Indiana State Highway Commission and the Federal Highway Administration, U.S. Department of Transportation is duly appreciated.

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LIST OF SYMBOLS

$\%AS_a$	- Percent AE residue or asphalt added
$\%AS_t$	- Percent total asphalt content
$\%W$	- Percent initial moisture added
$\%W_a$	- Percent water absorbed (in Water Sensitivity Test)
$\%WC$	- Percent moisture retained
AC	- Asphalt cement
AE	- Asphalt emulsion
C	- Cohesimeter value
D_2	- Displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi (34.5 to 689 kPa), measured in revolutions of a calibrated pump handle
G_b	- Bulk specific gravity
L	- Weight, in gm, necessary to cause failure of the specimen in Cohesimeter Test
MC	- Medium curing cutback
P_h	- Horizontal pressure in stabilometer
P_v	- Applied vertical pressure in stabilometer
R	- Hveem Resistance value
S	- Hveem Stabilometer value

HIGHLIGHT SUMMARY

In this laboratory study, the effects of different factors on the properties of a cold-recycled asphalt mixture were investigated. The factors investigated were the amount and type of added binder, the amount of added moisture, the added virgin aggregate, the compactive effort and the curing time. The binder materials that were added to the recycled mixtures included AE-150, AE-90, MC-3000 and AC-2.5.

A laboratory procedure for preparing and testing cold recycled mixtures was developed and used in the study. Specimens were compacted with the Gyratory machine and tested in the Hveem Stabilometer and Cohesimeter. The Water Sensitivity Test was used to evaluate the resistance of the recycled mixtures to water. The response variables measured and evaluated in this study include the Hveem Resistance Value (R-Value), the modified Hveem Stabilometer Value (S-Value), the Cohesimeter Value (C-Value), the Bulk Specific Gravity, the Percent Moisture Retained and the Percent Water Absorbed (in the Water Sensitivity Test).

The study indicated that the Gyratory machine could be a potentially valuable tool in the evaluation of long time performance of recycled mixtures. Unstable recycled mixtures could be detected during

gyratory compaction by the increasing gyratory angle in the gyrograph. Instability of a recycled pavement is usually detected after some period of traffic compaction when rejuvenation of the old binder has taken place. The shearing action and the high compactive effort of the gyratory compaction are believed to cause the old and the new binders to act together and thus the long term effect of the rejuvenating action could be detected during compaction.

The results of the study showed that the most important factor to the performance of a cold recycled mixture was its total effective binder content. Excessive binder content was the major cause of instability of a recycled mixture. It was hypothesized that different added virgin binders had different rejuvenating effects and thus caused the differences in the properties of the recycled mixtures. A simplified model of the recycled mixture based on this hypothesis was presented.

Recycled mixtures of higher binder contents generally showed greater resistance to water. The binders, in the order of decreasing susceptibility to water, were AE-90, MC-3000, AE-150 and AC-2.5.

A testing procedure for cold recycled bituminous mixtures was recommended from the results of this study.

CHAPTER 1

INTRODUCTION

One of the major costs of the highway system has been the repairing and replacing of worn-out pavements. Discarded pavement material has been put back into use on a limited basis for many years. Recently, the increasing price of pavement binder material, the scarcity of aggregate resources, the increasing fuel costs and the problem of disposal of solid wastes have made the recycling of old pavement material an attractive process, socially and economically. The benefits of recycling old pavement material may include substantial savings in cost, conservation of aggregate resources, reduction in fuel consumption and reduction in environmental pollution.

There are three general methods in recycling asphalt concrete pavement, namely, surface, hot-mix and cold-mix recycling (34)*. In the surface recycling process, the surface of an existing asphalt pavement is "recycled" in-place. The pavement surface may be scarified, heated, remixed, relaid and rolled. The finished product may be used as the final surface or may in some instances be overlaid with an asphalt surface course. In the hot-mix recycling process, existing pavement material is removed, crushed and mixed hot with added asphalt at a

* Number in parentheses indicate references listed in the bibliography.

central plant. New aggregates may be added in this process. In the cold-mix recycling process, existing pavement material is removed, crushed and remixed cold, in-place or sometimes, in plant. New asphalt or sometimes new aggregates may be added. The finished product is usually used as a stabilized base, to be overlaid with an asphalt surface course. In general, the finished product of the cold recycling process is not as stable as that produced by the hot recycling process. However, in cold-mix recycling, little or no heat is used, less and simpler construction equipment is needed, and thus construction costs can be substantially reduced. Using the cold-mix process also eliminates the problem of air pollution, which the hot mix recycling process may encounter.

In recent years, many asphalt pavements have been recycled and put into service. Some of these recycled pavements have performed satisfactorily, while others have not. Much work still remains to be done in the development of an appropriate laboratory design procedure for recycled asphalt pavements.

This laboratory study had the following objectives:

1. To evaluate the effects of different factors on the properties of a cold-mixed, recycled asphalt material - namely
 - a. amount and type of added binder
 - b. amount of added moisture
 - c. added virgin aggregate
 - d. compactive effort
 - e. curing time

2. To determine the suitability of cold recycled asphalt mixture for stabilized base or surface course.
3. To develop some guidelines for the design of cold-mix recycled pavement from the understanding of the behavior of these recycled mixtures.

CHAPTER 2

LITERATURE REVIEW

2.1 Cold-Mix Recycling Process

One of the most common ways to dispose of old pavements is to use them as embankment material (60). Old asphalt mixtures can be put back into use in the road without the application of heat. This process of re-using discarded asphalt pavement material without the application of heat is known as cold-mix recycling. One form of cold recycling is to use the crushed old pavement material as a base course without the addition of virgin aggregates or binder material (5). In other cases, new binder material is added to the crushed asphalt pavement material, mixed cold, and recompactd into stabilized base or surface course. When the recycled material is used as a surface course, a wearing course or seal coat is usually applied.

2.2 Binder Materials Used In Cold-Mix Recycling

Some of the binders added to the cold-recycled mix are medium curing cutbacks such as MC-800 (9,33), cement & water (9), soft asphalt cement having a penetration grade of 200-250 (7) and a slow or medium setting asphalt emulsion such as CMS-2 (23,34). In some experimental projects, combinations of two binder materials are used — such as asphalt cement having a penetration grade of 100, cement & water (9).

Old, hardened asphaltic concrete can be softened with certain rejuvenating agents. In an experimental project of cold recycling of asphaltic concrete pavement in Texas, Reclamite, an asphalt softening agent was used to soften the aged asphalt (23). Reclamite, diluted with water, was dispersed throughout the crushed material and allowed to set for a minimum of six hours before Cationic Emulsion (CMS-2) was added to the mix.

2.3 Problems Encountered In Cold-Mix Recycling Process

The cold-mix recycling process may offer savings in cost with respect to hot-mix recycling in that little or no heat is used. Due to the fact that little or no heat is applied to the mix, it is more difficult to mix the crushed pavement material thoroughly and to obtain a good coating with the new binder material. Initial pulverizing and mixing are usually enhanced by the adding of water. To facilitate coating of the mix, an asphalt binder is sometimes heated to a high temperature before being delivered to the mix (7). Various rejuvenating agents can be used to facilitate blending and coating (15,23).

A cold recycled mix is also more difficult to compact. The number of passes required of the compactor may have to be greater. When an emulsion is used as an additional binder, water is usually added to facilitate compaction. However, the time required for curing to the required strength is longer when the moisture content is higher. When cutbacks or emulsions are used, a curing period is usually required for the pavement to achieve its required strength.

The most common form of failure in the recycled pavement is the phenomena of bleeding after the pavement has been in service for a period of time. Bleeding is the upward movement of asphalt in a pavement creating a film of asphalt on the surface.

Recycled projects have so far been done mostly on a trial-and-error basis. Reasons for the failure of some recycled pavements are not yet understood. It was also observed that reports of unsuccessful projects were rarely found in the literature.

2.4 Laboratory Design Methods For Recycled Asphalt Mixtures

Many mix designs for recycled mixtures are based on intuition and trial-and-error processes. Since recycling projects have become more popular and larger in scale, a laboratory analysis of recycled mix designs takes on more importance. Methods of laboratory analysis of recycled mixtures that have been tried vary from place to place. There is yet no standardized or widely used laboratory design procedure. Some guidelines for laboratory design procedures for hot recycled mixtures have been suggested by some researchers, but little work has been done in the area of cold-mix recycling.

Conventional testing procedures have been used in the evaluation of recycled mixtures. They include the Marshall Stability Test, Hveem Stability & Cohesimeter Test, Splitting Tensile Test (15) and Resilient Modulus Test (33,15). In most cases, an extraction is performed on the old pavement material to determine the gradation of the existing aggregate, its asphalt content and properties of the old asphalt binder. An extraction is sometimes conducted on the recycled

mixtures after the addition of new binder material. Tests on the recovered bitumen include the penetration, viscosity and ductility tests.

The above mentioned tests were used primarily for hot recycled mixtures but were sometimes used for cold recycled mixtures as well. In cold-mix recycling, the mixing and coating, which are affected by the construction method as well as the mixture design, have a great influence on the performance of the mixture. The laboratory analysis will have to be correlated with field experience and the type of equipment available.

In a cold-recycling project in Michigan in which an asphalt cement of penetration grade of 200-250 was used (7), the laboratory tests included the extraction of bitumen from cores to determine the bitumen content and the penetration on recovered asphalt. Cores were again taken from the recycled pavement, and bitumen content and penetration on the recovered asphalt were again determined. The density of the compacted pavement was also measured.

So far, no specific test method has been proven to be more suitable than others in the evaluation of a recycled mixture. Whether or not these conventional testing procedures can be used to evaluate recycled mixes effectively remains to be evaluated by field experience.

CHAPTER 3

EQUIPMENT AND MATERIAL

3.1 Equipment

The major pieces of equipment used in this laboratory study include the jaw crusher, the gyratory testing machine (compactor), the Hveem Stabilometer and the Hveem Cohesimeter.

3.1.1 Jaw Crusher

The jaw crusher, shown in Figure 1 was used to crush the old pavement material for use in the laboratory analysis. Material was crushed by the vibratory motion of the jaw. The opening of the crusher is adjustable. The maximum opening of the crusher was set at 1 inch (2.54 cm.). Thus, theoretically, material coming out of the jaw crusher would have a maximum size of 1 inch (2.54 cm.).

3.1.2 Gyratory Testing Machine

Figure 2 shows the gyratory testing machine used for compaction of the specimens. The gyratory machine has a fixed upper roller. The angle of gyration was set at 1 degree, and the ram pressure was adjusted to 200 psi (1.38 MPa). The heating system of the gyratory machine was not used. The mold and the mold chuck were operated at room temperature. Room temperature was at 70-75°F (21-24°C).

FIGURE 1 JAW CRUSHER

FIGURE 2 GYRATORY TESTING MACHINE

The gyrograph recorder records the shear displacement of a specimen during compaction (gyratory angle). Figure 3 illustrates a typical gyrograph band.

3.1.3 Hveem Stabilometer & Compression Machine

Figure 4 shows the Hveem Stabilometer and compression machine used in the study. Specimens were tested in the stabilometer at room temperature instead of the 140°F (60°C) called for in ASTM D156Q-71.

The compression machine applied test loads at a head speed of 0.05 inch per minute (0.02 mm. per second) up to a maximum of 6,000 lbs (26.69 kN).

3.1.4 Hveem Cohesimeter

The Hveem Cohesimeter used in the study is depicted in Figure 5. The Cohesimeter measures the tensile strength or cohesion of the mixture. Tests were conducted at a temperature of 140°F (60°C). The heater inside the insulated box kept the temperature at 140°F (60°C) during testing. The load was applied at a rate of 1,800 g per minute.

3.2 Binder Materials

Virgin asphalt materials that were added to the recycled mixtures included AE-150, AE-90, MC-3000 and AC-2.5.

3.2.1 AE-150

AE-150 mixing grade emulsified asphalt was used for the major portion of the laboratory investigation. It was formulated and manufactured by the K.E. McConnaughay Laboratory in Lafayette, Indiana. Its physical properties are as follows:

FIGURE 3 TYPICAL GYROGRAPH BANDS

FIGURE 4 HVEEM STABILOMETER & TESTING MACHINE

FIGURE 5 HVEEM COHESIOMETER

Residue by distillation	70.0%
Penetration of distillation residue 77°F (25°C), 5 sec., 100 g.	215
Oil distillate	5%
Float test on distillation residue	200 ⁺ sec.

3.2.2 AE-90

AE-90 mixing grade emulsified asphalt used in the study was also formulated and manufactured by the K.E. McConnaughay Laboratory in Lafayette, Indiana. It has the following physical properties:

Residue by distillation	71.0%
Penetration of distillation residue 77°F (25°C), 5 sec., 100 g.	120
Oil distillate	0%
Float test on distillation residue	200 ⁺ sec.

3.2.3 MC-3000

MC-3000 is a highly viscous medium curing cutback. It was heated to a temperature of 200°F (93°C) before mixing. The cutback had the following physical properties:

Residue from distillation to 680°F (360°C), by volume	94.6%
Penetration of distillation residue 77°F (25°C), 5 sec., 100 g.	240
Distillate, percent by volume of total distillate to 680°F (360°C)	
to 500°F (260°C)	0%
to 600°F (315°C)	40%

3.2.4 AC-2.5

An asphalt cement with a penetration of 200 was used in the study. The asphalt cement was manufactured and supplied by American Oil Company, Whiting, Indiana. After being heated to a temperature of 350°F (177°C) for 2-3 minutes, the asphalt cement had a retained penetration of 170 to 180.

The asphalt cement was heated to 350°F (177°C) before mixing with the recycled mixtures.

3.3 Salvaged Pavement Material

Approximately 500 pounds (227 Kg) of salvaged pavement material were taken from SR 32, Indiana, to be used in this laboratory study. The material was excavated with hoes from an area in the centerline of the road where extensive alligator cracks were present and were forming a pot hole. The location is at a point called "Perryville Hill", approximately one mile (1.6 Km) east of Perrysville, Indiana. SR 32 is an old, stage-constructed highway. Its construction records show the following:

- 1975 - The pavement received a full-width sand and squeegee treatment.
- 1974 - The pavement received a full-width sand and squeegee treatment.
- 1971 - The pavement received HAE Type 2 surface for full 18' width.
- 1959 - The pavement received a bituminous surface treatment for full 16' width.

1958 - The pavement received Bituminous Coated Aggregate surfacing, 1 to 6 inches thick, 20' wide.

1940 - State took over the road from the county; road was gravel.

3.3.1 Crushed Pavement Material

The pavement material was crushed in the laboratory using a jaw crusher set at 1 inch (2.45 cm) opening. A typical crushed pavement material is depicted in Figure 6. The crushed material was sieved into 6 size-groups — $+\frac{1}{2}$ " (12.5 mm), $\frac{1}{2}$ "- $\frac{3}{8}$ " (12.5-9.5 mm), $\frac{3}{8}$ "- $\#4$ (9.5-4.75 mm), $\#4$ - $\#8$ (4.75-2.36 mm), $\#8$ - $\#16$ (2.36-1.18 mm) and size less than $\#16$ (1.18 mm). The percentage by weight of the total for each size group is given below:

<u>Size-Group</u>	<u>Percent Of Total</u>
$+\frac{1}{2}$ " (+12.5 mm)	35.7
$\frac{1}{2}$ "- $\frac{3}{8}$ " (12.5-9.5 mm)	16.5
$\frac{3}{8}$ "- $\#4$ (9.5-4.75 mm)	22.1
$\#4$ - $\#8$ (4.75-2.36 mm)	11.7
$\#8$ - $\#16$ (2.36-1.18 mm)	5.9
$\#16$ - (1.18 mm -)	8.1

The pavement material in all size groups were to be recombined in this same proportion. This was done to obtain homogeneity in each batch of pavement material used for the study.

FIGURE 6 CRUSHED PAVEMENT MATERIAL

3.3.2 Recovered Asphalt

An extraction performed on the pavement material indicated a bitumen content of 4.5 to 5.0% by weight of aggregate. The asphalt that was obtained by the Reflux Extraction Method (ASTM D 2172-72 Method B) and the Abson Recovery Method (ASTM D 1856-69) conducted by the Research and Training Center, ISHC, W. Lafayette, Indiana, had a penetration of 38 (77°F (25°C), 100g, 5 sec.).

3.3.3 Recovered Aggregate

Extraction of bitumen was performed on the pavement material before and after the crushing operation. Sieve analysis of the recovered aggregate showed no degradation of the aggregate due to the crushing operation. The recovered aggregate contained mainly sand and gravel. The gradation values were obtained from sieve analysis of the recovered aggregate from 3 batches of crushed pavement material (1000 g each). The gradation of the recovered aggregate fell within the Indiana specification for Type II No.8 aggregate (see Figure 7).

3.4 Virgin Aggregate

Virgin aggregate used in this study was a sand and gravel obtained from the Western Indiana Aggregate Corporation gravel pit in West Lafayette, Indiana. The sand and gravel consists mainly of limestone, dolomite and a small amount of granite and quartz. They were washed, dried and sieved into standard sieve sizes.

CHAPTER 4

DESIGN OF THE EXPERIMENT

This laboratory study consisted mainly of three phases. The first phase dealt mainly with choosing the response variables and establishing a testing procedure for the study. This is described in Chapter 5, the chapter on the development of the experimental procedure. The laboratory procedures developed in Phase I were used in Phase II and Phase III, which were the main body of this study. In the second phase of the study, effects of several factors to the recycled mixtures were investigated using AE-150 as a virgin binder material. In the third phase, the study was extended to three other binder materials, namely, AE-90, MC-3000 and AC-2.5.

The following sections consist of the descriptions of the response variables, the experimental parameters and the experimental designs for Phase II and Phase III of the study.

4.1 Response Variables

The main concern of this study was the suitability of the cold-mix recycled material as a stabilized base or as a surface course for pavement. The response variables measured were to give indications of the quality of performance as a stabilized base or as a surface course. The six response variables chosen are described in the following.

4.1.1 Hveem Resistance Value (R-Value)

The Hveem Resistance Value (R-Value) is used in the California Division of Highway for the evaluation of stabilized base mixtures. It measures the resistance to deformation as a function of the transmitted lateral pressure to that of the applied vertical pressure. Specimens of 4 inches (101.6 mm) in diameter and about 2½ inches (63.5 mm) in height is tested in the Hveem Stabilometer at room temperature. The testing procedure was similar to that of the Hveem Stabilometer Test with the exception that the vertical pressure is applied only up to 160 psi (1.10 kPa). The equation for calculating the R-Value is as the following:

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

where

R = Hveem Resistance Value

P_v = Applied vertical pressure, 160 psi (1.10 MPa)

P_h = Horizontal pressure at $P_v=160$ psi (1.10 MPa)

D_2 = Displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi (34.5 to 689 kPa), measured in revolutions of a calibrated pump handle

4.1.2 Hveem Stabilometer Value (S-Value)

The Hveem Stabilometer Value (S-Value) is a stability value used in the design criteria for hot-mix surface course. The Hveem stabilometer test used in this study was modified. Samples were tested at room temperature instead of at 140°F (60°C) as specified in the ASTM

standards. The equation for calculating the S-Value is as follows:

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

where

S = Hveem Stabilometer Value

P_v = Applied vertical pressure, 400 psi (2.76 MPa)

P_h = Horizontal pressure at $P_v=400$ psi (2.76 MPa)

D_2 = Displacement of stabilometer fluid, number of turns of pump handle necessary to increase horizontal pressure from 5 to 100 psi (34.5 to 689 kPa)

4.1.3 Cohesimeter Value (C-Value)

Cohesimeter value (C-Value) is usually used in the design criteria for surface course mixture. It measures the cohesive character of the mix. Specimens after testing in the stabilometer were tested in the Cohesimeter at 140°F (60°C). The equation for calculating the C-Value is as follows:

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

where

C = Cohesimeter Value, gm per in.

L = Weight necessary to cause failure, gm

H = Height of specimen, in.

4.1.4 Bulk Specific Gravity (G_b)

The bulk specific gravity was obtained by the Saturated Surface Dry method, ASTM D2726. The specific gravity gives an indication of the degree of compaction and the compactibility of a mix.

4.1.5 Percent Moisture Retained (%MC)

Percent moisture retained is the moisture retained in the specimen at the time of testing, expressed as percent by weight of the dry mixture. It was determined by drying the crushed specimen in the oven at 230°F (110°C) for 24 hours. It gives some indication of the degree of curing for mixtures using asphalt emulsion as additional binder.

4.1.6 Percent Water Absorbed (% W_a)

Percent water absorbed is expressed as a percent by weight of the mixture before submersion in water. It was obtained by the difference in weight of the specimen after it is submerged in water for 24 hours. It gives an indication of the amount of permeable voids in the compacted specimen.

4.2 Factors (Independent Variables)

Factors that affect the performance of an asphalt mix are of most concern in a mix design. The parameters under investigation in this study were believed to be important factors in affecting the properties of a recycled asphalt mix. They are described in the following sections.

4.2.1 Percent AE Residue or Asphalt Added ($\%AS_a$)

Percent AE residue or asphalt added is expressed as the percent by weight of the total mixture. For ease of comparison between different mixes, another variable, Percent Total Asphalt Content ($\%AS_t$), was also used.

4.2.2 Percent Moisture Added Initially ($\%W$)

Percent moisture added is the amount of water added initially to the mixture and is expressed as percent by weight of total mix.

4.2.3 Curing Time

Curing time is the time allowed for a specimen to gain strength between the time of compaction and the time of testing. Two curing times were used. They were 1 day and 7 days.

4.2.4 Virgin Aggregate

Two gradations of virgin aggregate (consisting of sand and gravel) were used. One gradation consisted of coarse aggregates only. The other gradation used represented an Indiana Type II No.8 aggregate. Either 0% or 25% of the virgin aggregate was used.

4.2.5 Compactive Effort

Different compactive efforts were produced by different numbers of revolutions made by the gyratory compactor. Most of the specimens were compacted at 40 revolutions. Other compactive efforts investigated were 10, 30 and 50 revolutions.

4.2.6 Types Of Binder Materials

Four types of binder materials were used. They were AE-150, AE-90, MC-3000 and AQ-2.5.

4.3 Experimental Designs

Laboratory studies in Phase II of the study consisted mainly of four sets of experiments, and Phase III studies consisted mainly of one set of experiments. They are described in the following sections.

4.3.1 Study Design No.1

The first set of experiments was to determine the effects of curing time, percent moisture added and percent AE residue added, on the properties of the recycled mixture. It was a completely randomized 2X3X4 factorial design (see Table 1). One to three replicates were made per cell. The aims of this study were to determine the optimum amount of AE residue and moisture to be added to the recycled mix and to study the extent of the effect of curing time. This set of experiments represented a total of 54 specimens.

4.3.2 Study Design No.2

The second set of experiments was to investigate the effects of virgin aggregate on the properties of recycled mixtures. The independent variables were:

1. Virgin aggregate gradation — Two different gradations of sand and gravel were used; one consisted of coarse aggregates, and the other was a typical Indiana Type II No.8 aggregate.

TABLE 1 FACTORIAL DESIGN FOR THE STUDY
OF THE EFFECT OF %AE RESIDUE
ADDED, %W ADDED AND CURING TIME
ON PROPERTIES OF RECYCLED MIXTURES

% AS _a (AE residue added) % W (water added) CURING TIME		0	1	2	3
1 DAY	0	1*	3	3	2
	1	1	3	3	2
	2	1	3	3	2
7 DAYS	0	1	3	3	2
	1	1	3	3	2
	2	1	3	3	2

NOTE:

* Number indicates the number of replicates per cell.

BINDER MATERIAL: AE-150

COMPACTIVE EFFORT: 40 REVOLUTIONS

TEST: DRY

TABLE 2 DESIGN FOR THE STUDY OF THE EFFECT OF VIRGIN AGGREGATE ON THE PROPERTIES OF RECYCLED MIXTURES

CURING TIME	VIRGIN AGGREGATE % AS ^a (total asphalt) % W (water content added)	COARSE		TYPE II	
		4.5 %	5.5 %	4.5 %	5.5 %
1 DAY	0	X	X		
	1	X	X	X	X
7 DAYS	0	X	X		
	1	X	X	X	X

NOTE:

BINDER MATERIAL: AE-150

COMPACTIVE EFFORT: 40 REVOLUTIONS

25 % VIRGIN AGGREGATE

X 3 REPLICATES PER CELL, TESTED DRY

2. Percent Moisture Added — Two levels of %W were used (0% and 1%) for mixtures with coarse virgin aggregate. For mixtures with Type II virgin aggregate, only one level of %W was used (1%).
3. Percent Total Asphalt Content — The two levels of %AS_t used were 4.5% and 5.5%.
4. Curing time — The two levels of curing time used were 1 day and 7 days.

Restriction on randomization was present due to the fact that testing on the mixes with coarse aggregates were performed before the mixes with Type II virgin aggregate. The experimental design is shown in Table 2. This set of experiments represented a total of 36 specimens.

4.3.3 Study Design No.3

The third set of experiments was to study the effect of water on the recycled mixtures by means of the Water Sensitivity Test. Only the mixes with parameters that gave fairly good performances in the dry tests were studied. The independent variables were:

1. Virgin aggregate gradation — Two kinds (Coarse or Type II), for mixes with virgin aggregate added.
2. Percent Total Asphalt Content, %AS_t — Two levels (4.5% and 5.5%).
3. Curing time — Two levels of curing time (1 day and 7 days) were used for mixes with 25% Type II aggregate. For the rest, only one curing time (7 days) was used.

TABLE 3 DESIGN FOR THE STUDY OF THE
EFFECT OF WATER ON THE
PROPERTIES OF RECYCLED MIXTURES

% Virgin Aggregate Virgin Agg. Gradation %AS ₁₀ (Asphalt Content) CURING TIME	0 %		25 %			
			COARSE		TYPE II	
	4.5 %	5.5 %	4.5 %	5.5 %	4.5 %	5.5 %
1 DAY					X	X
7 DAYS	X	X	X	X	X	X

NOTE:

BINDER MATERIAL: AE-150

COMPACTIVE EFFORT: 40 REVOLUTIONS

MOISTURE ADDED: 1%

X 2 REPLICATES PER CELL, TESTED IN
WATER SENSITIVITY TEST

The experimental design is shown in Table 3. This set of experiments represented a total of 16 specimens.

4.3.4 Study Design No.4

In the fourth set of experiments, the effects of different compactive efforts on the properties of the recycled mixtures were studied. Three different compactive efforts (10, 30 and 50 revolutions at 200 psi (1.38 MPa)) were used. Specimens were tested in dry and wet conditions. The experimental design is shown in Table 4. This set of experiments represented a total of 12 specimens.

4.3.5 Study Design No.5

This set of experiments represented Phase III of the study. The main objective of this study design was to investigate the effect of different bituminous materials when used as additional binder materials to the recycled mix. The independent variables were:

1. Binder material — Three kinds of binder materials were used, namely, AE-90, MC-3000 and AC-2.5.
2. Virgin aggregate — Two levels of virgin aggregate were used (0% or 25% of Type II aggregate).
3. Percent Total Asphalt Content, $\%AS_t$ — Two levels of $\%AS_t$ were used for mixes with 25% virgin aggregate (4.5% and 5.5%). For mixes with no virgin aggregate, only one level of $\%AS_t$ (5.5%) was used.
4. Curing time — Two levels of curing time (1 day and 7 days).

Restriction on randomization was present due to the fact that mixes with the same binder materials were performed in the same period

TABLE 4 DESIGN FOR THE STUDY OF THE
EFFECT OF COMPACTIVE EFFORT ON
THE PROPERTIES OF RECYCLED
MIXTURES

COMPACTION CONDITION OF TEST	10 REV.	30 REV.	50 REV.
	X	X	X
WATER SENSI- TIVITY	X	X	X

NOTE:

BINDER MATERIAL: AE-150

AE RESIDUE ADDED: 1%

MOISTURE ADDED: 1%

CURING TIME: 1 DAY

NO VIRGIN AGGREGATE ADDED

X 2 REPLICATES PER CELL, TESTED WET OR DRY

of time. The experimental design of this set of experiments is shown in Table 5. There were a total of 90 specimens in this set of experiments.

The Asphalt Institute Design Criteria for base course material uses the Resistance R_t Value which was a combination of R and C values, both obtained at 70°F (25°C). R_t is determined as follows:

$$R_t = R + 0.05C$$

where

R = Hveem R-Value

C = Cohesimeter Value

Criteria	Requirements
R_t after Vacuum Soak for light and medium traffic DTN under 100	70 min.
for heavy and very heavy traffic DTN over 100	78 min.

TABLE 5 DESIGN FOR THE STUDY OF THE EFFECT OF BINDER MATERIAL ON THE PROPERTIES OF RECYCLED MIXTURES

Virgin Aggregates % AS ₂ (Asphalt Content) Curing Time Binder Material	0 %		25 %	
	4.5 %	5.5 %	4.5 %	5.5 %
AE-90	1 DAY	⊗	⊗	⊗
	7 DAYS	⊗	⊗	⊗
MC-3000	1 DAY	⊗	⊗	⊗
	7 DAYS	⊗	⊗	⊗
AC-2.5	1 DAY	⊗	⊗	⊗
	7 DAYS	⊗	⊗	⊗

NOTE: MOISTURE ADDED (FOR AE-90): 1%
 COMPACTIVE EFFORT: 40 REVOLUTIONS
 VIRGIN AGGREGATE: TYPE II
 X 3 REPLICATES PER CELL, TESTED DRY
 O 2 REPLICATES PER CELL, TESTED WET

CHAPTER 5

DEVELOPMENT OF THE LABORATORY PROCEDURE

5.1 Introduction

There is , at present, no standardized or widely accepted laboratory procedure for the analysis of cold recycled asphalt mixtures. In the development of the laboratory procedure to be used in this study, considerations were made of the following points.

1. There should be considerable ease in the preparation and testing of the recycled samples.
2. Preparation of sample should resemble the actual field condition (e.g. degree of mixing, initial compaction, traffic compaction and curing time).
3. There should be consistency in the preparation of the samples.
4. Response variables measured should give indication of qualities of performance of the mix as a stabilized base or surface course.
5. Common problems encountered in recycled pavements hopefully could be detected in the laboratory testing method used.

5.2 Compaction Method

In the process of choosing a compaction method, trial mixes were made using three compaction methods, namely, Marshall, Hveem Kneading and Gyratory compactions. It was found that the Hveem Kneading

compactor was not suitable for compacting cold-mix recycled asphalt pavement material. Due to the fact that no heat was applied during the kneading compaction process, the asphalt binder and pavement material tended to stick to the foot of the Hveem Kneading compactor. Among the three compactors, the gyratory compactor gave the most consistent results. Other researches have also demonstrated that the gyratory compactor produces consistent samples and compaction conditions resembling the actual field conditions (14,28). The gyratory compaction was thus chosen as the compaction method to be used in the study. In accordance with one of the standard gyratory compaction methods, the gyratory angle was set at 1 degree, the ram pressure was set at 200 psi (1.38 MPa), and a fixed roller was used.

According to the ASTM standard, 30 revolutions of the gyratory compaction at 200 psi (1.38 MPa) ram pressure is equivalent to 75 blows of the standard Marshall hammer on each side of the specimen. This compaction effort is also equivalent to one year's compaction under medium traffic. A large compactive effort was decided to be used, so that the phenomena of bleeding could be detected in the laboratory testing. The phenomena of bleeding is one of the most common problem encountered in recycled pavements. Bleeding often results when the binder that is added has a softening effect on the old binder already present in the existing pavement. Thus, bleeding could be a problem at some time in the future and not be detected at earlier stages. A compactive effort of 40 revolutions at 200 psi (1.38 MPa) was used in the major portion of the laboratory study. The compacted specimens would resemble pavement material under heavy traffic compaction. Any

instability of the recycled mix due to the additional compaction of traffic would be able to be detected in the laboratory testing.

5.3 Specimen Preparation Procedure

The major portion of the laboratory investigation utilized AE-150 as a binder material. The preparation procedure was adopted to suit this type of binder material. The mixing and curing procedure adopted followed closely the procedure developed and used by Dr. A.A. Gadallah in his Ph.D. thesis, "A Study of the Design Parameters for Asphalt Emulsion Treated Mixtures". The following is a brief summary of the procedure adopted.

Preparation Procedure:

1. Crushed pavement material is batched, based on the proportion of material in each size group as it came out of the crusher.
2. The required amount of water (if any) is added to the material and mixed thoroughly with spoon by hand.
3. The mixture is left for 10-15 minutes before asphalt emulsion is added. If binder materials other than asphalt emulsion are used, steps 1 to 3 will be omitted.
4. The required amount of asphalt emulsion or other asphalt binder material is added and mixed using a mechanical mixer for 2 minutes with 30 seconds of hand mixing with a spoon within the mixing period.
5. The mix is cured for one hour in a forced-draft oven at 140°F (60°C) and then remixed for 30 seconds with mechanical mixer before compaction.

6. The mix is compacted with a gyratory compactor according to the standard procedure.
7. The compacted specimen is extruded from the mold within 10 minutes.
8. Specimens are then left to cure at room temperature for some specified length of time before testing.

5.4 Water Sensitivity Test

Water sensitivity test was used to measure the resistance of the recycled mixtures to water. The method recommended in a recent laboratory report from the Asphalt Institute (4) was used. The procedures are briefly summarized below:

1. Specimens are to be subjected to one hour of vacuum at 30 mm Hg.
2. After one hour period, water at room temperature of 72°F (22°C) is drawn into the vacuum chamber submerging the specimens and vacuum saturating them.
3. The vacuum is released and the specimens are then left in the water bath for 24 hours before testing.
4. Prior to testing, the saturated surface dry weight of the specimen is determined to calculate the percentage of water absorption.

5.5 Testing Procedure

Specimens were tested in the Stabilometer at room temperature and in the Cohesimeter at 140°F (60°C). From the Stabilometer Test, two variables were obtained, namely, the Hveem R-Value and the modified

Hveem S-Value. From the Cohesimeter Test, the Cohesimeter value was obtained.

The R-Value is used in the design criteria for stabilized base material. It is thus an appropriate variable to be studied. The S-Value and the C-Value are generally used in the design criteria for hot-mix surface course. They will give some indications of the performance of the recycled mix as a surface course. The S-Value obtained was modified in that specimens were tested at room temperature instead of at 140°F (60°C) as specified in the standard Hveem Stabilometer test.

In the process of determining a proper testing procedure, investigations were made on the feasibility of repeated testing on the same specimen with the stabilometer. It was found that both the R and the S values showed increases in values at repeated testing for some stable mixtures (see Appendix A). The possibility of testing the specimens more than once in the stabilometer (for the study of the effect of curing time) was thus ruled out. However, it was found that the value D_2 , the displacement value used in the calculation for both the R-Value and the S-Value did not change at repeated testing. D_2 is a function mainly of the surface texture of the specimen. It is thus appropriate to test a specimen in the stabilometer up to a load of 6000 lbs. (26.69 kN) according to the standard Hveem Stabilometer testing procedure, and to calculate the R-Value as well as the S-Value from the obtained data (see Section 4.1.1 and Section 4.1.2 for the equations for calculating the R and the S values). It was, thus, decided to obtain both the R and the S values in one testing.

The following is a brief description of the testing procedures adopted for this study.

Testing Procedure:

1. Bulk specific gravity of the specimen was determined one to two hours before the testing. The standard procedure used was ASTM D2726, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimen.
2. Specimen was dried by blowing with electric fan for one hour before the specimen is tested in the stabilometer.
3. Specimen was tested in the stabilometer in accordance with the procedures of ASTM D1560, Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus. Test was performed at room temperature rather than at 140°F (60°C) as required in the ASTM standard.
4. After being tested in the stabilometer, the specimen was kept in the oven at 140°F (60°C) for at least 2 hours before being tested in the Cohesimeter. Cohesimeter test was performed in accordance with ASTM D1560.
5. Specimens were crushed after the Cohesimeter test and kept in the oven at 230°F (110°C) for 24 hours.
6. Weight of specimen was taken before and after the 24 hours' oven drying. The loss in weight was used to determine the amount of retained moisture in the specimen.

Slight modifications of the above procedures were made for some experimental designs. They will be described in the chapters dealing with them.

CHAPTER 6
EFFECT OF ADDED ASPHALT EMULSION ADDED MOISTURE AND
CURING TIME ON PROPERTIES OF RECYCLED MIXTURES

6.1 Introduction

This chapter covers the first set of experiments of this laboratory study. The main objectives of this set of experiments were to determine the optimum amount of moisture and asphalt emulsion residue to be added to the recycled mixture used, and to determine the extent of the effect of curing time. The experimental design is shown in Table 1 in Chapter 4 (Design of the Experiment). This was a completely randomized three-way factorial design with four levels of added asphalt emulsion (%AS_a), three levels of added moisture content (%W) and two levels of curing time. This design resulted in 24 different cells (mix combinations). Three replicate specimens per cell were tested for cells with 1% and 2% added AE, two replicates per cell were tested for cells with 3% added AE, and one replicate per cell was tested for cells with 0% added AE.

Specimens were prepared according to the procedures described in Section 5.3. AE-150 was used as additional binder material. Specimens were compacted with the gyratory compactor for 40 revolutions at a ram pressure of 200 psi (1.38 MPa). The response variables measured were the Hveem R and S stability values, the bulk specific gravity and the percent retained moisture.

In this set of experiments, the specimens were not dried in the oven at 230°F (110°C) as was done for the other specimens. The percent moisture retained was estimated from the amount of initial moisture, the amount of added moisture and the recorded weight loss of the mixture during the mixing and the curing process.

6.2 General Observation

6.2.1 Mixing And Coating

The asphalt emulsion was observed to have fairly good coating and mixing properties with the crushed pavement material. The coating and mixing of the mixtures were improved further by the one hour curing in the oven at 140°F (60°C) and 30 seconds remixing. It was observed that the mixing operation became more and more difficult as the amount of added asphalt emulsion increased. When 3% of AE residue was added to the recycled mixture, the mixture became very sticky and difficult to be handled. It was also observed that the addition of water did facilitate the mixing operation.

6.2.2 Compaction

The mixtures became easier to compact as the amount of added AE residue increased. However, the mixtures began to show signs of instability when the percent added AE residue was 2% or higher. When the mixtures became unstable during compaction, the gyrograph would show bigger and bigger gyration angles. Typical gyrograph bands for mixtures with 1, 2 and 3% added AE residue are shown in Figure 8. Some signs of instability were shown in the gyrograph band for the mixture with

1% added AE residue

2% added AE residue

3% added AE residue

FIGURE 8 TYPICAL GYROGRAPH BANDS FOR RECYCLED MIXTURES

2% added AE residue. For the mixture with 3% added AE residue, the instability of the mix was unquestionably displayed in the gyrograph band.

6.2.3 Testing

In determining the Hveem S stability values, specimens have to be loaded to 480 psi (3.31 MPa), and values of P_h (horizontal pressure of the stabilometer) when $P_v=400$ psi (2.76 MPa) are used in the calculation for the S-Values. The pressure gage of the stabilometer can only go up to a pressure of $P_h=200$ psi (1.38 MPa). If a relatively unstable specimen is tested, P_h will be greater than 200 psi (1.38 MPa) when P_v is at 400 psi (2.76 MPa). Thus, for an unstable mix, the specimen can not be loaded to a vertical pressure of 400 psi (2.76 MPa), and the value of P_h at $P_v=400$ psi can not be obtained directly for calculating the S-Values. In testing the relatively unstable mixes, the specimens were loaded until P_h reached a pressure of 200 psi (1.38 MPa) and the values of P_h at $P_v=400$ psi (2.76 MPa) were extrapolated.

6.3 Analysis Of Results

The effects of the experimental factors on the response variables of the recycled mixtures were analyzed with the aid of the Analysis of Variance (ANOVA) statistical method. The ANOVA determined whether the effects of certain factors and interactions of factors were significant. The means of the response variables in each mix combination (cell) were used in observing any physical trends that might be present. Finally, subjective judgements on the performance of the mixtures were also made.

The crushed pavement material was determined to have an asphalt content of 4.5%. Thus, the percent added asphalt content ($\%AS_a$) of 0, 1, 2 and 3% will correspond to the total asphalt content ($\%AS_t$) of 4.5, 5.5, 6.5 and 7.5%. For ease of comparison between different mixes, the values of $\%AS_t$ will be used throughout this entire study.

6.3.1 Model For The Response Variables

The mathematical model used for the response variables in this three-way completely randomized design is given below:

$$Y_{ijkl} = \mu + A_i + W_j + C_k + AW_{ij} + AC_{ik} + WC_{jk} + AWC_{ijk} + \epsilon_{(ijk)l}$$

where

Y_{ijkl} = Response variable

μ = Overall mean

A_i = Effect of added asphalt emulsion, $\%AS_a$

W_j = Effect of added moisture, $\%W$

C_k = Effect of curing time

AW_{ij} = Interaction effect of A_i with W_j

AC_{ik} = Interaction effect of A_i with C_k

WC_{jk} = Interaction effect of W_j with C_k

AWC_{ijk} = Interaction effect of A_i with W_j with C_k

$\epsilon_{(ijk)l}$ = Error term, NID ($0, \sigma^2$)

The subscripts have the following values:

$$i = 1, 2, 3, 4 ; \quad j = 1, 2, 3 ; \quad k = 1, 2 ; \quad l = 1, 2, 3 .$$

The three factors A, W and C are fixed. The i values of 1, 2, 3 and 4% correspond to the $\%AS_a$ values of 0, 1, 2 and 3%. The j values of 1, 2 and 3 correspond to the $\%W$ value of 1 and 2%. The values of k

of 1 and 2 correspond to the curing time of 1 day and 7 days.

6.3.2 Test For Homogeneity Of Variance

One major assumption in ANOVA is the homogeneity of variance. The assumption of homogeneity of variance was checked before making the Analysis of Variance. The Foster-Burr Q-Test* was used in testing the homogeneity of variance. The assumption of homogeneity of variance would be accepted if the q-test values were less than the q-critical values at $\alpha = 0.001$. If the homogeneity of variance for any response variable was not accepted, an appropriate transformation would be applied to the variable, and the transformed variable would be used in making the Analysis of Variance. Since the Analysis of Variance is a fairly robust method (relatively insensitive to the deviations from the assumptions of normality and homogeneity of variance) (1), the assumption of normality were not checked.

The results of the Foster-Burr Q-Test were summarized in Table 6. Since there was only one replicate sample per cell for the cells with 0% added AE residue, the data in these cells were not used in the test for homogeneity of variance.

6.3.3 ANOVA

The results of the ANOVA for the response variables are summarized in Table 7. A typical ANOVA table is shown in Table B1 in the Appendices. The transformed variable G_b^{15} was used in the ANOVA, since it satisfied the homogeneity of variance assumption.

* For reference, see pp.22-23 of Anderson V.L. and McLean R.A., "Design Of Experiments — A Realistic Approach".

TABLE 6: BURR-FOSTER Q-TEST FOR HOMOGENEITY OF VARIANCE (Study Design No.1)

<u>Variable</u>	<u>Average Degree Of Freedom Per Sample</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
G_b	2	18	.2825	Rejected **
G_b^{10}	2	18	.2368	Rejected **
G_b^{15}	2	18	.2165	Accepted **
S	2	18	.1326	Accepted *
R	2	18	.1389	Accepted *
%WC	2	18	.1100	Accepted *

* $Q_{2,18,.01} = .178$

** $Q_{2,18,.001} = .228$

TABLE 7: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Study Design No.1)

<u>Source Of Variation</u>	<u>Response Variable :</u>	<u>R</u>	<u>S</u>	<u>%WC</u>	<u>G_b</u>	<u>G_b¹⁵</u>
A		S.	S.	S.	S.	S.
W		N.S.	S.	S.	N.S.	N.S.
C		S.	S.	S.	N.S.	N.S.
AW		N.S.	S.	N.S.	N.S.	N.S.
AC		S.	N.S.	N.S.	N.S.	N.S.
WC		N.S.	N.S.	S.	N.S.	N.S.
AWC		N.S.	N.S.	N.S.	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

The following sections deal with the evaluation of each of the response variables.

6.3.4 Hveem R And S Stability Values

Since both the Hveem R stability value and the Hveem S stability value measure the stability of the mixture, it is more convenient to consider them side by side. This will be done in this and the subsequent chapters.

It was observed that the highest R and S values were obtained when there were 0% added asphalt emulsion. Stability values decreased as the amount of added asphalt content increased. Figures 9 and 10 show the values of R and S as a function of percent AE residue added ($\%AS_a$) and curing time. The ANOVA results indicated that the main effects of $\%AS_a$ and curing time were significant to both the R and the S values. The interaction effect of $\%AS_a$ with curing time was significant to the R-Value but not to the S-Value. It can be observed that the differences in the R-Values between the one day and the seven days cured specimens are greater at the levels of 2 and 3% added AE residue than those at 0 and 1% added AE residue.

The ANOVA results showed that the effect of the initial moisture added ($\%W$) was not significant for the R-Values, but was significant for the S-Values. They also showed that the interaction effect of $\%AS_a$ with $\%W$ was significant to the S-Values. Plots of average R and S values v.s. percent moisture added for different total asphalt content are presented in Figure 11 and 12. No physical trend was noted in Figure 11; the effect of moisture added was shown to be insignificant.

FIGURE 9 AVERAGE HVEEM R STABILITY VALUES AS FUNCTIONS OF PERCENT AE RESIDUE ADDED AND CURING TIME

FIGURE 10 AVERAGE HVEEM S STABILITY VALUES AS FUNCTIONS OF PERCENT AE RESIDUE ADDED AND CURING TIME

FIGURE 11 AVERAGE HVEEM R STABILITY VALUES
PLOTTED AGAINST PERCENT MOISTURE
ADDED

NOTE: * Percent Total Asphalt Content

FIGURE 12 AVERAGE HVEEM S STABILITY VALUES
AS FUNCTIONS OF %W AND %AS_t

Note:

* Percent Total Asphalt Content, %AS_t

For the S-Value, it was observed that stability increased with increasing %W if 0% AE residue was added. If 1% or more of AE residue was added, the S-Values decreased with increasing %W. The optimum amount of moisture to be added to the recycled mixture was not determined. Since the R-Value was the more important response variable of the two, the effect of moisture added was considered to be insignificant. The level of 1% added moisture was chosen to be used in the later experiments.

6.3.5 Percent Moisture Retained

The percent moisture retained (%WC) in this set of experiments was estimated by subtracting the recorded weight losses of the mixture (for the one hour oven curing period and the air curing period) from the estimated initial amount of moisture. The amount of initial moisture was the sum of the moisture in the pavement material, the moisture from the asphalt emulsion and the moisture added. The pavement material was determined to have a moisture content of .3%. Moisture from the AE added and the moisture added were known.

The ANOVA results indicated that the main effects of the three factors (%AS_a, %W and curing time) and the interaction of %W and curing time were significant to the percent retained moisture. Figure 13 presents the %WC as a function of the moisture added and the total asphalt content for 1 day and 7 days cure. It could be seen that the %WC increased with increasing %W and %AS_t and decreased with increasing curing time. Figure 14 depicts the average percent moisture retained as a function of percent moisture added for 1 day and 7 days cure. It

FIGURE 13 PERCENT MOISTURE RETAINED AS FUNCTION OF PERCENT MOISTURE ADDED AND TOTAL ASPHALT CONTENT FOR ONE DAY AND SEVEN DAYS CURE

NOTE:

* Percent Total Asphalt Content

FIGURE 14 AVERAGE PERCENT MOISTURE RETAINED
AS FUNCTION OF PERCENT MOISTURE
ADDED FOR ONE AND SEVEN DAYS CURE

showed the interaction effect of %W with curing time in that at 0 and 1% levels of %W, 1 day and 7 days cured specimens had approximately the same average values of %WC. However, at 2% level of %W, the 7 days cured specimens had significantly less retained moisture than the 1 day cured specimens.

6.3.6 Bulk Specific Gravity

The ANOVA results indicate that the percent added AE residue was the only significant factor to the bulk specific gravity of the recycled mixtures. Figure 15 shows the values of bulk specific gravity plotted against the percent moisture added. It should be noted that G_b did not vary much with the variation of %W. The average bulk specific gravity reached its maximum value at an asphalt content of 6.5% (2% added AE residue). Figure 16 depicts the bulk specific gravity as a function of percent AE residue added (or percent total asphalt content).

6.3.7 Inspection Of Compacted Specimens

Figure 17 presents the typical specimens with 0% and 1% added AE residue. It was noted that the specimens with no added AE residue had a coarse surface texture. They were not very durable, and flakes fell from the specimen easily. The specimens with 1% added AE residue had lower R and S values than the specimens with no added AE residue, but they looked much more durable. Water Sensitivity Tests were to be run on these mixes to further evaluate these mixes.

Figure 18 depicts the specimens with 2% and 3% added AE residue. The specimen with 2% added AE residue showed slight bleeding phenomena. The specimen with 3% added AE residue demonstrated excessive bleeding.

FIGURE 15 BULK SPECIFIC GRAVITY PLOTTED AGAINST PERCENT MOISTURE ADDED

NOTE:

* Percent Total Asphalt Content

FIGURE 16 AVERAGE BULK SPECIFIC GRAVITY AS FUNCTION OF PERCENT TOTAL ASPHALT CONTENT

FIGURE 17 TYPICAL COMPACTED SPECIMENS OF RECYCLED
MIXTURES OF 0% AND 1% ADDED AE RESIDUE

Note:

A — Specimen with 1% added AE residue

B — Specimen with 0% added AE residue

FIGURE 18 TYPICAL COMPACTED SPECIMENS OF RECYCLED
MIXTURES OF 2% AND 3% ADDED AE RESIDUE

Note:

A — Specimen with 3% added AE residue

B — Specimen with 2% added AE residue

6.4 Summary of Results

The results from this set of experiments are only applicable to material obtained from one roadway site and are summarized by the following statements:

1. Unstable recycled mixtures could be detected during gyratory compaction by the increasing gyratory angle in the gyrograph. In this study, it was found that mixtures with 2% and 3% added AE residue demonstrated a condition of instability.
2. The unstable compacted specimens displayed the phenomena of bleeding. The instability was due to the excessive asphalt content of the mix.
3. While the addition of water facilitates the mixing process, the added moisture was found to have no significant effect on the Hveem R stability values. No optimum percent added moisture was determined.
4. Curing time had a significant effect on the Hveem S and R stability values. Stability values at 7 days cure were significantly higher than those at 1 day cure.
5. The optimum amount of AE residue to be added to the recycled mixture was found to be between 0% and 1%. Specimens with no added binder material displayed the highest stability values.
6. The percent moisture retained at time of testing depended on the amount of added asphalt emulsion, the amount of added moisture and the curing time.
7. The specific gravity of compacted specimens was found to be affected only by the amount of added asphalt emulsion.

CHAPTER 7

RECYCLED MIXTURE WITH ADDED VIRGIN AGGREGATE

7.1 Introduction

This chapter deals with the second set of experiments, in which the effects of added virgin aggregate on the properties of the recycled mixtures were investigated. The main objectives of this set of experiments were to study the effects of added virgin aggregates and to determine whether the previous findings regarding the effects of certain factors (%W, %AS_a and curing time) were also applicable to the recycled mixtures with added virgin aggregates. The experimental design is shown in Table 2 in Chapter 4 (Design Of The Experiment). The recycled mixtures were blended with 25% of virgin aggregate (by weight of the total amount of aggregate). Two gradations of virgin aggregate were used. One gradation represented coarse aggregate of three sieve size groups. The percentage by weight of each size group is given below:

1" - 3/4" (25.0-19.0 mm)	52%
3/4" - 3/8" (19.0 -9.5 mm)	40%
#4 - #8 (4.75-2.36 mm)	8%

This proportioning was selected so that the gradation of the combined aggregate would approach the Fuller's maximum density gradation. The gradation of the combined aggregate is shown in Figure 19. The other gradation represents a typical Indiana Type II No.8 aggregate. The

NOTE: A — Gradation of Recovered Pavement Aggregate
 B — Gradation of Combined Aggregate (Old + Coarse Virgin Agg.)
 C — Fuller's Maximum Density Curve ($P = 100(d/D)^5$)

FIGURE 19 GRADATION OF COMBINED AGGREGATE

gradation used is shown in Figure 20. Two levels of added moisture (0% and 1%) were used for the mixtures with coarse virgin aggregate; one level of added moisture (1%) was used for the ones with Type II virgin aggregate. For both cases, there were two levels of asphalt content (4.5% and 5.5%) and two levels of curing time (1 day and 7 days).

The specimens with coarse virgin aggregate were tested before the specimens with Type II virgin aggregate were tested. This imposed a restriction on the randomization of the experiment. The preparation procedures for the mixtures with coarse virgin aggregate were slightly different than those for the mixtures with Type II aggregate. In the first case, virgin aggregate was mixed with the crushed pavement material before the asphalt emulsion was added. In the latter case, the asphalt emulsion was mixed with the virgin aggregate for 30 seconds before they were combined with the recycled mixtures. The balance of the procedures for both cases were the same as the procedures described in Section 5.3.

Samples were tested according to the techniques described in Section 5.3. The response variables measured were the Hveem R and S stability values, the Cohesimeter (C) value, the Bulk Specific Gravity and the Percent Moisture Retained.

7.2 General Observations

It was observed that the second method of applying the asphalt emulsion unto the mix (mixing it first with the virgin aggregates) gave the virgin aggregates a better coating. The one hour oven curing at 140°F (60°C) and the remixing also improved the coating of the

FIGURE 20 GRADATION OF TYPE II NO. 8 AGGREGATE

aggregate. The mixing process was facilitated by the addition of moisture. It was noted that the mixing process became more difficult as the amount of asphalt emulsion was increased.

The specimens with coarse virgin aggregate and 5.5% total asphalt content showed some instability from the gyrograph during compaction.

7.3 Analysis Of Results

Since this was not a full factorial design, the analysis of variance using one mathematical model would be very complicated. It was decided to re-arrange the study design into two factorial designs. The Analysis of Variance would be performed on each of the two designs. The two factorial designs are shown in Tables 8 and 9. The cells with coarse virgin aggregate and 1% added moisture appear in both designs. Thus, this same group of data would be used in both designs.

7.3.1 Model For The Response Variables

The mathematical model for the response variables for the first design (coarse virgin aggregate) is given below:

$$Y_{ijkl} = \mu + A_i + W_j + C_k + AW_{ij} + AC_{ik} + WC_{jk} + AWC_{ijk} + \epsilon_{(ijk)l}$$

where

Y_{ijkl} = Response variable

μ = Overall mean

A_i = Effect of total asphalt content, % A_t

W_j = Effect of added moisture, % W

C_k = Effect of curing time

AW_{ij} = Effect of the interaction of A_i with W_j

- AC_{ik} = Effect of the interaction of A_i with C_k
 WC_{jk} = Effect of the interaction of W_j with C_k
 AWC_{ijk} = Effect of the interaction of A_i with W_j with C_k
 $\epsilon_{(ijk)l}$ = Error term, NID $(0, \sigma^2)$

The subscripts have the following values:

$$i, j, k = 1, 2 ; \quad l = 1, 2, 3 .$$

The mathematical model for the response variables for the second design (coarse and Type II aggregate with 1% added moisture) is given below:

$$Y_{ijkl} = \mu + G_i + \delta_{(i)} + A_j + C_k + GA_{ij} + GC_{ik} + AC_{jk} + GAC_{ijk} + \epsilon_{(ijk)l}$$

where

- Y_{ijkl} = Response variable
 μ = Overall mean
 G_i = Effect of virgin aggregate gradation
 $\delta_{(i)}$ = Restriction error, due to different time of testing for the two groups of samples
 A_j = Effect of total asphalt content, $\%AS_t$
 C_k = Effect of curing time
 GA_{ij} = Effect of the interaction of G_i with A_j
 GC_{ik} = Effect of the interaction of G_i with C_k
 AC_{jk} = Effect of the interaction of A_j with C_k
 GAC_{ijk} = Effect of the interaction of G_i with A_j with C_k
 $\epsilon_{(ijk)l}$ = Error term, NID $(0, \sigma^2)$

The subscripts have the following values:

$$i, j, k = 1, 2 ; \quad l = 1, 2, 3 .$$

7.3.2 Test For Homogeneity Of Variance

Tests for homogeneity of variance of the response variables were performed for the two designs. The results of the Foster-Burr Q-Test were summarized in Tables 10 and 11. All the response variables satisfied the homogeneity of variance at $\alpha = 0.001$ level. No transformation of data was needed to perform the ANOVA.

7.3.3 ANOVA

The results of the ANOVA for the response variables for the two designs are summarized in Tables 12 and 13. A typical ANOVA table for the first design is shown in Table B2 and a typical ANOVA table for the second design is shown in Table B3 in the Appendices. The ANOVA results were used to aid the evaluations of the mixtures, which are presented in the following sections.

7.3.4 Mixtures With Coarse Virgin Aggregate

The samples of 4.5% total asphalt content had significantly higher Hveem S and R stability values than those of 5.5%. The mixture of 5.5% asphalt was considered to be unstable, since it had an average Hveem R stability value of less than 80. (Most specifications require that stabilized base has a minimum Hveem R stability value of 85) The increase in strength due to curing time was not significant in the Hveem R stability values, but was significant in the Hveem S stability values. Figure 21 shows the average R and S values as functions of $\%AS_t$ and curing time.

**TABLE 8 FACTORIAL DESIGN FOR MIXTURES WITH
COARSE VIRGIN AGGREGATE (Part I,
Study Design No.2)**

CURING TIME		% W		% AS _t	
		0		1	
1 DAY	4.5	X	X		
	5.5	X	X		
7 DAYS	4.5	X	X		
	5.5	X	X		

NOTE:

BINDER MATERIAL: AE-150

COMPACTIVE EFFORT: 40 REVOLUTIONS

25% COARSE VIRGIN AGGREGATE

X 3 REPLICATES PER CELL, TESTED DRY

TABLE 9 FACTORIAL DESIGN FOR MIXTURES WITH VIRGIN AGGREGATES (Part 2, Study Design No. 2)

CURING TIME		VIRGIN AGGREGATE		COARSE	TYPE II
		% AS†			
1 DAY	4.5	X	X		
	5.5	X	X		
7 DAYS	4.5	X	X		
	5.5	X	X		

NOTE:

BINDER MATERIAL: AE-150
COMPACTIVE EFFORT: 40 REVOLUTIONS
MOISTURE ADDED: 1 %
25% VIRGIN AGGREGATE
X 3 REPLICATES PER CELL, TESTED DRY

TABLE 10: BURR-FOSTER Q-TEST FOR HOMOGENEITY OF VARIANCE (Part 1, Study Design No.2)

<u>Variable</u>	<u>Average Degree Of Freedom Per Sample</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
G _b	2	8	.4361	Accepted**
S	2	8	.3018	Accepted*
R	2	8	.3958	Accepted*
%WC	2	8	.1758	Accepted*

* $Q_{2,8,.01} = .412$

** $Q_{2,8,.001} = .537$

TABLE 11: BURR-FOSTER Q-TEST FOR HOMOGENEITY OF VARIANCE (Part 2, Study Design No.2)

<u>Variable</u>	<u>Degree Of Freedom</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
G _b	2	8	.3726	Accepted [*]
S	2	8	.2465	Accepted [*]
R	2	8	.4433	Accepted ^{**}
$\frac{C}{\sigma^2}C$	2	8	.1723	Accepted [*]
C	2	8	.4028	Accepted [*]

* $Q_{2,8,.01} = .412$

** $Q_{2,8,.001} = .537$

TABLE 12: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Part 1, Study Design No.2)

Source Of Variation	Response Variable :	<u>G_b</u>	<u>S</u>	<u>R</u>	<u>%WC</u>
A		N.S.	S.	S.	N.S.
W		N.S.	N.S.	N.S.	S.
C		N.S.	S.	N.S.	N.S.
AW		N.S.	S.	N.S.	N.S.
AC		N.S.	N.S.	N.S.	N.S.
WC		N.S.	N.S.	N.S.	N.S.
AWC		N.S.	N.S.	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

TABLE 13: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Part 2, Study Design No.2)

<u>Source Of Variation</u>		Response Variable :	<u>G_b</u>	<u>S</u>	<u>R</u>	<u>%WC</u>	<u>C</u>
Gradation, G			N.S.	S.	N.S.	N.S.	S.
%AS _t ,	A		N.S.	S.	S.	S.	S.
Curing Time ,	C		N.S.	S.	N.S.	N.S.	S.
	GA		N.S.	S.	N.S.	N.S.	N.S.
	GC		N.S.	N.S.	N.S.	N.S.	N.S.
	AC		N.S.	N.S.	N.S.	N.S.	N.S.
	GAC		N.S.	N.S.	N.S.	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

FIGURE 21 AVERAGE R AND S STABILITY VALUES AS FUNCTIONS OF PERCENT AS_t AND CURING TIME (RECYCLED MIXTURES WITH 25% COARSE VIRGIN AGGREGATE.)

NOTE:

* Percent Total Asphalt Content

The ANOVA results showed that the main effect of added moisture was not significant to the Hveem S or R stability values. However, the effect of the interaction of $\%AS_t$ with $\%W$ was significant for the S-Value. This interaction effect was also found to be significant to the S-Value in the ANOVA results for the first set of experiments. Figure 22 depicts the average R and S values as functions of $\%AS_t$ and $\%W$. It was noted that the specimens with 4.5% asphalt had significantly higher S-Values at 0% added moisture than at 1% added moisture.

For the levels of factors tested, the effects of all the factors were not significant for the specific gravity. The samples had an overall average specific gravity of 2.396, which was slightly greater than the specific gravity of a similar specimen with no virgin aggregate.

The percent retained moisture was dependent on the amount of added moisture.. The ANOVA result showed that the percent added moisture was the only significant factor to the amount of retained moisture. Figure 23 shows the percent retained moisture as a function of $\%W$ and curing time.

Data collected for the Cohesimeter (C) values were incomplete. Out of the 24 specimens, only 17 specimens were tested for their C-Values. It was decided not to analyze these data in this design. Part of these data would be used in the analysis in the second design, however.

7.3.5 Mixtures With Type II Virgin Aggregate

In the Analysis of Variance for the second design, δ_1 , the restriction error due to testing at different time for the two groups

NOTE:

* Percent Total Asphalt Content, %AS_t

FIGURE 22 AVERAGE HVEEM R AND S STABILITY VALUES
AS FUNCTIONS OF %AS_t AND %W (Mixtures
With 25% Coarse Virgin Aggregate)

FIGURE 23 PERCENT RETAINED MOISTURE AS
FUNCTION OF PERCENT MOISTURE
ADDED AND CURING TIME (MIXTURES
WITH 25% COARSE VIRGIN AGGREGATE.)

NOTE:

* Percent Moisture Added Initially

of specimens, was assumed to be negligible. The significance of the effect of different aggregate gradation could be tested thus.

The average Hveem S and R stability values for the specimens with Type II virgin aggregate were higher than those for the specimens with coarse virgin aggregate. Figure 24 shows the average S and R values for the two groups of specimens at the two asphalt content and the two curing time. The R and S values at 4.5% asphalt content were significantly higher than those at 5.5%. The ANOVA results showed that the effect of different gradation of virgin aggregate was significant to the S-Value, but not to the R-Value at $\alpha = 0.05$ level. The effects of curing time and the interaction of $\%AS_t$ with aggregate gradation were also shown to be significant to the S-Value. S-Values were shown to be increasing with curing time. The interaction effect was noted in the fact that the differences in the S-Values of the two groups of specimens were greater at 4.5% asphalt content than at 5.5% asphalt content.

The average bulk specific gravity for the specimens with Type II virgin aggregate was 2.379. The ANOVA results showed that there was no significant difference in specific gravity between the two groups of specimens. For the levels of factors tested, there was no significant factor to the specific gravity.

The percent moisture retained, $\%WC$, is presented in Figure 25 as a function of $\%AS_t$ and curing time. The ANOVA results showed that $\%AS_t$ was the only significant factor.

The Cohesimeter (C) values were affected significantly by the three factors ($\%AS_t$, Aggregate Gradation and Curing Time). Figure 26

FIGURE 24 S AND R STABILITY VALUES FOR RECYCLED MIXTURES WITH COARSE AND TYPE II VIRGIN AGGREGATE

NOTE:

* Percent Total Asphalt Content

FIGURE 25 AVERAGE % RETAINED MOISTURE AS
FUNCTION OF %AS_T AND CURING TIME
(Mixtures with Coarse and Type II Aggregate)

shows the average C-Values plotted as functions of $\%AS_t$, aggregate gradation and curing time. The C-Values of the specimens with Type II virgin aggregate were greater than those with coarse virgin aggregate. They were higher at 4.5% asphalt content than at 5.5% asphalt content, and they increased with increasing curing time. The average C-Values for all the mix combinations were above 100, indicating good cohesion properties.

7.4 Discussion Of Results

The most important factor to the stabilities of the mixtures is the asphalt content, as noted from the results of the previous two sets of experiments. The mixtures become unstable when too much asphalt binder is added to the mixtures. The mixtures with added virgin aggregate had fairly high stability values at 4.5% asphalt content. However, at 5.5% asphalt content, the mixtures became slightly unstable.

The pavement material used in this study did not show any degradation in aggregate sizes. Improvements to the aggregate gradation of the material by the addition of virgin aggregate were not needed. Thus, the improvements to the properties of the recycled mixtures by the addition of virgin aggregate could not be tested effectively in this set of experiments. However, the results showed that virgin aggregate could be added to a recycled material to produce a fairly stable mixture.

The specimens with added coarse aggregate had slightly lower stability values than the ones with added Type II aggregate. This difference is believed to be due to the fact that the same amount of

FIGURE 26 COHESION VALUES AS FUNCTIONS OF ASPHALT CONTENT, AGGREGATE GRADATION AND CURING TIME (Part 2, Study Design No.2)

coarse aggregate has smaller total surface area and thus requires a lesser amount of asphalt binder to coat.

It was believed that the mixture at 4.5% asphalt content could make a good stabilized base material. It had an average R-Value of greater than 90 at one day curing.

7.5 Summary Of Results

Findings in this set of experiments are summarized into the following points.

1. The percent total asphalt content was a significant factor to the Hveem R stability value, the Hveem S stability value and the Cohesimeter value of the recycled mixture with added virgin aggregate. For the two levels of asphalt content tested, the highest R, S and C values were obtained at 4.5% asphalt content.
2. The effect of percent added moisture was not significant to the Hveem R and S stability values, for the levels of factor tested.
3. Specimens with added Type II aggregate had higher Hveem R and S stability values and Cohesimeter values than those with added coarse aggregate.
4. Specimens increased in strength with curing time.
5. The amount of retained moisture was affected by the amount of added moisture and added asphalt emulsion.
6. For the levels of factors tested, the specific gravity was not affected significantly by any factor.

CHAPTER 8

EFFECT OF WATER ON PROPERTIES OF RECYCLED MIXTURES

8.1 Introduction

This chapter deals with the third set of experiments, in which the Water Sensitivity Tests were run on some specific recycled mixtures. The main objective of this set of experiments was to determine the effects of water on a few recycled mixtures that showed relatively good performances when tested in dry condition. The experimental design was shown in Table 3 of Chapter 4 (Design of the Experiment). There were three main groups of recycled mixtures in this study design — they were mixtures with no virgin aggregate, mixtures with 25% coarse virgin aggregate and mixtures with 25% Type II virgin aggregate. Specimens in each group were tested at different times. Two levels of percent total asphalt content (4.5% and 5.5%) were used in each group. AE-150 was used as additional binder material. The first two groups of specimens (with 0% and with 25% coarse virgin aggregate) were tested at 7 days curing. For the third group of specimens (with 25% Type II virgin aggregate), two levels of curing time (1 day and 7 days) were used. 1% added moisture was used for all the specimens. There were a total of 8 cells, and two replicate specimens were tested per cell.

The specimens were subjected to a 24 hours water-saturated exposure before being tested in the stabilometer and the cohesiometer. The

experimental procedures used (the Water Sensitivity Test and the rest of the testing procedures) were described in Sections 5.4 and 5.5.

The response variables measured were the Hveem R and S stability values, the Cohesimeter (C) value, the Specific Gravity and the Percent Moisture Absorbed.

8.2 Analysis Of Results

In the analysis of the results in this set of experiments, it was decided to make two separate evaluations. Comparisons among the three groups of specimens were made at 7 days curing. The effect of curing time was evaluated from the results of the specimens with Type II virgin aggregate. The means of the response variables in each mix combination were used in the evaluation. The restriction errors due to testing at different time periods were assumed to be negligible.

8.2.1 Retained Hveem R And S Stability

Values In Water Sensitivity Test

Comparisons were made among the average Hveem R and S stability values of the three groups of specimens. For each mix combination, comparisons were made to the previous results of the dry tests, and the percent retained Hveem R and S stability values were calculated. Figures 27 and 28 show the retained Hveem R and S stability values in the Water Sensitivity Test at 7 days curing.

It was noted that the mixture with no added asphalt emulsion and no added virgin aggregate was affected greatly by the Water Sensitivity Test. In the dry tests, this mixture (of no added AE and virgin aggregate) had the highest R and S values. In the Water Sensitivity

FIGURE 27 RETAINED HVEEM R STABILITY VALUES IN WATER SENSITIVITY TEST (7 DAYS CURING)

FIGURE 28 RETAINED HVEEM S STABILITY VALUES IN WATER SENSITIVITY TEST (7 DAYS CURING)

Test, the mixture with 25% Type II virgin aggregate and 4.5% asphalt content showed the highest R and S values, and the mixture with no virgin aggregate and 5.5% asphalt had the second highest R and S values (Their values were very close).

The mixture with coarse virgin aggregate and 5.5% asphalt, which was a relatively unstable mix in the dry test, was greatly affected by the Water Sensitivity Test. With the exception of this mix combination, it was observed that the mixtures at the higher asphalt content (5.5%) were hardly affected by the action of water. At 4.5% asphalt content, the decrease in strength due to the effect of water was significant.

6.2.2 Retained Cohesimeter Values In Water Sensitivity Test

Reduction in the Cohesimeter values was observed in the Water Sensitivity Test. Figure 29 shows the retained C-Values in the Water Sensitivity Test at 7 days curing. The effect of water was greater at 4.5% asphalt content. However, the retained C-Values at 4.5% asphalt content were still higher.

8.2.3 Percent Absorbed Moisture

The percent absorbed moisture in the Water Sensitivity Test at 7 days curing is shown in Figure 30 as a function of $\%AS_t$ and aggregate types. The $\%W_a$ gave an indication of the amount of permeable voids in the specimens. It was noted that the specimens with 25% coarse virgin aggregate had the least voids. The specimens at higher asphalt content had less permeable voids than those at lower asphalt content.

FIGURE 29 RETAINED COHESIMETER VALUES IN WATER SENSITIVITY TEST (7 DAYS CURING)

FIGURE 30

PERCENT ABSORBED MOISTURE IN
WATER SENSITIVITY TEST
(7 DAYS CURING).

8.2.4 Effect Of Curing Time

Two curing times (1 day and 7 days) were used for the group of specimens with 25% Type II virgin aggregate, in this set of experiments. The effect of curing time in the Water Sensitivity Test was evaluated from the behavior of these specimens.

Figure 31 shows the retained average Hveem R and S stability values plotted as functions of curing time and $\%AS_t$ for this group of specimens. It was observed that the retained R and S values in the Water Sensitivity Test increased with time.

Figure 32 shows the retained average Cohesimeter values plotted as a function of curing time and $\%AS_t$. It was shown that the retained Cohesimeter values also increased with time.

The percent absorbed moisture did not change significantly with curing time.

8.2.5 Specific Gravity

The measured specific gravity of the specimens used in the Water Sensitivity Test was consistent with that of similar specimens used in the dry test. Thus, the comparison of results made between the dry and the wet specimens was valid.

8.3 Summary Of Results

The results of this set of experiments can be summarized into the following points.

1. The Hveem R and S stability values of the recycled mixtures with no added asphalt emulsion were reduced greatly in the Water Sensitivity Test.

FIGURE 31 RETAINED HVEEM R AND S STABILITY VALUES AS FUNCTIONS OF CURING TIME AND % AS₊ (MIXTURES WITH 25% TYPE II VIRGIN AGGREGATE).

FIGURE 32 RETAINED COHESION VALUE AS
FUNCTION OF CURING TIME AND % AS_t
(MIXTURE WITH 25% TYPE II VIRGIN
AGGREGATE).

2. With the exception of the mixtures with 25% coarse virgin aggregate, the specimens at 5.5% asphalt content were hardly affected by the Water Sensitivity Test, in their Hveem R and S stability values.
3. The specimens with coarse virgin aggregate was greatly affected by the action of water in their Hveem R and S stability values.
4. The Cohesimeter values of all the specimens were reduced in value by the effect of water.
5. Increased curing time gave specimens increased Hveem R and S stability and Cohesimeter values in the Water Sensitivity Test.

CHAPTER 9
EFFECT OF COMPACTIVE EFFORT ON
PROPERTIES OF RECYCLED MIXTURES

9.1 Introduction

In the preparation of specimens for the previous experiments, a relatively high compactive effort had been used. According to the ASTM standard, 30 revolutions of gyratory compaction at 200 psi (1.38 MPa) ram pressure is equivalent to one year's compaction under medium traffic. The compactive effort of 40 revolutions at 200 psi (1.38 MPa) would resemble condition of heavy traffic compaction. As stated earlier, this high compactive effort was chosen so that the phenomena of excessive bleeding or instability of a recycled mixture, that might occur after some period of traffic compaction, could be detected. For mixtures that show signs of asphalt bleeding and instability at this compactive effort, it may be concluded that these mixtures might become unstable after some period of traffic compaction. For the relatively stable mixtures that do not show signs of bleeding, the performance was further evaluated by the Hveem R and S stability values and the Cohesimeter values. However, these measured properties are those of a highly compacted specimen. It is questionable whether these measured properties will give a good indication of the actual performance of the recycled mixture. In the fourth set of experiments, the effect of

different compactive efforts was investigated. The main objectives of this set of experiments were to study the effect of different compactive efforts on the response variables of the recycled mixtures and to determine how the measured response variables of the specimens compacted by 40 gyratory revolutions at 200 psi (1.38 MPa) could be applied to conditions of less or more compactive efforts.

The experimental design is shown in Table 4 in Chapter 4 (Design of the Experiment). The three compactive efforts studied were 10, 30 and 50 revolutions at 200 psi (1.38 MPa) ram pressure with the gyratory machine. The mix combination used was one that showed relatively high stability values in both the wet and the dry tests — the mixture with no virgin aggregate and 1% added AE residue (or 5.5% total asphalt content). 1% moisture was added initially to the mixtures. Both the dry and the wet (Water Sensitivity Test) testing conditions were used. Two replicate specimens were tested per cell at 1 day curing. The response variables measured were the Hveem R stability value, the Hveem S stability value, the Cohesimeter value, the specific gravity, the percent retained moisture (for dry test) and the percent absorbed moisture (for the water sensitivity test).

9.2 Analysis Of Results

The results of these experiments were analyzed with the aid of the Analysis of Variance statistical method. The physical trend of the response variables were studied by observing their mean values in each cell. The analysis of the results is presented in the following sections.

9.2.1 Model For Response Variables

The mathematical model for the response variables, to be used in the Analysis of Variance, is given below:

$$Y_{ijk} = \mu + N_i + T_j + NT_{ij} + \epsilon_{(ij)k}$$

where

Y_{ijk} = Response variable

μ = Overall mean

N_i = Effect of number of revolutions of gyratory compaction

T_j = Effect of condition of test (dry or wet test)

NT_{ij} = Effect of the interaction of N_i with T_j

$\epsilon_{(ij)k}$ = Random error, NID $(0, \sigma^2)$

The subscripts have the following values:

$$i = 1, 2, 3 ; \quad j, k = 1, 2 .$$

The two factors were fixed. The i values of 1, 2 and 3 correspond to the compactive efforts of 10, 30 and 50 revolutions, and the j values of 1 and 2 correspond to the dry and the wet testing conditions respectively.

9.2.2 Test For Homogeneity Of Variance

The Foster-Burr Q-Test for the homogeneity of variance was performed on the response variables. Their results were summarized in Table 14. All the response variables tested satisfied the homogeneity of variance at $\alpha = 0.01$ level.

TABLE 14: FOSTER-BURR Q-TEST FOR HOMOGENEITY OF VARIANCE (Study Design No.4)

<u>Variable</u>	<u>Degree Of Freedom</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
G _b	1	6	.3210	Accepted *
R	1	6	.6443	Accepted *
S	1	6	.3397	Accepted *
C	1	6	.5065	Accepted *

* $Q_{1,6,.01} = .744$

9.2.3 ANOVA

The results of the ANOVA for the response variables are summarized in Table 15. A typical ANOVA table is shown in Table B4 in the Appendices. Due to the small number of data, significance was tested at $\alpha = 0.10$ level for all the factors and response variables.

9.2.4 Hveem R And S Stability Values

Figure 33 shows the average Hveem R and S stability values plotted as functions of compactive efforts for the results of the dry and the Water Sensitivity Tests. It was noted that the R and the S values were highest at a compactive effort of 30 revolutions. The ANOVA results showed that the effect of compactive effort was not significant for the levels of compactive effort tested.

For the levels of compactive effort tested, the effect of water was significant for the R and the S values.

9.2.5 Cohesimeter Value

It was noted that the Cohesimeter values increased significantly with increasing compactive effort. Figure 34 depicts the average Cohesimeter values plotted as a function of compactive effort for the dry and the Water Sensitivity Test. The ANOVA results showed that the interaction effect of compaction with condition of test was significant. It was noted that the decrease in C-Value due to the effect of water was present only at the lower compactive efforts of 10 and 30 revolutions.

TABLE 15: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Study Design No.4)

<u>Source Of Variation</u>		Response Variable :	<u>G_b</u>	<u>S</u>	<u>R</u>	<u>C</u>
Compactive Effort,	N		S.	N.S.	N.S.	S.
Condition Of Test,	T		N.S.	S.	S.	N.S.
	NT		N.S.	N.S.	N.S.	S.

Note:

S. = Significant at $\alpha = 0.10$

N.S. = Not Significant at $\alpha = 0.10$

FIGURE 33 HVEEM R AND S STABILITY VALUES AS FUNCTIONS OF COMPACTIVE EFFORTS FOR DRY AND WET TESTS.

FIGURE 34 COHESION VALUES AS FUNCTIONS OF COMPACTIVE EFFORTS FOR DRY AND WET TESTS.

9.2.6 Specific Gravity And Percent Moisture Absorbed

Specific gravities of the specimens increased with increasing compactive effort. Figure 35 shows the average specific gravity as a function of compactive effort. The amount of moisture absorbed in the water sensitivity test decreased with increasing compactive effort (or with increasing specific gravity). Figure 36 presents the percent moisture absorbed as a function of compactive effort.

9.2.7 Percent Retained Moisture

The percent retained moisture at 1 day curing did not differ significantly for different compactive efforts. Figure 37 depicts the percent retained moisture plotted as a function of compactive effort.

9.3 Discussion Of Results

It has been shown that the Hveem R and S stability values of the recycled mixtures did not change significantly with compactive efforts from 10 to 50 revolutions at 200 psi (1.38 MPa) ram pressure of the gyratory machine. The R and the S values measured previously from the specimens compacted by 40 revolutions at 200 psi (1.38 MPa) could be representative values of the mixtures for a wide range of compaction conditions.

The Cohesimeter value and the specific gravity increased with compactive effort. Adjustments in these values would have to be made for different compaction conditions.

In general, the high compactive effort used (40 revolutions at 200 psi (1.38 MPa)) is quite suitable for the evaluation of the

FIGURE 35

SPECIFIC GRAVITY AS FUNCTION
OF COMPACTIVE EFFORT.

FIGURE 36 PERCENT WATER ABSORBED AS FUNCTION OF COMPACTIVE EFFORT IN WATER SENSITIVITY TEST.

FIGURE 37 PERCENT WATER RETAINED AS FUNCTION OF COMPACTIVE EFFORT (1 DAY CURING).

recycled mixture. It can detect signs of instability that may occur after additional traffic compaction, and still gives representative R and S stability values for a wide range of compaction conditions.

This same compactive effort (40 revolutions at 200 psi (1.38 MPa)) was used in the rest of the study.

CHAPTER 10

EFFECTS OF BINDER TYPES ON PROPERTIES OF RECYCLED MIXTURES

10.1 Introduction

In the fifth set of experiments, three additional bituminous materials (AE-90, MC-3000 and AC-2.5) were investigated as binders for the recycled pavement mixtures. The experimental design is shown in Table 5 in Chapter 4 (Design of the Experiment).

For each binder material, there were three groups of specimens:

1. Specimens with 0% virgin aggregate and 5.5% total binder content.
2. Specimens with 25% Type II virgin aggregate and 4.5% total binder content.
3. Specimens with 25% Type II virgin aggregate and 5.5% total binder content.

The two levels of curing time were 1 day and 7 days. For each case, three replicate specimens were tested in a dry condition and two were tested in a wet condition (Water Sensitivity Test).

The response variables measured were the Specific Gravity, the Hveem R stability value, the Hveem S stability value, the Conesimeter value, the Percent Moisture Retained (for specimens with added AE) and the Percent Moisture Absorbed (for Water Sensitivity Test).

Mixes with the same added binder were tested in the same period of time. A restriction on the randomization was thus imposed.

The main concern of this chapter is to answer the following questions.

1. What are the differences in the physical properties of the recycled mixtures with different added binders?
2. Which asphalt material is more suitable to be used as an additional binder to the cold recycled mixture?

In the following sections, the results of the testing for each added binder are analyzed separately. Following these analyses, a comparison of the effects of different added binder materials is made.

10.2 Mixtures With AE-90 As The Added Binder

In this section, the performance of AE-90 as the added binder to the recycled mixtures is evaluated and compared to that of AE-150.

The preparation and testing procedures for these specimens were the same as those for the specimens with AE-150 added. One percent moisture was added to all the mixtures initially. When virgin aggregate was used, the asphalt emulsion was first added to the virgin aggregate and mixed for 30 seconds before mixing with the pavement material.

The means of the response variables in each mix combination were used to observe for their physical trends. They were also compared to those of the similar mixtures with AE-150 as the added virgin binder. The Analysis of Variance was performed on the response variables from this group of specimens. Its results were also compared to the results

of the ANOVA on the response variables from the similar specimens with AE-150 as the added virgin binder.

10.2.1 Model For The Response Variables

The mathematical model for the response variables for this group of specimens was given below:

$$Y_{ijkl} = \mu + A_i + C_j + T_k + AC_{ij} + AT_{ik} + CT_{jk} + ACT_{ijk} + \epsilon_{(ijk)l}$$

where

Y_{ijkl} = Response variable

μ = Overall mean

A_i = Effect of asphalt content and virgin aggregate

C_j = Effect of curing time

T_k = Effect of condition of test (wet or dry)

AC_{ij} = Effect of the interaction of A_i with C_j

CT_{jk} = Effect of interaction of C_j with T_k

AT_{ik} = Effect of interaction of A_i with T_k

ACT_{ijk} = Effect of interaction of A_i with C_j with T_k

$\epsilon_{(ijk)l}$ = Error term, NID(0, σ^2)

The subscripts have the following values:

$$i, l = 1, 2, 3 ; \quad j, k = 1, 2 .$$

The i value of 1 corresponds to the mixture with no virgin aggregate and 5.5% total asphalt content; the i value of 2 corresponds to 25% virgin aggregate and 4.5% total asphalt; the i value of 3 corresponds to 25% virgin aggregate and 5.5% total asphalt. The j values of 1 and 2 correspond to 1 day and 7 days curing respectively. The k values of 1 and 2 correspond to the dry and the wet tests.

10.2.2 Test For Homogeneity Of Variance

The Foster-Burr Q-Test for homogeneity of variance was performed on the response variables. All the response variables satisfied the homogeneity of variance at $\alpha = 0.01$ level. Results of the Foster-Burr Q-Test were summarized in Table 16.

10.2.3 ANOVA

The results of the ANOVA for the response variables for this group of specimens are summarized in Table 17. For ease of comparison between the two binders, AE-150 and AE-90, ANOVA was also performed on the response variables for the similar specimens with AE-150 added. The results of this ANOVA are summarized in Table 18. A typical ANOVA table for a response variable is shown in Table B5 in the Appendices.

10.2.4 Hveem R And S Stability Values

Figure 38 shows the average Hveem R stability values in the dry and the water sensitivity tests as functions of curing time for the three mix combinations. It was noted that the mixture with 25% virgin aggregate and 4.5% total asphalt content had the highest R-Value in the dry test. The mixture with no virgin aggregate and 5.5% total asphalt content had the highest R-Value in the wet test. It was noted that the mixture with 4.5% asphalt experienced a significant reduction in strength due to the action of water.

The average Hveem S stability values in the dry and the water sensitivity tests are presented in Figure 39. It was noted that the mixture with no virgin aggregate and 5.5% asphalt had the highest S-Values.

TABLE 16: BURR-FOSTER Q-TEST FOR HOMOGENEITY OF VARIANCE (Mixtures With AE-90 Added)

<u>Variable</u>	<u>Degree Of Freedom</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
G _b	2	12	.1747	Accepted*
S	2	12	.1441	Accepted*
R	2	12	.2414	Accepted*
C	2	12	.1937	Accepted*

* $Q_{2,12,.01} = .273$

TABLE 17: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Mixtures with AE-90 Added)

<u>Source Of Variation</u>	Response Variable :	<u>G_b</u>	<u>S</u>	<u>R</u>	<u>C</u>
Aggregate & %AS _t ,	A	S.	S.	S.	S.
Curing Time ,	C	N.S.	S.	S.	S.
Condition Of Test ,	T	N.S.	S.	N.S.	S.
	AC	N.S.	N.S.	N.S.	S.
	AT	N.S.	S.	N.S.	N.S.
	CT	N.S.	S.	N.S.	N.S.
	ACT	N.S.	N.S.	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

TABLE 18: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Mixtures With AE-150 Added)

Source Of Variation	Response Variable :	<u>G_b</u>	<u>S</u>	<u>R</u>	<u>C</u>
Aggregate & %AS _t ,	A	S.	S.	S.	S.
Curing Time ,	C	N.S.	S.	S.	S.
Condition Of Test ,	T	N.S.	N.S.	N.S.	S.
	AC	N.S.	N.S.	N.S.	N.S.
	AT	N.S.	N.S.	N.S.	N.S.
	CT	N.S.	N.S.	N.S.	N.S.
	ACT	N.S.	N.S.	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

FIGURE 38 HVEEM R STABILITY VALUES IN DRY AND WET TEST FOR MIXTURES WITH AE-90 ADDED

FIGURE 39 HVEEM S STABILITY VALUES IN DRY AND WET TEST FOR MIXTURES WITH AE-90 ADDED

The Hveem R and S stability values increased significantly with curing time. The reduction in the S-Value due to the effect of water was significant. The effect of water was greater for lower asphalt content and for shorter curing time. (The ANOVA results showed that the effects of the interaction of curing time with condition of test and the interaction of percent asphalt and virgin aggregate with condition of test were significant to the S-Values.)

These mixtures (with AE-90 binder) generally showed higher S and R values than the similar mixtures with AE-150 binder, with the exception of the mixture with 25% virgin aggregate and 4.5% asphalt content. These mixtures (with AE-90 binder) were more susceptible to the action of water than the similar mixtures with AE-150 binder. For the mixtures with AE-90 binder, the ANOVA results indicated that the effect of water was significant to the S-Values. For the similar mixtures with AE-150 binder, the ANOVA results showed that the effect of water was not significant either to the R or to the S values.

10.2.5 Cohesimeter Values

The Cohesimeter values of the mixtures with AE-90 binder were close to those of the mixtures with AE-150. Figure 40 shows the average C-Values for the mixtures with AE-90 binder. The C-Values for these mixtures all exceeded 100. The effects of asphalt content and virgin aggregate, curing time, and condition of test were significant.

10.2.6 Specific Gravity And Percent Absorbed Moisture

The effect of virgin aggregate and asphalt content was significant to the specific gravity. The percent absorbed moisture (in the water

FIGURE 40 • AVERAGE COHESION VALUES FOR MIXTURES WITH AE-90 ADDED

sensitivity test) was higher for specimen with lower specific gravity. These were the same for the specimens with AE-150 added.

Figure 41 shows the comparisons of the specific gravities and percents absorbed moisture of the mixtures with the two added binders (AE-90 and AE-150).

10.2.7 Percent Moisture Retained

The percents moisture retained (at time of testing) of these specimens were close to those of the similar mixtures with AE-150 binder. This could indicate that the curing rates of the two grades of asphalt emulsion were similar.

10.2.8 General Observation

AE-90 was less viscous than AE-150 and was easier to mix with the pavement material or the virgin aggregate.

It was noted that the asphalt emulsion coated the pavement material and the virgin aggregate fairly well. The one hour oven curing at 140°F (60°C) also further improved the coating property.

No indication of instability was observed during the gyratory compaction of the specimens.

10.2.9 Summary Of Results

The finding of the analysis in this section can be summarized into the following observations.

1. Mixtures with AE-90 as the added binder generally had higher Hveem R and S stability values than those with AE-150 as the added binder.

FIGURE 41 SPECIFIC GRAVITY (G_b) AND PERCENT ABSORBED MOISTURE ($\%W_d$) FOR MIXTURES WITH AE-90 AND AE-150 ADDED

2. The effect of water was greater on the mixtures with AE-90 than the mixtures with AE-150.
3. The Cohesimeter values of the mixtures with AE-90 were close to those of the mixtures with AE-150.
4. The curing rate of AE-90 was close to that of AE-150.
5. The specific gravity of the specimens with AE-90 was slightly lower than that of the specimens with AE-150.

10.3 Mixtures With MC-3000 As The Added Binder

This section deals with the evaluation of the recycled mixtures with MC-3000 as the added binder.

MC-3000 is a very viscous cutback at room temperature. It would be very difficult to pour and mix at room temperature. In the preparation of the specimens, the cutback was heated to a temperature of 200°F (93°C) before mixing with the recycled pavement material. For the mixture with 25% added virgin aggregate, half of the cutback to be added was first mixed with the virgin aggregate for half a minute; the virgin aggregate was then mixed with the pavement material and the rest of the cutback. No moisture was added to the mixture.

The curing process for the mixtures with added asphalt emulsion was used to obtain similar experimental conditions. The mixtures were cured in the oven for 1 hour at 140°F (60°C) and remixed for 30 seconds before compaction.

For ease of handling, some specimens of the same parameters were prepared and tested at the same time. This created a restriction on the randomization process of the testing of the samples, and thus a

restriction error was present. It was the author's belief that this restriction error was significant for the Cohesimeter value. Thus, ANOVA was not performed on the Cohesimeter values.

10.3.1 ANOVA

The mathematical model used for the specimens with AE-90 added was used here for the Analysis of Variance. This model was described in Section 10.2.1.

The Foster-Burr Q-Test was performed on the response variables. All the response variables satisfied the homogeneity of variance assumption at $\alpha = 0.01$ level. Its results are summarized in Table 19.

The results of the ANOVA on the response variables are summarized in Table 20.

10.3.2 Hveem R And S Stability Values

The effect of curing time was insignificant to the R and the S values, according to the ANOVA results. The R and the S values for this group of specimens were close to those of the similar mixtures with added AE-90 at 7 days curing. Figures 42 and 43 present the R and the S values for the dry and the wet tests. It was noted that the effect of water was greater for the specimens of lower binder content. (Specimens with 25% virgin aggregate and 4.5% binder experienced a significant reduction in strength.) The ANOVA results indicated that the effect of water was significant to the S-Values but not to the R-Values.

The specimens with 25% virgin aggregate and 4.5% binder had the highest R and S values.

TABLE 19: BURR-FOSTER Q-TEST FOR HOMOGENEITY OF VARIANCE (Mixtures With MC-3000 Added)

<u>Variable</u>	<u>Degree Of Freedom</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
G _b	2	12	.1083	Accepted*
S	2	12	.1372	Accepted*
R	2	12	.2175	Accepted*

Note:

$$* Q_{2,12,.01} = .273$$

TABLE 20: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Mixtures With MC-3000 Added)

<u>Source Of Variation</u>	Response Variable :	<u>G_b</u>	<u>S</u>	<u>R</u>
Aggregate & %AS _t , A		S.	S.	S.
Curing Time , C		N.S.	N.S.	N.S.
Condition Of Test , T		N.S.	S.	N.S.
	AC	N.S.	N.S.	N.S.
	AT	N.S.	N.S.	N.S.
	CT	N.S.	N.S.	N.S.
	ACT	N.S.	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

FIGURE 42 HVEEM R STABILITY VALUES IN DRY AND WET TEST FOR MIXTURES WITH MC-3000 ADDED

FIGURE 43 HVEEM S STABILITY VALUES IN DRY AND WET TEST FOR MIXTURES WITH MC-3000 ADDED

10.3.3 Cohesimeter Values

The mixture with no virgin aggregate and 5.5% asphalt had the highest average Cohesimeter value among the three groups of specimens. This is similar to the case of the mixtures with asphalt emulsion added. The effects of curing time and water were not significant. The average Cohesimeter values of these specimens were close to those of the mixtures with added AE-90 at 7 days curing.

10.3.4 Specific Gravity And Percent Absorbed Moisture

The average specific gravities and the percents absorbed moisture of these specimens were close to those of the specimens with asphalt emulsion added (within 1%). The mixture with 25% virgin aggregate and 5.5% asphalt had the highest specific gravity and the least permeable voids.

10.3.5 General Observation

When the cutback was heated up to 200°F (93°C) for mixing, some smoke and odor were noted. The cutback cooled rapidly in the initial mixing process and combined with the aggregate fines to form small clumps. The pavement material was observed to be only partially coated. The coating of the pavement material was greatly improved by the one hour oven curing and the remixing process.

No sign of instability was observed during the compaction process.

10.3.6 Summary Of Results

The findings in this section can be summarized into the following observations.

1. Curing time did not have any significant effect on the properties of the recycled mixtures with MC-3000 added.
2. The Hveem R stability value, the Hveem S stability value and the Cohesimeter value of these specimens (with MC-3000 added) were close to those of the similar specimens with added AE-90.
3. The effect of water was greater on the specimens of lower binder content.
4. The Hveem R stability value, the Hveem S stability value and the Cohesimeter value were affected mainly by the binder content and the virgin aggregate.
5. The specific gravities of these specimens were similar to those of the specimens with added asphalt emulsion.

10.4 Mixtures With AC-2.5 As The Added Binder

In this section, the properties of the recycled mixtures with AC-2.5 as the added binder are evaluated.

The asphalt cement to be added was heated to 350°F (177°C) before being mixed with the recycled material. The preparation procedures for these mixtures were similar to those for the mixtures with added MC-3000, described in Section 10.3. Some specimens of the same parameters were prepared and tested at the same time. A restriction on the randomization process was thus present.

The three groups of specimens (see 10.1) showed very similar properties. Due to the presence of the restriction error and the closeness of the measured variables, it was decided to perform the ANOVA only on the Hveem R and S stability values.

10.4.1 ANOVA

The mathematical model used for the specimens with AE-90 and MC-3000 was again used for the Analysis of Variance.

Table 21 presents the results of the Foster-Burr Q-Test for homogeneity of variance. The two variables satisfied the homogeneity of variance assumption at $\alpha = 0.01$ level. Results of the ANOVA are summarized in Table 22.

10.4.2 Hveem R And S Stability Values

The effects of water and curing time were not significant to the Hveem R and S stability values, for the mixtures with AC-2.5 as the added binder. The three groups of specimens had approximately the same R-Values. The specimen with 25% virgin aggregate and 4.5% asphalt had the highest average S-Value. ANOVA results showed that the differences among the R-Values of the three groups of specimens were not significant. However, the differences among the S-Values of the three groups were significant. Figures 44 and 45 show the R and the S values of these specimens in the dry and the wet tests at 1 day and 7 days curing.

10.4.3 Cohesimeter Value

The mixture with no virgin aggregate and 5.5% asphalt had the highest Cohesimeter value, among the three groups of specimens. This is similar to the results of the mixtures with the other binders.

The Cohesimeter values were slightly higher than those of the mixtures with the other binders.

TABLE 21: BURR-FOSTER Q-TEST FOR HOMOGENEITY OF VARIANCE (Mixtures With AC-2.5 Added)

<u>Variable</u>	<u>Degree Of Freedom</u>	<u>No. Of Samples</u>	<u>Q Statistics</u>	<u>Homogeneity Of Variance</u>
S	2	12	.1216	Accepted *
R	2	12	.2730	Accepted *

* $Q_{2,12,.01} = .273$

TABLE 22: SUMMARY OF ANOVA RESULTS FOR RESPONSE VARIABLES
(Mixtures With AC-2.5 Added)

<u>Source Of Variation</u>	<u>Response Variable :</u>	<u>S</u>	<u>R</u>
Aggregate & %AS _t ,	A	S.	N.S.
Curing Time ,	C	N.S.	N.S.
Condition Of Test ,	T	N.S.	N.S.
	AC	N.S.	N.S.
	AT	N.S.	N.S.
	CT	N.S.	N.S.
	ACT	N.S.	N.S.

Note:

S. = Significant at $\alpha = 0.05$

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

FIGURE 44 HVEEM R STABILITY VALUES IN THE DRY AND WET TEST FOR MIXTURES WITH AC-2.5 ADDED

FIGURE 45 HVEEM S STABILITY VALUES IN THE DRY AND WET TEST FOR MIXTURES WITH AC-2.5 ADDED

10.4.4 Specific Gravity And Percent Absorbed Moisture

The mixture with 25% virgin aggregate and 5.5% asphalt had the highest specific gravity and the least permeable voids, among the three groups of specimens.

The average specific gravities of these specimens (with AC-2.5) were close to those of the mixtures with the other binder materials (within 1%).

10.4.5 General Observation

Some smoke and odor were noted during the heating and the mixing process of the asphalt cement. The asphalt cement hardened quite rapidly during the cold mixing process, and the mixing became quite difficult. The pavement material was observed to be only partially coated with the added asphalt cement. After the one hour's oven curing at 140°F (60°C), the mixture was at a temperature of around 120°F (49°C) and the virgin asphalt cement was softer and easier to mix with. The coating of the pavement material was noted to improve greatly after the one hour's oven curing and the 30 seconds' remixing.

All the specimens were observed to be stable during the gyratory compaction process.

10.4.6 Summary Of Results

The findings in this section can be summarized into the following observations.

1. Curing time did not have any significant effect on the properties of the recycled mixtures with AC-2.5 added.

2. The Hveem R and S stability values were not affected by the water sensitivity test.
3. The three groups of specimens (see 10.1) had approximately the same Hveem R stability values. Their differences in Hveem S stability values and Cohesimeter values were significant. The specimen with 25% virgin aggregate and 5.5% asphalt had the highest S-Value. The specimens with no virgin aggregate and 5.5% asphalt had the highest C-Value.
4. The specific gravities of these specimens (with AC-2.5) were similar to those of the specimens with the other added binder materials.

10.5 Comparisons Of Effects Of Different Binders

In this section, comparisons of the four binder materials (AE-150, AE-90, MC-3000 and AC-2.5) as to their effects on the properties of the recycled mixtures are made. The means of the response variables in the dry and the water sensitivity tests were used in making the comparisons.

For each binder material, the data used in making the comparisons were from the three groups of specimens, namely:

1. 0% virgin aggregate and 5.5% total asphalt content;
2. 25% Type II virgin aggregate and 4.5% total asphalt content;
3. 25% Type II virgin aggregate and 5.5% total asphalt content.

10.5.1 Comparisons In Hveem R And S Stability Values

The Hveem R and S stability values (in dry and wet test) of the mixtures with AE-90, MC-3000 and AC-2.5 as the added binders have been presented previously in Figures 38, 39, 42, 43, 44 and 45. For the

purpose of comparisons of the four different binders, the R and S values of the similar mixtures with AE-150 as the added binders are presented in Figures 46 and 47.

It was noted that for the group of specimens with 25% virgin aggregate and 4.5% total binder content, there were only slight differences in stability values among the mixtures with the four different binder materials. For the other two groups of specimens, the general trends indicated that the order of decreasing stability values, in terms of the added binders, was: AC-2.5, MC-3000, AE-90 and AE-150. The differences in stability values among the different binders were most significant for the group of specimens with 25% virgin aggregate and 5.5% total asphalt content. A proposed explanation for the behavior of these mixtures is described in Section 10.6.

The mixtures with AC-2.5 as the added binder were most resistant to the action of water. (They showed the highest percentages of retained stabilities in the water sensitivity test.) The trends showed that the binders, in the order of decreasing resistance to water, were AC-2.5, AE-150, MC-3000 and AE-90.

The mixtures with asphalt emulsion added showed significant increase in R and S values with increasing curing time. The mixtures with added MC-3000 and AC-2.5 did not.

10.5.2 Comparisons In Cohesimeter Values

Due to the presence of the restriction errors (due to the restriction on randomization) and the wide scatterness of the obtained data, comparisons in Cohesimeter values using the obtained data might

FIGURE 46 HVEEM R STABILITY VALUES IN DRY AND WET TEST
FOR MIXTURES WITH AE-150 ADDED

FIGURE 47 HVEEM S STABILITY VALUES IN DRY AND WET TEST FOR MIXTURES WITH AE-150 ADDED

be misleading. It was decided to use the overall mean (overall average of the dry and the wet test results at 1 day and 7 days cure) of each mix combination for the purpose of observing the general physical trends.

Figure 48 presents the average Cohesimeter values of the different mixtures. It was noted that the group of specimens of 0% virgin aggregate and 5.5% asphalt had the highest average C-Values. The mixtures with the added binder AC-2.5 showed slightly higher average C-Values than the mixtures with the other binders. The effect of asphalt content and virgin aggregate was greater than that of binder type. All mixtures had average C-Values of above 100.

10.5.3 Comparisons In Specific Gravities

Figure 49 presents the average specific gravities of different mixtures. It was noted that the mixtures of 25% virgin aggregate and 5.5% asphalt had the highest specific gravities. Specific gravity was affected mainly by the asphalt content and virgin aggregate.

10.6 A Simplified Model For Recycled Mixture

A simplified model for the recycled mixture is presented in this section to explain the behavior of these recycled mixtures. For ease of illustrating the model, some hypothetical figures are used and serve only for illustrative purposes.

The asphalt binders in old pavement materials are usually hardened and have lost most of their original characteristics. For practical purpose, the asphalt is considered to be only partially "effective". New asphalt will have to be added to the recycled mixture to replace

FIGURE 48 AVERAGE COHESIONETER VALUES OF MIXTURES WITH DIFFERENT ADDED BINDERS

FIGURE 49 SPECIFIC GRAVITIES (G_b) OF MIXTURES WITH DIFFERENT ADDED BINDERS

the "ineffective" portion of the existing binder, in order to restore the mixture to the desired characteristics. Various binders, when added, may have rejuvenating effects on the old asphalt. The total amount of effective asphalt is the sum of the amount of virgin asphalt, the amount of original effective asphalt and the amount of effectively rejuvenated asphalt. This can be expressed in the following equation:

$$A_{te} = A_v + A_e + A_r$$

where

A_{te} = Total effective asphalt content, %

A_v = Amount of added virgin asphalt, %

A_e = Amount of original effective asphalt content, %

A_r = Amount of rejuvenated asphalt, %

The amount of rejuvenated asphalt depends on the type and amount of virgin asphalt (or rejuvenating agent), the amount of ineffective asphalt, and the curing time. This can be expressed in the following equation.

$$A_r = A_r(B, A_v, A_{ie}, T)$$

where

B = Type of added virgin binder

A_{ie} = Amount of ineffective asphalt, %

T = Curing time

The stability of a bituminous mixture depends mainly on the type of aggregate, the gradation of aggregate and the asphalt content. When the gradation of aggregate and the type of aggregate are fixed, the stability of a mixture will be mainly a function of the total asphalt content. In the case of the recycled mixtures considered, it could be

assumed that the stability of the mixtures was mainly a function of the total effective asphalt content. This can be expressed by the following equation:

$$\begin{aligned} S &= S(A_{te}) \\ &= S(A_v + A_e + A_r) \end{aligned}$$

where

S = Stability of the mixture

Since the rejuvenating effect of the virgin asphalt is a function of time, the total "effective" asphalt content will change with time, and thus the stability of the mixture will also change with time. The measured stability value of a mixture will only indicate the short term property of the mixture. However, it is believed that the combination of the high compactive effort and the shearing action of the gyratory compactor forces the new and the old binder to act together and give an indication of the possible rejuvenating action that could take place. The behavior measured during the compaction process thus could indicate the long term behavior of the mixtures.

The pavement material used in this study was not severely aged. (Recovered asphalt had an average penetration of 38). Most of the asphalt can be considered to be effective. Thus, the asphalt binder in the pavement material is assumed to be 80% "effective". Figure 50 depicts the percentages of the total effective asphalt content of the four types of mixtures, with this assumption.

Added binders with different rejuvenating effects will cause the recycled mixtures to have different total effective asphalt contents. These differences will be greater when the amount of added virgin

FIGURE 50 TOTAL EFFECTIVE ASPHALT CONTENT OF FOUR MIX COMBINATIONS

NOTE: * Percent Asphalt

binder is greater. For the mixture of 25% virgin aggregate and 5.5% total asphalt, the virgin binder amounts to 2.25% of the total mix. The differences in the rejuvenating effect of the different binders are manifested in this group of mixtures. For this group of mixtures, significant differences in Hveem R and S stability values are noted among the mixtures of different added binders (see Section 10.5.1). At this level of asphalt content, it is expected that stabilities will decrease with increasing asphalt content. The mixtures with virgin binder of greater rejuvenating effect will have higher effective asphalt content and thus stabilities of lower values. Thus, the binders, in the order of decreasing rejuvenating effect, are AE-150, AE-90, MC-3000 and AC-2.5. (For this group of mixtures, the order of decreasing stabilities, in terms of the added binders, was: AC-2.5, MC-3000, AE-90 and AE-150.)

Similar trend was shown in the group of mixtures with 0% virgin aggregate and 5.5% total asphalt. (Their effective asphalt contents were approximately the same as those of the mixtures of 25% virgin aggregate and 5.5% total asphalt.) However, since the amount of added binder was much less, the differences in the rejuvenating effects of the different binders were less apparent.

In summary, in the above model, it is assumed that the stability of the recycled mixture was affected mainly by its total effective asphalt content. Different rejuvenating effects of different virgin binders added caused the differences in the total effective asphalt content and thus the differences in the stability values as well.

10.7 Summary And Discussion On The Differences Of The Four Binders

It has been noted that the stabilities of the mixtures depend mainly on the percent total asphalt content (or the total effective asphalt content). Thus, the most important factor in the design of the recycled mixture will be the control of the percent total effective asphalt content (taking into account the rejuvenating effects of the added binders).

Both the MC-3000 and AC-2.5 had to be heated to a high temperature before they could be mixed with the pavement material. This was not necessary for AE-150 and AE-90. Asphalt emulsions can coat the pavement material fairly well in the cold mixing process. However, some curing time has to be allowed for the mixtures with added asphalt emulsion to reach their fullest strengths. Given sufficient curing time, the strengths of the mixtures with added asphalt emulsion will be comparable to those of the mixtures with added MC-3000 or AC-2.5.

In consideration of the resistance to water, the binder AC-2.5 would be preferred over MC-3000, and AE-150 would be preferred over AE-90.

In actual field construction, the performance of the recycled mixtures will also depend on how well the virgin aggregate and asphalt is mixed with the old pavement material, and on how well the virgin asphalt coats the aggregate. The choice of binder material should be determined by the construction equipment and methods available, the amount of time available for curing, and economic factors.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The conclusions reported here are from an in-depth investigation of only one pavement material, and thus can only be considered applicable to this type of pavement material. They are also limited to the levels of factors tested. Conclusions made at the end of the previous chapters are summarized as follows:

1. The instability of the recycled mixtures could be detected during gyratory compaction by the increasing gyratory angle in the gyrograph. The unstable compacted specimens showed the phenomena of asphalt bleeding. The cause of this instability was attributed to the excessive asphalt content of the mix. Compaction with the gyratory machine was a feasible way to detect this problem.
2. The total percent asphalt content (or the total percent effective asphalt content) was the controlling factor for the properties of the recycled mixtures.
3. When asphalt emulsion was used as additional binder, the addition of water could facilitate the mixing process. However, for the levels of added moisture tested, the effect of added moisture to the stability of the mixtures was not significant.

4. Recycled mixtures with added asphalt emulsion displayed an increase in Hveem R and S stability and Cohesimeter values with curing time. Those mixtures with added MC-3000 and AC-2.5 did not.
5. When coarser virgin aggregates were used, less virgin binder was required since the same weight of coarser aggregate had less surface area to be coated.
6. Virgin aggregate could be added to the recycled mixture to produce a stable mix.
7. The effects of water on the properties of the recycled mixtures were tested using the Water Sensitivity Test. The effect of water on the recycled mixtures increased with decreasing total asphalt content. When asphalt emulsion was used, the effect of water also decreased with curing time. The binders, in the order of decreasing resistance to water, are AC-2.5, AE-150, MC-3000 and AE-90.
8. For the range of compactive efforts from 10 to 50 revolutions at 200 psi (1.38 MPa) with the gyratory machine, the Hveem R and S stability values of the recycled mixtures did not change significantly. The Cohesimeter values and the specific gravities increased with increasing compactive efforts.
9. 40 revolutions at 200 psi (1.38 MPa) with the Gyratory machine was a suitable compactive effort for the testing of the recycled mixtures. Specimens displayed Hveem R and S stability values that were representative of the mixture over a wide range of compaction conditions. The compaction technique could

also detect indication of instability in the various recycled mixtures.

10. It was hypothesized that virgin binder had a rejuvenating effect on the old asphalt. The binders, in the order of decreasing rejuvenating effects, are AE-150, AE-90, MC-3000 and AC-2.5.
11. The relatively stable recycled mixtures (such as mixtures of 4.5% and 5.5% total asphalt content) had Hveem R stability values of above 85. They would be suitable for use as a stabilized base material.

11.2 Recommendations

Based on the results of this laboratory study, the author makes the following recommendations, regarding the laboratory design of the cold-mix recycled pavement.

11.2.1 Compaction Of Specimens

It is believed that a high compactive effort with the gyratory machine will force the old and the new asphalt to act as one. The instability of the mixture which may occur after some period of traffic compaction and/or rejuvenating action might be detected in the laboratory analysis if a high compactive effort with the gyratory machine is used. The effect of the rejuvenating action and the additional traffic compaction on the recycled mixtures are hard to predict. The author thus recommends that a high compactive effort should be used in the laboratory analysis of cold-recycled mixtures to detect this problem.

The gyratory machine should be used to form the specimens since it is known to give a more consistent compactive effort.

11.2.2 Recommended Testing Procedures for Cold-Recycled Mixtures

The testing procedures employed in this study were effective in evaluating the properties of cold-recycled mixtures. (Refer to Section 5.3, 5.4 & 5.5 for details). It is recommended that these testing procedures be used to evaluate the performance of cold-recycled mixes. They are summarized briefly as follows:

1. The recycled mixtures are to be compacted cold at a high compactive effort with the gyratory machine in accordance to ASTM Standard Designation D 3387-74T. A compactive effort of 40 revolutions at 200 psi (1.38 MPa) can be used.
2. The compacted samples are to be tested in the Stabilometer for their Hveem R stability values and modified Hveem S stability values. After the stabilometer test, the specimens are to be left in the oven at 140°F (60°C) for at least 2 hours and tested in the Cohesimeter at 140°F (60°C). Refer to ASTM Standard D 1560-71 and D2844-69).
3. Mixtures that do not show signs of instability at the high compactive effort of 40 revolutions at 200 psi (1-38 MPa) ram pressure can be further tested to obtain their representative properties at various stages of traffic compaction. These mixtures are to be compacted with the gyratory machine to a density compatible to the actual field conditions. The specimens are to be tested in a similar manner for their Hveem R and S stability values and C- values.

4. The Water Sensitivity Test as modified from the suggested Asphalt Institute method is to be used to determine the effect of moisture on the recycled mixtures. (Refer to Section 5.4).
5. The Hveem R and S stability and Cohesimeter values from the dry and the water sensitivity tests can be compared to evaluate the performance of the mixtures. The R-Value alone should be sufficient for the evaluation of the stability of the mixtures; however, the S-Value can be used to differentiate mixtures that had very similar R-Values. (For relatively stable mixtures, the R-Values are quite insensitive to the changes in stability.)

CHAPTER 12

RECOMMENDATIONS FOR FURTHER RESEARCH

The author would like to make the following recommendations for further research in the laboratory analysis of cold recycled mixtures.

1. This experimental study was limited to only one type of pavement material (in which the asphalt binder was only slightly hardened and the aggregate show no significant degradation). The laboratory investigations should be extended to include a pavement material whose binder is severely hardened and one whose aggregate has experienced severe degradation.
2. A fundamental property of asphalt mixture is the Resilient Modulus. The fundamental properties of the cold-recycled mixtures would be better understood if the resilient modulus of the recycled mixtures were measured. The Resilient Modulus Test is a non-destructive test. The same specimens could be tested repeatedly at different times to study the effect of curing time. The Resilient Modulus of a recycled mixture would be a valuable parameter for the design of flexible pavement thickness.
3. In this laboratory study, the three response variables used to evaluate the performance of the recycled mixtures were the

Hveem R stability value, the Hveem S stability value and the Cohesimeter value. Whether or not these variables give indication of the long term actual performance of the recycled mixtures, as they do to the fresh asphalt mixtures, would have to be further evaluated through a field study of the recycled pavements.

4. The results of this study show that the gyratory machine is a potentially valuable tool for the evaluation of recycled mixtures. An in-depth study of the gyratory compaction device as a means to evaluate long time performance of the recycled mixtures is recommended.

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APPENDICES

The three Appendices to this Report are not included in this copy of the Report. They are titled as follows:

Appendix A: Feasibility Study of Repeated Testing on the Same Specimens Using Hveem Stabilometer

Appendix B: Typical ANOVA Tables

Appendix C: Summary of Data

A copy of any or all of the Appendices may be obtained by writing to:

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